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# Stronger Arctic amplification from ozone-depleting substances than from carbon dioxide

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#### Abstract

LETTER

Arctic amplification (AA)—the greater warming of the Arctic near-surface temperature relative to its global mean value—is a prominent feature of the climate response to increasing greenhouse gases. Recent work has revealed the importance of ozone-depleting substances (ODS) in contributing to Arctic warming and sea-ice loss. Here, using ensembles of climate model integrations, we expand on that work and directly contrast Arctic warming from ODS to that from carbon dioxide ( $CO_2$ ), over the 1955–2005 period when ODS loading peaked. We find that the Arctic warming and sea-ice loss from ODS are slightly more than half (52%–59%) those from  $CO_2$ . We further show that the strength of AA for ODS is 1.44 times larger than that for  $CO_2$ , and that this mainly stems from more positive Planck, albedo, lapse-rate, and cloud feedbacks. Our results suggest that AA would be considerably stronger than presently observed had the Montreal Protocol not been signed.

#### 1. Introduction

Arctic amplification (AA)—the enhanced surface warming of the Arctic compared to the global mean is a prominent feature of climate change. It has been detected in observations in recent decades, and is robustly simulated by global climate models (Holland and Bitz 2003, Serreze *et al* 2009, Hartmann *et al* 2013). Within the Arctic, AA has resulted in substantial impacts on a wide spectrum of natural and human systems (Meredith *et al* 2019). Outside the Arctic, AA has been claimed to affect the frequency of extreme weather events in midlatitudes by altering the large-scale atmospheric circulation e.g., Francis and Vavrus (2012), Cohen *et al* (2014), Coumou *et al* (2018) although these claims and their underlying mechanisms are hotly debated e.g., Barnes (2013), Kretschmer *et al* (2016), Blackport and Screen (2020), Cohen *et al* (2020), Liang *et al* (2021). Understanding the causes of AA is, thus, not only an important scientific endeavour, but also one with regional and possibly global implications (Meredith *et al* 2019).

Much attention has been devoted to exploring the mechanisms behind AA. Many studies have emphasized the role of local feedback processes e.g., Goosse *et al* (2018), Stuecker *et al* (2018), Beer *et al* (2020), Feldl *et al* (2020), Chung *et al* (2021), of heat and moisture transport from lower latitudes e.g., Hwang *et al* (2011), Graversen and Burtu (2016), Gong *et al* (2017), Yang and Magnusdottir (2017), Yoshimori *et al* (2017), Graversen and Langen (2019), or even of biological processes e.g., Swann *et al* (2010), Park *et al* (2015, 2020), Pefanis *et al* (2020). However, much uncertainty remains as to the relative contributions

Less attention, however, has been devoted to assessing which anthropogenic forcings might be responsible for AA. There is little doubt that wellmixed greenhouse gases (GHGs) are the most important anthropogenic driver of Arctic warming e.g., Najafi et al (2015), Stjern et al (2019). While it is often assumed that the vast majority of the Arctic warming comes from CO<sub>2</sub>, a recent study (Polvani et al 2020) has reported that Arctic warming would have been reduced by a factor of two if the atmospheric amount of ozone-depleting substances (hereafter, ODS, which are halogen-containing gases such as chlorofluorocarbons) had not increased between 1955 and 2005 (ODS emissions actually increased from around the mid-1950s through the 1980s, and declined rapidly thereafter). Since the radiative forcing from ODS during 1955-2005 is estimated to be about one third of the radiative forcing from  $CO_2$  Meinshausen *et al* (2011), as estimated by, the study of Polvani et al (2020) raises the possibility that ODS may be more efficient at warming the Arctic than CO2. This importance of ODS for Arctic warming has also informed in a modeling study of Goyal et al (2019). Using the so-called 'world avoided' scenario, they found that present-day Arctic temperatures would be 1 to 2 K warmer than observed had ODS emissions not been regulated by the Montreal Protocol.

Hence, the goal of this paper: to determine whether the AA caused by ODS is greater than the one caused by CO<sub>2</sub>. Stjern et al Stjern et al (2019) recently quantified the AA caused by different drivers of climate change (CO<sub>2</sub>, CH<sub>4</sub>, black carbon, SO<sub>4</sub>, and the solar constant), and concluded that the annual mean AA is similar among those drivers. However, ODS were not included in their study, being considered minor forcing agents. ODS have long been known to be potent greenhouse gases (Ramanathan et al 1987, Shine 1991), with Global Warming Potentials thousands of times larger than CO<sub>2</sub> Hodnebrog et al (2013, 2020), and have been shown to considerably affect the climate system not only at high Southern latitudes (Solomon et al 2015) and in the tropics (Polvani and Bellomo 2019), but also in the Arctic(Polvani et al 2020).

