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The Importance of Non-CO_2 Greenhouse Gases to Arctic Warming and Sea-Ice Loss

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Abstract Anthropogenic emissions of greenhouse gases (GHGs) are the main cause of Arctic climate change. While carbon dioxide (CO_2) is undoubtedly the largest contributor, the impact of non-CO_2 GHGs on the Arctic system has not been quantified to date. Here we perform and analyze a new set of climate model experiments designed for this purpose. Focusing on the period 1955–2015, we show that the five important non-CO_2 GHGs have warmed the Arctic by 0.72–1.11 K, and melted 0.90–1.21 million km^2 of September sea ice. These values amount to 60%–90% of the impacts from CO_2 alone. Individual forcing experiments reveal that ozone-depleting substances have caused the strongest non-CO_2 impact, followed by tropospheric ozone and methane, with smaller roles for nitrous oxide and stratospheric ozone. Our findings suggest an alternative pathway to mitigate Arctic climate change, whose effectiveness may depend on whether non-CO_2 emissions are abated separately from each other or concomitantly.

Plain Language Summary The Arctic has experienced accelerated warming and rapid sea-ice loss during the past decades. While carbon dioxide (CO_2) emissions due to human activities have been widely recognized as the major cause, the roles of other non-CO_2 greenhouse gases–notably methane, ozone-depleting substances, and tropospheric ozone–remain unquantified. Our study shows that the cumulative contributions of non-CO_2 greenhouse gases to Arctic warming and sea-ice loss may be nearly as important as that from CO_2 alone. Curbing the emission of non-CO_2 greenhouse gases, therefore, provides a complementary pathway to mitigate Arctic climate change.

Key Points:

- Five non-CO_2 greenhouse gases have warmed the Arctic by 0.72–1.11 K, and melted 0.90–1.21 million km^2 of September sea ice since 1955
- Total non-CO_2 impacts on Arctic climate amount to 60%–90% of those from CO_2 alone
- Non-CO_2 impacts on global warming only accounts for 60%–78% of those from CO_2 alone

Supporting Information:

Supporting Information may be found in the online version of this article.

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1. Introduction

The Arctic climate system has undergone dramatic changes over the past several decades (Pörtner et al., 2019). In particular, amplified warming in the Arctic surface air temperature (Chylek et al., 2022; Previdi et al., 2021; Rantanen et al., 2022; Taylor et al., 2022) and the rapid disappearance of sea ice (Druckenmiller et al., 2025; Finocchio et al., 2022; Parkinson & Comiso, 2013; Smedsrud et al., 2022; J. Stroeve et al., 2007; J. Stroeve & Notz, 2018) have caused much alarm. These changes are so severe that, under current nationally determined contributions to mitigate greenhouse gas (GHG) emissions, the Arctic is expected to transform into an entirely new regime (J. C. Stroeve et al., 2025) by 2100. A recent study has reported that the Arctic will likely be ice-free in September by 2050 (Jahn et al., 2024) under all future scenarios. A strong linear relationship has been established between sea-ice loss and the cumulative anthropogenic emissions (Notz & Stroeve, 2016) of carbon dioxide (CO_2), making it, unquestionably, the dominant driver of recent trends. However, it is also widely recognized that, beyond CO_2, several other GHGs have contributed to climate change (Forster et al., 2021; Myhre et al., 2014), yet little is known about their impact in the Arctic.

Among well-mixed non-CO_2 gases, we examine methane (CH_4), nitrous oxide (N_2O), and halogenated compounds containing chlorine and bromine collectively referred to here as ozone-depleting substances (ODS). Although the emissions and atmospheric concentrations of these gases are significantly lower than those of CO_2 and their lifetimes are shorter than CO_2, these GHGs are far more effective at trapping heat per molecule. For example, the 100-year global warming potential (GWP) of CH_4 is approximately 30 times greater than that of CO_2 (Etminan et al., 2016; Forster et al., 2021), and for N_2O it is 273 times greater (Forster et al., 2021; World Meteorological Organization (WMO), 2022). As for ODS, their GWPs are typically thousands of times greater

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than CO_2: for instance, for trichlorofluoromethane (CFC-11) and dichlorodifluoromethane (CFC-12), the two most abundant ODS, the 100-year GWPs are, respectively, 6,400 and 12,500 times greater than for CO_2 (World Meteorological Organization (WMO), 2022).

Among non-well-mixed GHGs, we focus on ozone (O_3), a short-lived yet potent non-CO_2 climate forcer (Forster et al., 2021). It is now well established that tropospheric and stratospheric ozone trends are governed by very different anthropogenic emissions and chemical reactions, and that their climate impacts are distinct: it is therefore important to consider them separately. Stratospheric ozone (hereafter O_3S, commonly known as "the ozone layer") was depleting rapidly in the late twentieth century due to the increasing concentrations of ODS. However, the discovery of the ozone hole over the South pole (Farman et al., 1985) and its underlying causes (Molina & Molina, 1987; Solomon et al., 1986) led to the signing and implementation of the Montreal Protocol, with evidence that the ozone layer is now healing (Solomon et al., 2016). In contrast, tropospheric ozone (hereafter O_3T), which forms from the oxidation of nitrogen oxides and volatile organic compounds (from anthropogenic pollution), has shown a continuous upward trend over recent decades, driven by increasing emissions of its precursors (Cooper et al., 2014; Stevenson et al., 2013; Yeung et al., 2019; Young et al., 2018). It is also important to appreciate that the bulk of the radiative forcing (RF) from ozone–and the associated surface warming–comes from O_3T, with only a small contribution from O_3S (Forster et al., 2021; World Meteorological Organization (WMO), 2022). Moreover, 40%–50% of RF from O_3T is estimated to come from the indirect effect of CH_4 (Iglesias-Suarez et al., 2018; Stevenson et al., 2013), such that the impact of O_3T could be also affected by the amount of CH_4.