The novelty of this study, which builds on the findings of Polvani *et al* (2020), is that we here conduct and analyze new ensembles of global climate model integrations specifically designed to contrast ODS to carbon dioxide, so as to isolate and compare their respective contributions to Arctic warming over the 1955–2005 period. We not only focus on Arctic near-surface air temperature and sea-ice changes, but also show that ODS cause an AA that is 44% stronger than that caused by  $CO_2$ . We further show that ODS and  $CO_2$  impacts are additive, and that the impact of stratospheric ozone depletion is negligible. Finally,

we perform a feedback analysis to understand the underlying mechanisms that allow ODS to produce stronger AA than CO<sub>2</sub>.

#### 2. Methods

In this study, we examine five ensembles of simulations-each consisting of ten ensemble members differing only in their initial conditions—carried out with the Community Earth System Model Hurrell et al (2013), CESM, version 1: two new ensembles performed to enable explicit comparison of ODS and CO<sub>2</sub> impacts and three ensembles from Polvani et al (2020). The simulations cover the 1955–2005 period, when ODS forcing increased rapidly Polvani et al (2020), see figure 1 in . The first ensemble consists of ten historical integrations performed by the CESM Large Ensemble Project (Kay et al 2015), hereafter referred to as ALL, to indicate that these runs were forced by all natural and anthropogenic historical forcings following the Coupled Model Intercomparison Project Phase 5 protocol Taylor et al (2012). The second and third ensembles of integrations, conducted as part of the Polvani et al (2020) study, are identical to ALL except that in the second ensemble the ODS concentrations are fixed at 1955 levels, while in the third ensemble both ODS and stratospheric ozone concentrations are fixed at their 1955 levels. To cleanly isolate the effect of  $CO_2$ , we performed a fourth ensemble of integrations with CO<sub>2</sub> concentrations fixed at 1955 levels. And finally, to test the linear additivity of the response to CO<sub>2</sub> and ODS, we performed a fifth ensemble of integrations with both CO2 and ODS concentrations fixed at their 1955 levels.

Focusing on the differences between the ALL ensemble and the fixed-forcing ensembles allows us to isolate the effect of the individual forcings on the Arctic climate. This leave-one-out approach follows Polvani et al (2011) and many others, including the recent studies contrasting the effects of aerosols and GHGs in the CESM Large Ensemble (Deng et al 2020, Deser et al 2020, England 2021). In the following analyses, we refer to the difference between the ALL and the fixed-ODS ensembles as ODS, as it isolates the impacts of ODS. Similarly CO2 stands for the difference between the ALL and fixed-CO<sub>2</sub> ensembles, as it isolates the impacts of CO<sub>2</sub>. Again,  $CO_2$  and ODS indicates the difference between the ALL and fixed-CO2-and-ODS ensembles. Finally, the impacts of stratospheric ozone are quantified as the difference between the fixed-ODS and fixed-ODS-and-O3 ensembles, and is denoted as Strat-O<sub>3</sub>.

To investigate the physical processes producing AA, we perform a feedback analysis based on the topof-atmosphere (TOA) energy budget over the Arctic domain, 4

$$\Delta R + \Delta F - \Delta H = 0,$$

where  $\Delta R$  denotes the change in net downward radiation at the TOA,  $\Delta F$  the change in horizontal convergence of atmospheric and oceanic energy transports, and  $\Delta H$  the change in the ocean heat storage (derived from ocean potential temperatures) in the Arctic, assuming that ocean uptake dominates and contributions from the atmosphere, land, and cryosphere are negligible due to their relatively small heat capacities. We estimate  $\Delta F$  as the difference between  $\Delta H$  and  $\Delta R$  (with the latter calculated from model output TOA radiative fluxes).  $\Delta R$  can be decomposed as follows:

$$\Delta R = \Delta R_{\rm F} + \Delta R_{\rm Planck} + \Delta R_{\rm LR} + \Delta R_{\rm AL} + \Delta R_{\rm WV} + \Delta R_{\rm CL}, \qquad (2)$$

where  $\Delta R_{\rm F}$  denotes the stratosphere-adjusted radiative forcing calculated with the Parallel Offline Radiative Transfer (PORT) model assuming fixed dynamical heating (Conley *et al* 2013),  $\Delta R_{\text{Planck}}$  the Planck feedback due to vertically uniform warming,  $\Delta R_{LR}$ the lapse-rate feedback due to vertically non-uniform warming,  $\Delta R_{\rm AL}$  the surface albedo feedback,  $\Delta R_{\rm WV}$ the water vapor feedback, and  $\Delta R_{\rm CL}$  the cloud feedback (calculated using the adjusted cloud radiative effect method of Soden et al (2008)). For the Planck feedback, we show the deviation from the globalmean value, and we refer to this as Planck'. The residual (or error) in our decomposition of  $\Delta R$  is estimated as the difference between  $\Delta R$  calculated directly from model output TOA radiative fluxes, and  $\Delta R$  calculated from equation (2). We use the Community Atmosphere Model version 5 radiative kernels (Pendergrass et al 2018) to compute the feedbacks in equation (2).

We focus on the annual and Arctic-mean energy budget differences between two 10-year time periods, 1996–2005 and 1955–1964; this methods yields results that are very similar to the those obtained from linear trend analysis (discussed in Polvani *et al* (2020)). We divide each component of equation (2) by the change in Arctic-mean surface air temperature ( $\Delta T_s$ ) to derive feedback parameters.

To test the statistical significance of trend differences, we perform a two-sided Student's *t*-test with the null hypothesis that the difference of 10-member ensemble-mean trends is zero. If the null hypothesis can be rejected with 10% significance level (i.e. the *p*-value less than 0.10), we refer to the ensemblemean trends as statistically different or separable. To test the robustness of our results and minimize the effect of internal variability, we employ a bootstrapping technique (Pedregosa *et al* 2011) and randomly sample twenty members from each ensemble of integrations 10 000 times with replacement (results are not sensitive to how many members are selected). We average over each of the re-sampled

members to obtain distributions of 10 000 ensemble means.

We also look at  $\Delta T_s$  from the observational largeensemble dataset provided by McKinnon and Deser (2018). This dataset informs us about the effects of internal variability, and also allows us to determine whether our model simulations are in line with observations.

In the analysis that follows, Arctic-mean values refer to the area-weighted average for the variable of interest over the Arctic domain, i.e.  $60^{\circ}N-90^{\circ}N$ . Similarly, global-mean (tropical-mean) values denote the area-weighted average over the global (tropical) domain, i.e.  $90^{\circ}S-90^{\circ}N$  ( $30^{\circ}S-30^{\circ}N$ ).

#### 3. Results

(1)

We begin by comparing the forced annual-mean Arctic warming and September sea-ice loss in *ODS* to those in *ALL* and *CO2* via examining the spatial distributions of their ensemble-mean surface air temperature (SAT) and sea-ice concentration (SIC) trends (figure 1). The SAT trends in ALL are comparable to those in  $CO_2$ , but with greater warming in the Laptev-East Siberian Seas, Barents-Kara Seas, and East Greenland Sea (c.f., figures 1(a) and b). Correspondingly, large negative September SIC trends appear in these regions in *ALL* and *CO2* (c.f., figures 1(e) and f). In contrast, *ODS* shows the strongest warming trends in the Laptev-East Siberian Seas, accompanied by large sea-ice loss in that region (figures 1(c) and g).

To quantitatively compare the 1955–2005 CO2 and ODS trends over the Arctic, we plot the Arcticmean annual-mean SAT trends for the ensemble averages, and for the individual ensemble members, in box-and-whisker plots in figure 2(a). Let us start by comparing the ALL and CO2 ensembles. The ensemble-mean SAT trend in ALL is 0.32  $K \cdot decade^{-1}$ , which is only slightly larger than the ensemble-mean trend for CO2, of 0.27 K  $\cdot$  decade<sup>-1</sup>. Note the considerable overlap between the ALL and CO2 SAT trend distributions derived from 10000 re-samples from bootstrapping (c.f., black and magenta distributions in figure 2(b). In fact, the ALL trends are statistically inseparable from the CO2 ones. Keeping in mind that the CO2 trends do not include the effect of aerosol forcings which is, however, present in the ALL trends, we conclude that—in this model, over the Arctic-the aerosol forcing is greatly offset by the presence of the other (non-CO<sub>2</sub>) greenhouse gases. This is also seen in the September sea-ice extent (SIE) trends, which are only slightly larger in ALL than in CO2, but with no statistically significant difference (figure 2(c)). For completeness, the entire seasonal evolution of the Arctic-mean SAT and SIE trends is shown in figure S1 (available online at stacks.iop.org/ERL/17/024010/mmedia): it shows



strong warming trends during late autumn and substantial Arctic sea-ice loss trends from August to October for both ensembles.