How do these non-CO_2 GHGs affect the Arctic climate system? While the international climate assessments routinely estimate the global mean RF from these non-CO_2 gases(Forster et al., 2021; Myhre et al., 2014), climate feedbacks are a crucial part of the response to increasing GHGs (Sherwood et al., 2020), especially over the Arctic (Goosse et al., 2018), and these can only be quantified with Earth system models. However, large ensembles are needed to obtain a statistically significant forced response for non-CO_2 GHGs, owing to their relatively small RF, and such models are expensive to run (C. J. Smith & Gasser, 2022). This explains why nearly all recent efforts to separate the effects of different climate forcings with Earth system models have focused on distinguishing between the cooling effects of aerosols and the warming effects of all well-mixed GHGs taken together (Gillett et al., 2016; Deser et al., 2020; D. M. Smith et al., 2022). As a consequence, beyond their RF, the individual climatic effects of non-CO_2 warming gases over the historical period remain to be quantified, notably over the Arctic.

We acknowledge a number of studies which have examined non-CO_2 GHGs with integrated assessment models, intermediate-complexity Earth system models, and Earth emulators (Harmsen et al., 2023; Ou et al., 2021; Van Vuuren et al., 2018). Such modeling studies have mostly focused on global mean surface temperature, as those simpler models generally lack realistic representations of physical processes and interactions between land, ocean, and cryospheric components. To the best of our knowledge, only for ODS and O_3S have simulations with comprehensive Earth system models been performed to assess their Arctic impact during the past decades. Those studies (Bushuk et al., 2023; Liang, Polvani, Previdi, et al., 2022; Polvani et al., 2020), which have been independently validated (Sigmond et al., 2023), have revealed an unexpectedly large impact of ODS on the Arctic climate system (and a very minor impact of O_3S) over the period 1955–2005. Additionally, those simulations were based on concentration-driven scenarios and mostly without the interactive-chemistry module included, potentially limiting the realistic representation of their effects (as well as of the simulations carried out in this study, see Section 2.2).

The goal of this study is to expand those results to include all major well-mixed and non-well-mixed non-CO_2 GHGs described above. Extending the analysis to the longer 1955–2015 period, we here quantify their individual and cumulative impacts to Arctic climate change, and we contrast them to the impact of CO_2 alone. Using 1955–1974 as the baseline, the 1996–2015 mean RF of CO_2 alone is 0.94 W/m^2 (Figure 1a). This is much larger than the corresponding individual values for CH_4, N_2O, ODS and O_3, but not larger than the sum of these non-CO_2 GHGs, which amounts to a considerable 0.78 W/m^2 (Figure 1a), suggesting that the cumulative climate impacts of these non-CO_2 GHGs might be comparable to the impact from CO_2 alone. Of course, this only considers the global-mean RF from these gases. To accurately quantify how much warming arises from these RFs at both global and Arctic scales, large ensembles of simulations with Earth system models are needed. We conduct a new set of Earth system model experiments designed for this purpose, and describe the details in Section 2. Results are present in Section 3, followed by discussion and conclusion in Section 4.