Let us now turn our attention to ODS, which contributed the largest non-CO2 increase in radiative forcing over the period 1955-2005 Myhre et al (2013), see, for instance, the orange bars in figure 8.6d of. As one can see in figure 2, the ODS ensemblemean Arctic SAT trend is 0.14 K  $\cdot$  decade<sup>-1</sup>, which is slightly more than half (52  $\pm$  35%, uncertainty is estimated by the full range of maximum and minimum difference between ODS and CO2) the CO2 ensemble-mean value. This difference in Arctic SAT trend is statistically significant at 10% level. A similarly large response to ODS is found for sea ice: the September SIE ensemble-mean trend for ODS is  $-0.16 \times 10^6 \cdot \text{km}^2 \cdot \text{decade}^{-1}$ , which again is more than half of the CO2 ensemble-mean value of  $-0.27 \times 10^6 \cdot \text{km}^2 \cdot \text{decade}^{-1}$ . This is an unexpected result, as the radiative forcing of ODS over this period is only one third of the CO<sub>2</sub> forcing Polvani et al (2020), see figure 1 in: the radiative forcing of ODS accounts for 28% of the CO<sub>2</sub> forcing over the Arctic domain based on our PORT model simulations, slightly larger than the estimate from Polvani et al (2020). Such discrepancy could be further understood if the effective radiative forcings of ODS and CO<sub>2</sub> are estimated. Clearly some enhanced climate feedbacks must at work under ODS forcing.

Before examining those, however, we ask whether the response to  $CO_2$  and ODS, the two largest well-mixed greenhouse-gas forcings over the halfcentury 1955–2005, is linearly additive. The question is answered in figure 2(a) (c.f., brown and green clusters). In our 10-member ensembles, we see no statistically significant difference between the  $CO2 \notin ODS$  trends, in which both  $CO_2$  and ODS increase in the model integrations over that period, and the sum of the CO2 and ODS trends (denoted CO2+ODS), in which  $CO_2$  and ODS alone increase in the model simulations, respectively. This linear additivity result holds for both annual-mean SAT and September SIE (and annual SIE shown in figure S2).

Since the increase of ODS is accompanied by the destruction of ozone, we also explore the potential impact of stratospheric ozone depletion over the Arctic. Much work has been done on the climate impacts of ozone depletion: while capable of reaching into the subtropics e.g., Kang *et al* (2011) those impacts have been largely confined to the Southern Hemi-sphere Previdi and Polvani (2014), for a comprehensive review, see, although a few studies have suggested a possible impact on the Northern Hemispheric circulation (Smith and Polvani 2014, Calvo *et al* 2015). Over the Arctic, however, our model simulations (see the *Strat-O*<sub>3</sub> results in figures 1 and 2) show that the impact of stratospheric ozone on SAT and SIE is negligible (with trends of  $0.02 \text{ K} \cdot \text{decade}^{-1}$  and



 $-0.002 \times 10^{6}$  km<sup>2</sup> · decade<sup>-1</sup>, respectively, which are not significantly different from zero). This should not be surprising, as the radiative forcing from ozone depletion is small even over Antarctica (Chiodo *et al* 2017), where stratospheric ozone loss is much larger than over the Arctic.

Let us now turn to AA, and specifically to contrasting AA caused by ODS to AA caused by CO<sub>2</sub>, which is the main goal of this study. We start by examining the Arctic-mean SAT trends against global-mean trends for ODS and CO2 (figure 3(a)). First, note that the SAT trends for CO2 are larger than for ODS, for both Arctic and global means; this is expected because the radiative forcing from CO<sub>2</sub> is larger than the one from ODS during the 1955-2005 time period Polvani et al (2020), see figure 1 in. The ensemble-mean global SAT trend for CO2 (big red dot in figure 3(a) is 2.67 times larger than that for ODS (big blue dot in figure 3(a)). However, for Arctic SAT trends the former is only 1.92 times larger than the letter, suggesting a weaker Arctic warming forced by CO<sub>2</sub> than by ODS with respect to global warming—a manifestation of AA signature. Second, AA occurs in both CO2 and ODS, and is clearly visible from the fact that the ensemble means (large red and blue dots) are found above the one-to-one line (in dashed gray) that marks where Arctic and global warming trends are of equal magnitude. Third, we estimate the strength of AA from the linear least-squares slope of Arctic SAT trends against global SAT trends using the 10 000 re-sampled ensembles. We find that the *ODS* slope (3.59  $\pm$  0.05, solid blue line) is significantly larger than the *CO2* slope (2.73  $\pm$  0.06, solid red line), indicating that ODS causes a stronger AA than CO<sub>2</sub>.