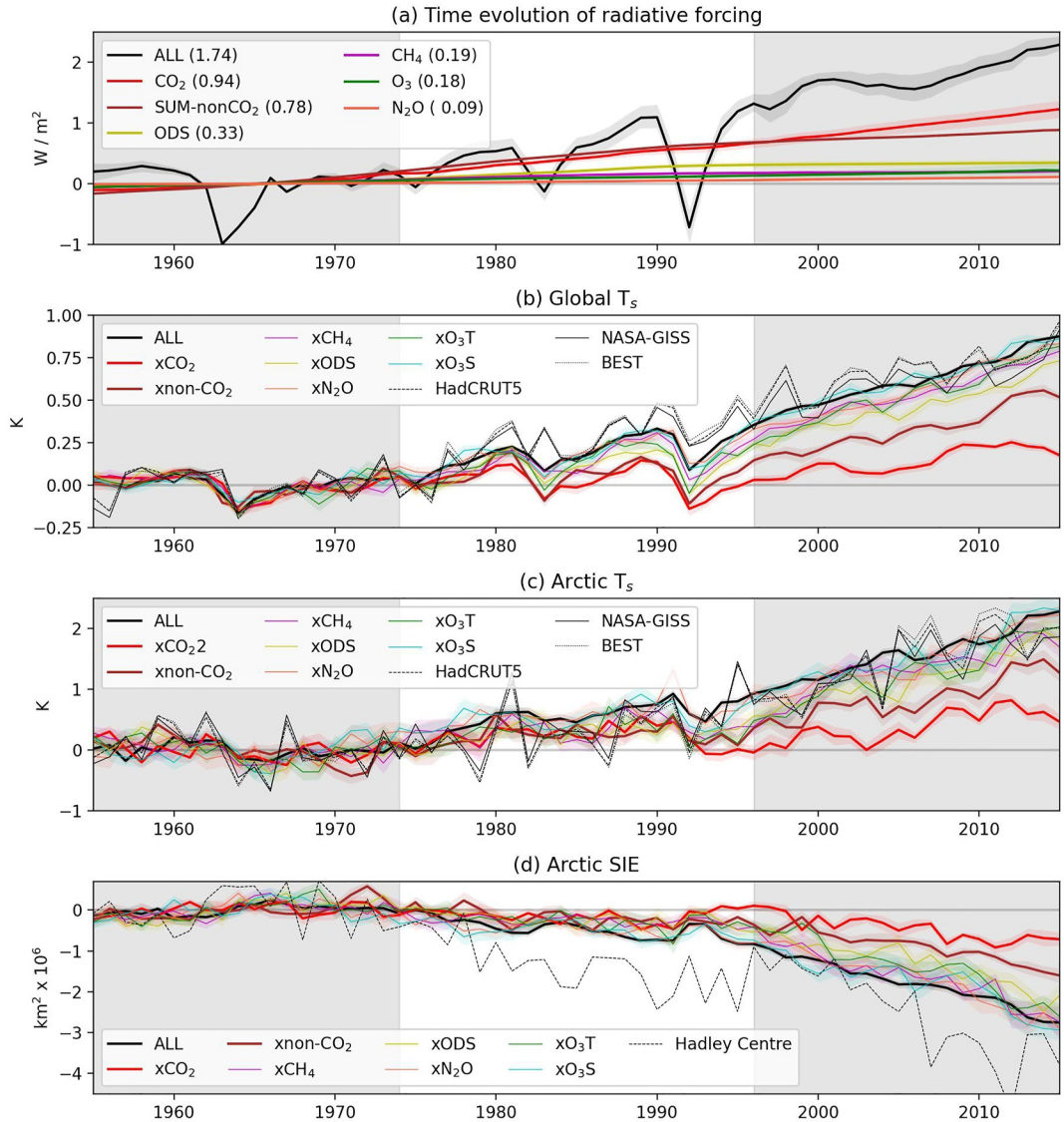

Figure 1. (a) The evolution of RFs for all anthropogenic and natural forcings over the 1955–2015 period (ALL) and for CO_2, CH_4, ODS, N_2O, and O_3 (which stands for total ozone, since the separate RF for O_3T and O_3S is not available), obtained from a CMIP6 data archive (Meinshausen et al., 2017). The line labeled SUM-nonCO_2 indicates the sum of the CH_4, ODS, N_2O and O_3 RF. The color shading indicates the 95% uncertainty range, and the number in the parentheses after each label in the legend is the 1996–2015 mean value minus the 1955–1974 one. Evolution of annual (b) global and (c) Arctic surface temperature as well as (d) September Arctic sea ice extent (SIE) relative to the mean values from 1955 to 1974 for observations (black solid, dashed, dotted lines), and the ensemble-means under all forcings (ALL, black), fixed CO_2 forcing (red), fixed non-CO_2 forcing combined (dark brown), fixed CH_4 forcing (magenta), fixed ODS forcing (yellow), fixed N_2O forcing (orange), fixed tropospheric ozone forcing (O_3T, green), and fixed stratospheric ozone forcing (O_3S, cyan). The color shadings represent the range of one standard deviation across ensemble members, and the gray shadings represent the 1955–1974 and 1996–2015 periods.

2. Data and Methods

2.1. Observational Data Sets

To provide observational references in this study, we use three surface-air temperature products covering the global domain from the Goddard Institute for Space Studies of the National Aeronautics and Space Administration surface temperature analysis version 4 (GISTEMPv4, GISTEMP, 2023; Lenssen et al., 2019), the Met Office Hadley Centre/Climatic Research Unit global surface temperature data set version 5.0.1.0 (HadCRUT5,

Morice et al., 2021), and the Berkeley Earth surface temperature data set (BEST, Rohde & Hausfather, 2020). These temperature data sets were constructed based on 2-m air temperature observations over the global land and sea-surface temperature over the global ocean. For observational sea-ice concentration, we use the sea-ice concentration product from the Hadley Centre (Titchner & Rayner, 2014). The sea-ice data before 1979 has higher uncertainty, due to reconstruction using historical observations and statistical techniques, which leads to observation-model difference. Indeed, a previous study showed that the reconstructed time series of sea-ice concentration since 1840 undergo apparent dependency during the 1940–1970 period, when the "Walsh" data (Walsh et al., 2017) show higher values (Brennan & Hakim, 2022). As the "Walsh" data (Walsh et al., 2017) are the basis for constructing the Hadley sea-ice concentration data (Rayner et al., 2003), the observed sea-ice reference we present below can be affected by this uncertainty source. We also analyzed the sea-ice concentration product from the National Snow and Ice Data Center (DiGirolamo et al., 2022), but its temporal coverage is 1978 to present day, so we do not include it in this study. We present observational results for the period spanning 1955 to 2015 to align with the time period of our climate model simulations.

2.2. Climate Model Simulations

To examine and quantify the global and Arctic temperature and sea-ice responses to all forcing, we use the historical and future simulations from the large ensemble project of the Community Earth System Model version 1 (CESM1, Kay et al., 2015). The model components of CESM1 consist of the Community Atmosphere Model version 5 (CAM5), Parallel Ocean Program version 2 (POP2), Community Land Model version 4 (CLM4), and Los Alamos Sea Ice Model version 4 (CICE4). Simulations are forced with all forcing agents, including greenhouse gases, aerosol emissions, ozone, land-use changes, and natural forcings (i.e., volcanic and solar irradiance). In the historical period before 2005, the forcings are time-varying following the Coupled Model Intercomparison Project Phase 5 (Lamarque et al., 2010) historical experiment, whereas during 2006–2015, the forcings are given following the representative concentration pathway 8.5 (RCP8.5, Meinshausen et al., 2011). Here, we select 10 members (out of 40 members) based on 10 different ocean states in control simulation, which are forced by pre-industrial forcings. For simplicity, we refer to this set of simulations as ALL throughout the manuscript.

To address the impacts of non-CO_2 GHGs, we next conduct seven sets of single forcing CESM1 simulations in which the target forcing is prescribed in a way that its value is fixed at the 1955 level while other forcings evolve in the same way as in ALL. This forcing method is called the "all-but-one" method (Simpson et al., 2023). The climate forcers of interest in this study are the well-mixed greenhouse gases CO_2, CH_4, ODS, and N_2O, and the spatially varying stratospheric ozone (O_3S) and tropospheric ozone (O_3T), plus the combination of all of these non-CO_2 forcers. The last set represents the cumulative non-CO_2 forcing. Each set of simulations is initialized in 1955 from the 10 ensemble members of ALL. The difference between the fixed forcing and the ALL simulation reveals the response to that forcing. The forced response is obtained by averaging over the ensemble members (Deser et al., 2012).

We have performed seven ensembles of "all-but-one" forcing simulations: one each for the five major non-CO_2 GHGs (CH_4, N_2O, ODS, O_3T, and O_3S), plus one with all of these fixed together (to examine the additivity of the response), plus one with only CO_2 fixed (to contrast the non-CO_2 GHGs to carbon dioxide itself). We emphasize that no such simulations have been performed under any model intercomparison projects we are aware of, where well-mixed GHGs are typically lumped together. In addition, to detect if apparent shock signal appears during the first year of simulation, we look into, for example, CH_4 experiments and do not find the shock signals in the Arctic and global temperatures (Figure S1 in Supporting Information S1).

We also carry out single forcing CESM2–another version of CESM–simulations following the framework of the CESM2 Single Forcing Large Ensemble Project (Simpson et al., 2023). In this framework, CESM2 in integrated using the "only" method, which allows the forcing of interest to vary with time but fixes others at pre-industrial levels following the Detection and Attribution Model Intercomparison Project (Gillett et al., 2016) under the sixth phase of CMIP (CMIP6, Eyring et al., 2016). Due to computational limitations, we only completed CO_2-only, CH_4-only, ODS-only, and N_2O-only simulations, and we use the all well-mixed GHG (i.e., CO_2, CH_4, ODS, and N_2O) simulation conducted by the National Center for Atmospheric Research (Simpson et al., 2023). Each set of simulations includes 10 members.

In this study, we define the Arctic region as 60°N–90°N. We consider the period of 1955–2015. We calculate the difference between the ensemble-mean of the last 20 years (1996–2015) and the ensemble-mean of the first 20 years (1955–1974). We use the notation "δX" to represent this temporal difference of the variable X, and interpret δX as the response of X to a forcing agent.

2.3. Radiative Forcing

To estimate the radiative forcing for each climate forcer from 1955 to 2015, we analyze the radiative forcing data set from a recent study (Meinshausen et al., 2020). Applying the Monte Carlo ensemble technique, the data set provides the 5th to 95th uncertainty range for each forcing. This data set was used for the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) Working Group 1 (WG1) Annex 3.

2.4. Bootstrapping Technique

To robustly assess the uncertainty (internal variability) of the temperature and sea-ice responses and to increase the sample size, we perform a bootstrapping method. Specifically, we randomly sample the 10 ensemble members without replacement 10,000 times, and then compute the average over each resampled 10 ensemble members to obtain 10,000 ensemble means. The 2.5%–97.5% range of the 10,000 ensemble means is shown to represent the uncertainty. This method has been used in previous large-ensemble climate modeling studies (Jahn et al., 2016; Oehrlein et al., 2021; Sun et al., 2022).

2.5. Propagation of Uncertainty and Statistical Significance Test

In this study, the summed responses to individual non-CO_2 forcings are examined to assess the non-linearity with respect to the response to all non-CO_2 forcings combined. To estimate the uncertainty for non-CO_2 SUM responses, we apply a typical propagation of uncertainty for the standard deviation formulated as(Ooi et al., 2023):

$$\sigma_{\mathrm{SUM}} = \sqrt{\sigma^2_{CH_4} + \sigma^2_{ODS} + \sigma^2_{N_2O} + \sigma^2_{O_3T} + +\sigma^2_{O_3S}} \tag{1}$$

We then fit a normal distribution with σ_{SUM} to generate 10,000 samples, and show the 2.5%–97.5% range.

For spatial fields, we perform a two-tailed Student's t test with the null hypothesis that the last 20-year mean is the same as the first 20-year mean. If the null hypothesis can be rejected at the 95% significance level, we refer to the difference as statistically significant and mark it with stippling.

2.6. Arctic Amplification Factor

To quantify the strength of Arctic amplification, we calculate a factor defined by the Arctic ensemble-mean T_s response divided by the global one. If the factor is larger than 1, it implies that the Arctic temperature response is larger than the global one. Previous Arctic amplification studies adopted a similar definition, and discussed the physical interpretation in detail (Liang, Polvani, & Mitevski, 2022; Zhou et al., 2023).

2.7. Radiative Feedback Analysis

To investigate the underlying mechanism leading to Arctic warming and amplification, we perform the radiative kernel analysis following previous studies (Liang, Polvani, Previdi, et al., 2022; Polvani et al., 2020). We use the CAM5 radiative kernel (Janoski et al., 2024; Pendergrass et al., 2018) and decompose the radiation flux change at the top-of-atmosphere into contributions from the Planck feedback (PL), lapse-rate feedback (LR), albedo feedback (ALB), water vapor feedback (WV), and longwave and shortwave cloud feedbacks (LW and SW cloud). For the feedback X of interest, we calculate the corresponding radiation flux change as:

$$\delta R_X = \sum_i K_{X,i} \delta X_i, \tag{2}$$

where i denotes the spatial grids over the Arctic or globe. We then divide by the magnitude of the global-mean Planck feedback parameter $\lambda_0 = \frac{\delta R_{\mathrm{Planck}}}{\delta T_s}$ to convert to a temperature contribution as shown in Figure S2 in

Supporting Information S1. It is noted that the Planck feedback shown in the figure is the deviation from the global-mean value, which is positive in the Arctic.