To facilitate the quantitative comparison of AA in the ODS and CO2 ensembles, we define the AA factor (AAF) as the ratio of the Arctic-mean SAT trend to the global-mean SAT trend. These AAFs for each ODS and CO2 member, and for their ensemble-mean values, are graphically illustrated with box-and-whisker plots in figure 3(b). Consistent with the regression analysis in figure 3(a), the ODS ensemble-mean AAF (3.82) is larger than the CO2 ensemble-mean AAF (2.64) by a factor of 1.44. They are also statistically separable. We also show identical diagnostics for ALL (black lines, dots, and cluster in figures 3(a) and b): these are similar to those of CO2, as expected. In addition, the AAF for the ensemble-mean of observational large ensemble (2.62, green dots) is similar to those for ALL and CO2, suggesting the modeled AAFs are in line with the observational estimate. The above results clearly indicate that AA from ODS is larger than AA from CO<sub>2</sub>, and suggest that ODS are more effective GHGs than CO<sub>2</sub> in terms of generating AA.



**Figure 3.** (a) The Arctic-mean annual SAT trends vs. the global-mean annual SAT trends, for *ODS* (blue cluster), *CO2* (red cluster), and *ALL* (black cluster). The big dots show the ensemble-mean values, and the small dots the individual members. The solid and dashed lines are the linear least-squares fits and the corresponding 95% confidence interval range from the 10 000 re-samples. The dashed gray line has one-to-one slope. (b) Box-and-whisker plots for the Arctic amplification factor (AAF), with the whiskers showing the ranges of 10-member ensembles, and the orange horizontal lines showing the median values for *ALL*, *CO2*, and *ODS*. The big dots are the ensemble-mean values, the smaller dots the individual members. In both panels, the gray, magenta and cyan lighter dots show the 10 000 re-samples. The green dots present the results obtained from observational large ensemble.





Finally, we elucidate the mechanisms leading to a stronger AA in *ODS* than in *CO2*. In *ODS* and *CO2* individually, AA can be explained by more positive Planck', surface albedo, lapse-rate, and cloud feedbacks over the Arctic compared to the tropics (figures S3a and S3b). We find that differences in these same feedbacks between *ODS* and *CO2* (figure 4) explains the stronger AA from ODS than from  $CO_2$  forcing. In contrast, differences in radiative forcing, water

vapor feedback, and energy transport response act to oppose the stronger AA in *ODS* (as evidenced by the fact that these terms lie below the one-to-one line in figure 4). It is worth noting that the *ODS* and *CO2* cloud feedback parameters are nearly identical in the Arctic, but the former is more negative than the latter in the tropics. We are currently investigating the reasons for these feedback differences between *ODS* and *CO2*—including the seasonality of those differences and of AA—and we plan to report on this in a future paper.

#### 4. Summary and discussion

Building on the recent study of Polvani et al (2020), who highlighted the importance of ODS in warming the Arctic during the second half of the 20th century (when ODS became regulated by the Montreal Protocol), we have here further explored how ODS compare to CO<sub>2</sub> in terms of their Arctic impact with new large-ensemble simulations conducted. Using ensembles of global climate model integrations designed to isolate the respective impacts of ODS and CO<sub>2</sub> over the period 1955–2005, we have found that the Arctic warming and September sea-ice melting from ODS are slightly more than half of their CO<sub>2</sub> counterparts. This, we have shown, is due to the fact that AA caused by ODS is larger than the one caused by CO<sub>2</sub> (the AAF for ODS is 1.44 times larger than for CO<sub>2</sub>). And, finally, we have determined that differences in Planck', surface albedo, lapse-rate, and cloud feedbacks between ODS and CO2 can explain the stronger AA in response to ODS forcing. It will be important to validate these results with different climate models, and with larger ensembles, although Arctic climate responses consistent with ours have been reported in a recent study using a different climate model (Goyal et al 2019).

In conclusion, it is important to appreciate that while the large global warming potential of ODS has been known since the mid-seventies (Ramanathan 1975), it is only in the last decade that we have started to appreciate the profound and broad climate impacts of these gases. Well beyond causing the ozone hole over Antarctica, it is now clear that ODS have substantially contributed to global warming and to Arctic sea-ice loss. These recent findings confirm that the Montreal Protocol, originally signed to protect the stratospheric ozone layer, is in reality a major climate mitigation treaty as ODS affect the entire planet. The continued monitoring of ODS, therefore, is not only beneficial for the ozone hole healing in the Southern Hemisphere, but also a matter of great importance for Arctic climate change.

#### Data availability statement

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

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