3. Results

The time evolution of the ensemble mean, global mean near-surface air temperature (T_s) for these seven all-but-one cases, and for the ALL forcing reference case, is shown in Figure 1b. The ALL forcing case generally follows the observational trends though with less inter-annual variability due to the ensemble mean compared with observations, validating our model and making our decomposition meaningful. It is also clear that fixing CO_2 (red curve) results in a very considerable reduction in global warming, consistent with our expectation. Fixing each of the five non-CO_2 GHGs also reduces global warming, but by a much smaller amount, again in line with expectations. The key point is that when all five of the non-CO_2 GHGs are fixed together (brown curve), the reduction in T_s is no longer much smaller than for the fixed CO_2 case. It accounts for approximately half of the reductions in the CO_2 case. Correspondingly, similar reduction are also shown in Arctic T_s and SIE (Figures 1c and 1d). It is noted that, although the decreasing trends in observations and models are consistent, the observed SIE evolution details differ from simulated one (dashed and solid black lines in Figure 1d).

Next, to quantify the change in climate variable X over the period of interest (1955–2015), for each simulation we compute the difference between the first (1955–1974) and the last (1996–2015) 20-year periods. We prefer this method to a least-squares fit, as it does not assume that the evolution is linear in time. Then, subtracting the all-but-one value from the ALL forcing value, and taking the ensemble mean, yields the quantity δX, which represents the individual contribution of each GHG to the forced total warming.

Consider first the response in the ALL forcings case, for which the global δT_s is 0.61 ± 0.02 K, the Arctic δT_s is 1.56 ± 0.16 K, and δSIE is $-1.77 \pm 0.26 \times 10^6$ km^2 (Figures 2a and 2c). Note that these are close to the corresponding observational values (black symbols in Figure 2), confirming that CESM1 simulates the surface temperature responses realistically. However, the simulated sea-ice loss is smaller than observed one, reflecting the underestimation of sea-ice loss in CESM1 (Rosenblum & Eisenman, 2016). Note also that CO_2 makes a large contribution to those responses, roughly 75% of the ALL forcing values.

When considering the response to the five non-CO_2 GHGs, the individual response is much smaller, typically a fraction, of the one from CO_2. However, the cumulative response of these non-CO_2 GHGs (denoted SUM-nonCO_2) is remarkably large: over the Arctic, in particular, it is statistically indistinguishable from the CO_2 response (Figures 2b and 2c). This is perhaps not surprising, as the global radiative forcing of non-CO_2 GHGs amounts to 83% of the CO_2 value (Figure 1a). It is also important to emphasize the order of importance of the non-CO_2 GHGs, which is consistently the same: ODS cause the second largest impact after CO_2, followed by O_3T, CH_4, and N_2O in that order. The impact of stratospheric ozone is statistically insignificant for all metrics we have computed.

To examine whether the impacts of these non-CO_2 GHGs are additive, we have computed the response when all five forcings are held fixed at the same time. The response to the non-CO_2 GHG forcings added at the same time (non-CO_2) yields a similar, although somewhat smaller, than the one obtained by summing the individual responses (SUM-nonCO_2). However, their difference is not statistically significant. The forced Arctic surface warming of the non-CO_2 is 0.72 ± 0.17 K (Figure 2b), and the forced sea-ice loss is $0.90 \pm 0.18 \times 10^6$ km^2 (Figure 2c). These values are approximately 60% and 67% of the CO_2 responses, respectively. The responses of the individual warming and sea-ice loss responses added are 93% and 90% of the CO_2 responses, respectively. If we consider the non-CO_2 and SUM-nonCO_2 values as a plausible range, we conclude that from 1955 to 2015 the impact of non-CO_2 GHGs on the Arctic amounts to 60%–90% of the CO_2 impact.

We further find similar Arctic amplification produced by SUM-nonCO_2 and non-CO_2 (Figure 2d). The Arctic amplification factor, defined as the Arctic δT_s divided by the global counterpart (see Methods), for SUM-nonCO_2 is 3.01 ± 0.62, while for non-CO_2 it is 2.54 ± 0.34. The non-CO_2 forcings therefore produce 2.5 to 3 times stronger warming in the Arctic than warming in the rest of the globe compared to about 3 times Arctic warming than global warming for CO_2. We examine the underlying mechanism by analyzing the radiative feedbacks (see Methods), and find that the temperature (lapse-rate plus Planck) and albedo feedbacks are the main processes leading to the stronger SUM-nonCO_2 Arctic amplification (c.f., Figures S1c and S1d in Supporting Information S1).

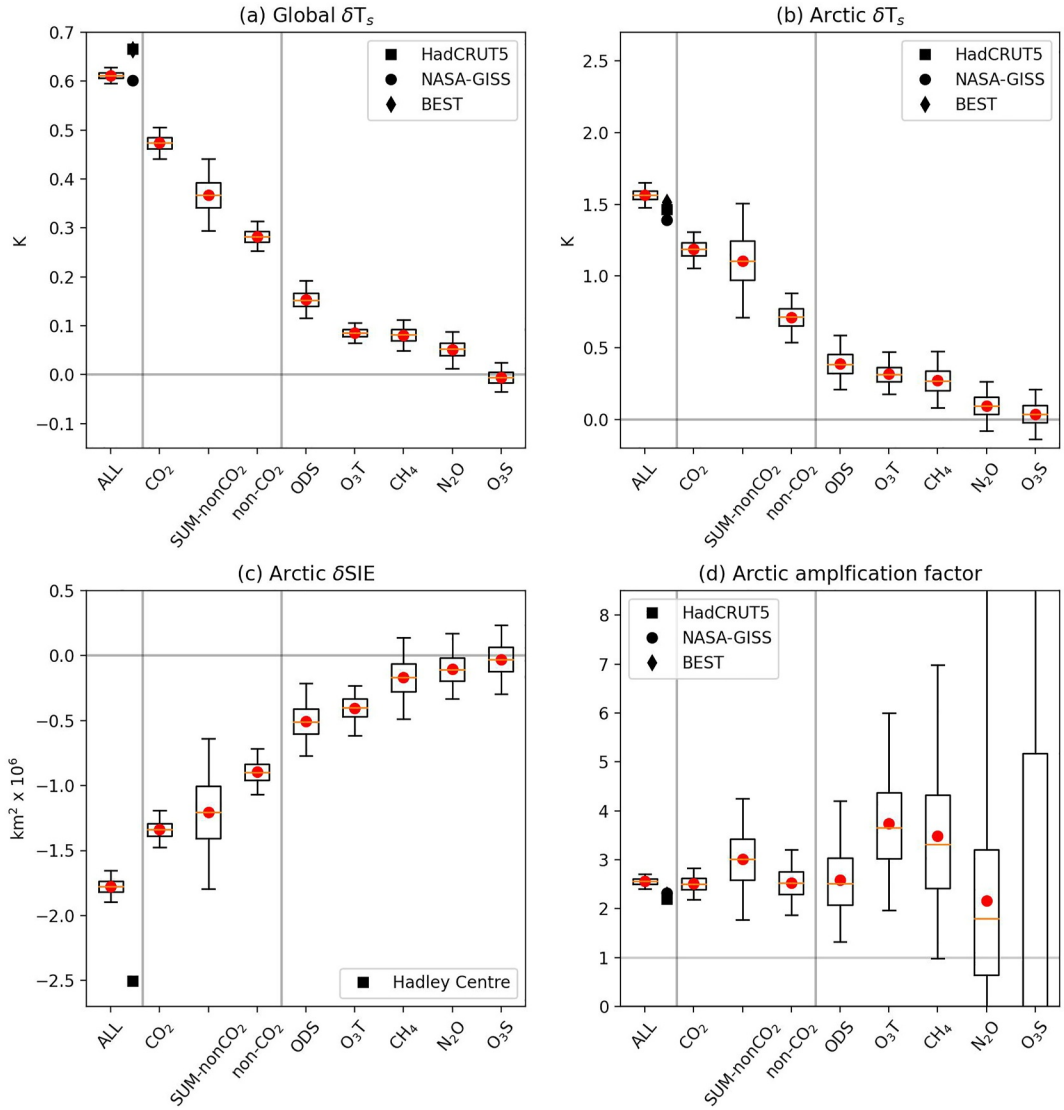

Figure 2. Surface air temperatures (T_s) and September sea-ice extent (SIE) responses to GHGs: (a) Annual global δT_s, (b) Annual Arctic δT_s, (c) September Arctic δSIE, and (d) the Arctic amplification. For the Arctic amplification factor of O_3S, unrealistic values appear due to near-zero global mean δT_s. The uncertainty is estimated from 10,000 bootstrapped random samples, and the 2.5%–97.5% range is shown in each panel. The blacks symbols denote the observational estimates.

To provide a clearer picture of the Arctic impacts of non-CO_2 GHGs, we examine the geographic distributions of δT_s over the Arctic (Figure 3). In the ALL forcing case δT_s shows large warming over the entire Arctic, considerably larger over the Arctic Ocean than above the high-latitude continents, as in the observations. Within the overall Arctic warming, three hotspots emerge: the East Siberian Sea, the Barents Sea, and the Greenland Sea (Figure 3b). These are clearly present in the CO_2 and SUM-nonCO_2 cases (Figures 3c and 3d), and also in the nonCO_2 case (though somewhat weaker, Figure 3e). The key point, however, is that while the warming caused by individual non-CO_2 GHGs (Figures 3f–3j) is relatively small (though statistically significant–for all non-CO_2 gases–over much of the Arctic), their combined impacts are considerable, and in fact comparable, to the impact of CO_2 alone with no discernible regional difference.

The same conclusion is reached when examining the sea-ice response. The total sea-ice loss in September caused by the non-CO_2 GHGs (Figures 4d and 4e) is considerable. Individual non-CO_2 GHGs (except O_3S) contribute to sea-ice loss in the Greenland Sea and the Laptev Sea, but only CH_4 and O_3T appear to have a strong signal in the Barents Sea (Figure 4). We also note that, for polar average Arctic sea-ice loss over the period 1955–2015, the

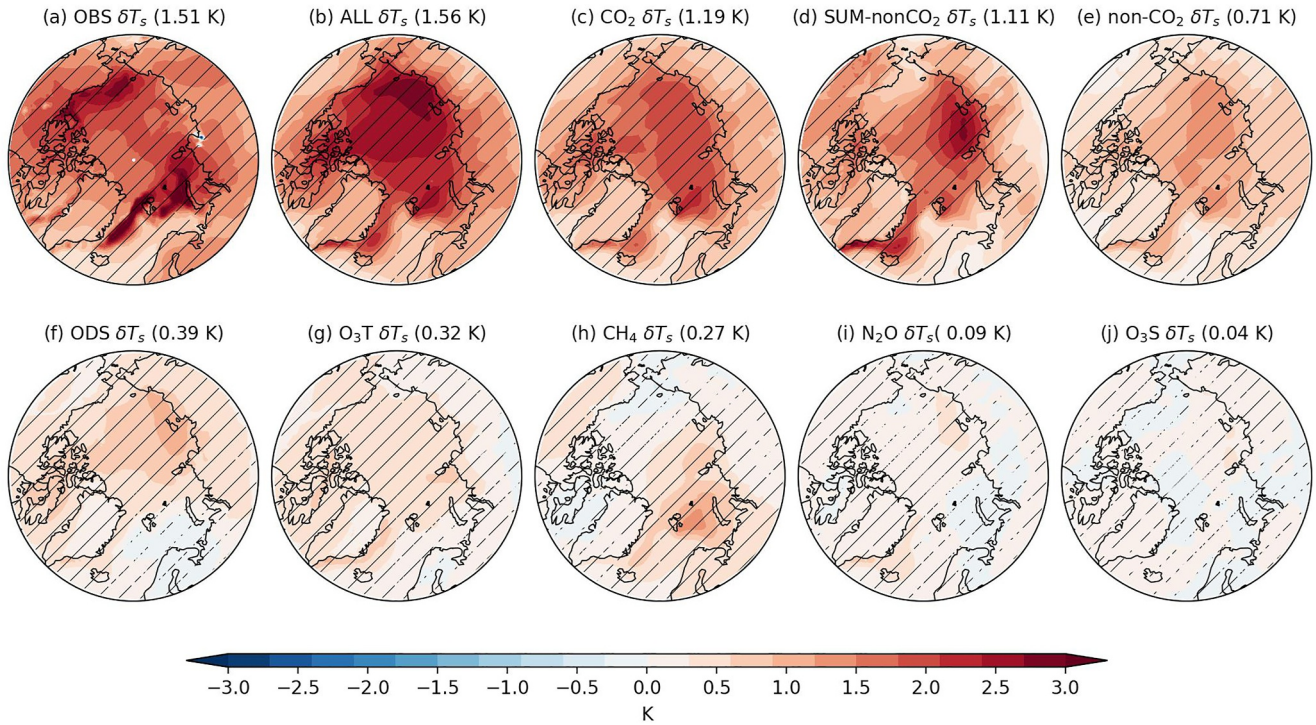

Figure 3. Arctic surface air temperature response (δT_s): (a) observation, (b) ALL forcings, (c) CO_2, (d) non-CO_2, (e) SUM-nonCO_2, (f) CH_4, (g) ODS, (h) N_2O, (i) O_3T, (j) and O_3S. The stippling indicates the response is statistically significant based on a two-tail Student's *t* test at 95% level. The numbers in parentheses in each panel indicate the Arctic means, reported in Figure 2b.

impact of O_3T is comparable to that of ODS. However, the regional sea-ice features of the response could be model dependent (notably for O_3T, which is not well-mixed). Also, given the relatively small radiative forcing of the non-CO_2 GHGs individually, these regional sea-ice impacts should be validated with other models and with larger ensembles.

4. Conclusions and Discussion

In summary, we have found that non-CO_2 GHGs have exerted substantial–and largely unappreciated–impacts on the Arctic climate during the second half of the 20th and the first decade of the 21st century. Our simulations show that Arctic surface warming and sea-ice loss caused by the combined effect of non-CO_2 GHGs might be comparable to those from CO_2, with a comparable Arctic amplification. Of particular interest is our finding that the Arctic warming and sea-ice loss caused by O_3T are comparable to the one from ODS (Figures 2b and 2c). As atmospheric concentrations of O_3T are likely to increase in the next few decades due to the increased emission of its precursors from industrial activities (Cooper et al., 2014; Stevenson et al., 2013; Yeung et al., 2019; Young et al., 2018), Arctic warming and sea-ice loss could be exacerbated by the higher levels of tropospheric ozone.

To avoid misunderstandings, it is crucial, at this point, to clarify that the attribution of the climate response to the individual GHGs we have quantified here is based on their atmospheric concentrations, and these need to be understood in the context of anthropogenic emissions, atmospheric chemistry, and chemistry-climate feedbacks. First, we here used a concentration-driven model to prescribe GHG forcing because we simply did not have an emission-driven model at our disposal. Such models are relatively rare at present, and are just now starting to become available as part of the recently proposed CMIP7 emissions-driven climate projections (Sanderson et al., 2024; Stecher et al., 2024). We hope that future emission-driven modeling studies will revisit and confirm the large effects of non-CO_2 GHGs reported here (Folberth et al., 2022; Stecher et al., 2024).

Second, and more importantly, we emphasize that our model does not include interactive atmospheric chemistry. Note that the same applies to the vast majority of models that have participated in all CMIP phases to date (e.g., only a handful among the dozens of models in CMIP6 included interactive chemistry, Keeble et al., 2020).

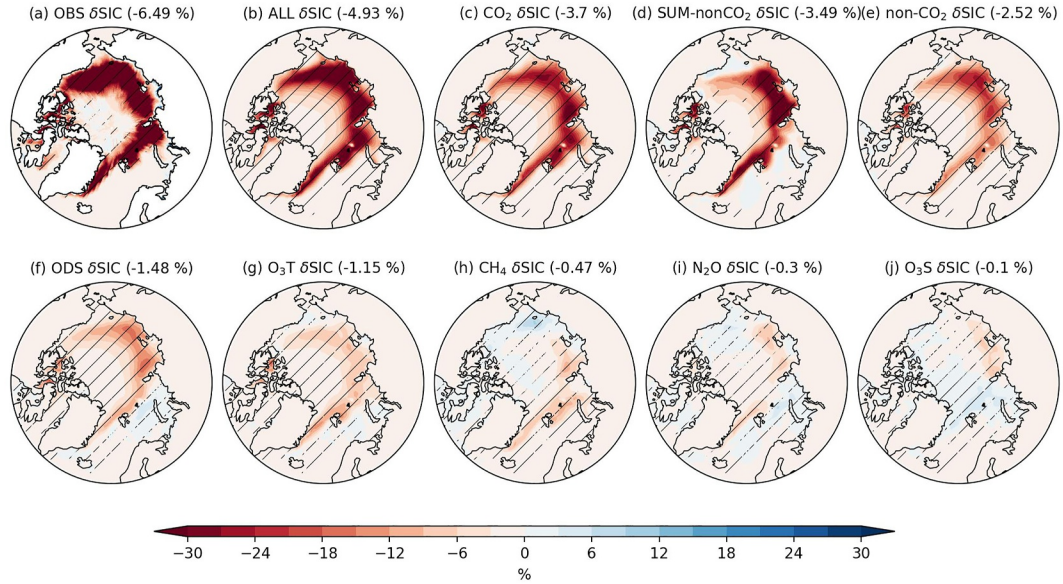

Figure 4. September Arctic sea-ice concentration response (δSIC): (a) observation, (b) ALL forcings, (c) CO_2, (d) non-CO_2, (e) SUM-nonCO_2, (f) CH_4, (g) ODS, (h) N_2O, (i) O_3T, (j) and O_3S. The stippling indicates the response is statistically significant based on a two-tail Student's *t* test at 95% level. The numbers in parentheses in each panel indicate the Arctic means.

Models with interactive chemistry are much more computationally expensive than without it, and the resources needed to run large ensembles with interactive-chemistry models to robustly estimate the response to weaker forcings (i.e., larger ensembles required) are thus prohibitively expensive at this time. Nonetheless, we are well aware that inclusion of atmospheric chemistry would play an important role in determining the precise values of the relative contribution of each of the non-CO_2 gases to Arctic climate. In particular, it has been estimated that 40%–50% of the radiative forcing from O_3T can be attributed to the increasing emission of CH_4 (Iglesias-Suarez et al., 2018; Stevenson et al., 2013), as O_3T is produced from the photochemical oxidation of CH_4 in addition to a smaller radiative forcing from the methane-induced stratospheric water vapor response. As a consequence, if our exercise had been based on emissions and interactive chemistry had been included, the relative role of CH_4 would very likely be larger what we have estimated here. But, as we await these more accurate calculations to become practically feasible, we emphasize that they will likely not alter the key finding of our study, which is that non-CO_2 GHGs, cumulatively, have had a large impact on global and Arctic climate, comparable to the impact of CO_2 alone.

Our modeling result also hints at a potential non-additivity in the response to non-CO_2 GHGs (given the considerable, albeit not statistically significant, difference between the nonCO_2 and SUM-nonCO_2 responses). This may be dependent on the methodology to prescribe forcings (Simpson et al., 2023). To address this question, we have analyzed an additional set of single-forcing simulations with a different version of CESM: these were performed with CESM2 (Danabasoglu et al., 2020) using the "only" method (instead of the "all-but-one" method adopted for CESM1), and only for the four well-mixed GHGs: specifically, CO_2 only, CH_4 only, N_2O only and ODS only, plus a case with all four together (denoted GHG, see Methods). Since we have the same set of single forcings available via CESM1, we can directly compare the individual and combined responses in these two models. As shown in Figure S3 in Supporting Information S1, we find a high degree of additivity among the four well-mixed GHGs, and this occurs in both versions of the model.

From this we conclude that, at least in the context of present-day CMIP-class concentration-driven climate models, the impact of well-mixed GHGs is indeed additive and, moreover, that this result is independent of the method use to prescribe the forcing (only-one vs. all-but-one). Our results with CESM1 and CESM2 also suggest that, if any non-additivity is present at all, it might be primarily related to O_3T, which is not a well-mixed GHG. More work is needed to explore this further, as non-additivity would obviously have important implications for the detection and attribution of climate change (Gillett et al., 2021; Najafi et al., 2015).

Finally, we recall that the United Nations Environment Program has recently released practical guidance to leverage the benefits of curbing non-CO_2 pollutants (Bahrami, 2024). Substantial cuts in non-CO_2 emissions, for example, the Global Methane Pledge (Malley et al., 2023), are noted to be important not only to limit warming in the coming decades to meet the goals of the Paris Agreement (Ou et al., 2021), but also to support sustainable socioeconomic development. In line with the Summary for Policy Makers in the Report from the Arctic Monitoring and Assessment Program (Assessment, 2021), our results indicate that mitigation of non-CO_2 emissions would help avoid future detrimental consequences for Arctic climate, ecosystems, air quality, and human health. Our findings thus suggest an complementary pathway to mitigate Arctic, and global, climate change.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The Python scripts for processing data, plotting figures, and the processed data are available on Y.-C. Liang's Zenodo repository (Liang, 2025). Model output analyzed in the study is currently stored on data servers (Derecho) at the National Center for Atmospheric Research in Boulder, CO, USA, and can be downloaded publicly at https://gdex.ucar.edu/datasets/d651027/. The observed HadCRUT temperature data version 5 (Morice et al., 2021) can be downloaded at https://www.metoffice.gov.uk/hadobs/hadcrut5/data/HadCRUT.5.0.2.0/download.html. The NASA-GISS temperature data version 4 (GISTEMP, 2023; Lenssen et al., 2019) can be download at https://data.giss.nasa.gov/gistemp/data_v4.html. The BEST temperature data (Rohde & Hausfather, 2020) can be downloaded at https://berkeleyearth.org/data/. The Hadley Centre sea-ice data version 5 (Titchner & Rayner, 2014) can be downloaded from https://climexp.knmi.nl/select.cgi?id=someone@somewhere&field=hadcrut5.

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