The recent emergence of Arctic Amplification

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Key Points:

- Arctic Amplification only started to occur in the second half of the 20th century. Prior to this the Arctic cooled under global warming.
- Without the increases in both aerosols and greenhouse gas emissions, Arctic Amplification would have occurred throughout the past century.
- Internal variability also plays an important role in setting the observed trends.

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Abstract

Arctic Amplification is robustly seen in climate model simulations of future warming and in the paleoclimate record. Here, we show that in the instrumental record Arctic Amplification is only a recent phenomenon, and that for much of the 20th century the Arctic cooled while the global-mean temperature rose. To investigate why this occurred, we analyze large ensembles of comprehensive climate model simulations under different forcing scenarios. Our results suggest that the global warming from greenhouse gases was largely offset in the Arctic by regional cooling due to aerosols, with internal climate variability also contributing to Arctic cooling and global warming trends during this period. This suggests that the disruption of Arctic Amplification was due to a combination of factors unique to the 20th century, and that enhanced Arctic warming should be expected to be a consistent feature of climate change over the coming century.

Plain Language Summary

Arctic Amplification is the phenomenon by which the Arctic warms at a faster rate than the global average. Evidence for the occurrence of Arctic Amplification is widely found in climate model simulations as well as in paleoproxy reconstructions of past climate changes. In this study, we investigate the extent to which Arctic Amplification has occurred in observations from the past century. We show that Arctic Amplification is only a recent phenomenon, and that for much of the 20th century, the Arctic cooled while the global-mean temperature rose. We investigate why this happened using a range of climate model simulations, and we find that there were two main causes for these opposing trends. The first is that regional cooling from aerosols counteracted the warming from greenhouse gases in the Arctic. However, this cannot fully explain the observed trends. The second is that natural fluctuations of the climate system manifested in a pattern of Arctic cooling under global warming. This suggests that the disruption of Arctic Amplification was due to a combination of factors unique to the 20th century, implying that enhanced Arctic warming should be expected to be a consistent feature of climate change over the coming century.

1 Introduction

Arctic Amplification, the phenomenon whereby the surface air temperature in the Arctic warms at an enhanced rate relative to the rest of the globe, is believed to be one of the most robust features of the climate system's response to external forcings. First identified in Manabe and Stouffer (1980), it has long been known that global climate models simulate amplified warming in the Arctic in response to climate forcing. For example, in response to a quadrupling of CO_2, CMIP5 models simulate a mean surface warming of over 10K in the Arctic, more than double the global mean surface warming (Pithan & Mauritsen, 2014). Amplified warming in the Arctic is a consistent feature of climate model projections of the coming century (Barnes & Polvani, 2015; Laine et al., 2016; Davy & Outten, 2020), and is found in both idealized and comprehensive climate models (Holland & Bitz, 2003; Langen & Alexeev, 2007; Franzke et al., 2017; Merlis & Henry, 2018; Beer et al., 2020). Furthermore, multiple lines of paleoclimate evidence indicate Arctic Amplification of warming and cooling in past warm and cold climates (CAPE, 2006; Masson-Delmotte et al., 2006; Miller et al., 2010; Park et al., 2019).

Many previous studies have investigated the potential causes of Arctic Amplification (Winton, 2006; Screen & Simmonds, 2010; Hwang et al., 2011; Serreze & Barry, 2011; Pithan & Mauritsen, 2014; Stuecker et al., 2018; Henry & Merlis, 2019; Previdi et al., 2020; Henry et al., 2021; Beer et al., 2020). A large array of mechanisms have been identified, including the sea ice albedo feedback, the lapse rate feedback, and changes in energy transports, however the precise contributions of these varied mechanisms remain unclear. For example, numerous studies have pointed to the surface albedo feedback as a fundamental process in driving Arctic Amplification (Screen & Simmonds, 2010; Dai et al., 2019; Chung et al., 2021), yet enhanced Arctic warming is found in climate model simulations even when the surface albedo feedback is disabled (Graversen & Wang, 2009). Untangling the drivers of Arctic Amplification is further complicated because different forcing agents, including CO_2, ozone depleting substances, black carbon, and industrial aerosols, can also have different imprints on the spatial pattern of surface warming (Navarro et al., 2016; Stuecker et al., 2018; Stjern et al., 2019; Polvani et al., 2020).

While many studies have focused on the causes and effects of Arctic Amplification in climate model simulations, relatively little attention has been paid to this phenomenon in the observational record. In this study, we focus on the extent to which Arctic Amplification has occurred in the instrumental record over the past century. We begin by analyzing several observational products to quantify the nature of Arctic Amplification during the past century, and then we use large ensembles of comprehensive climate model simulations to quantify how industrial aerosols, greenhouse gases, and internal climate variability have contributed to the observed trends.

2 Data and methods

2.1 Observations

We focus on the past century (1921-2020), eschewing earlier times due to the relative lack of temperature measurements. We analyze five different observational products for our analysis of near surface air temperature (SAT) trends over the instrumental record: GISTEMPv4 (Lenssen et al., 2019; GISTEMP, 2021), HadCRUT5 (Morice et al., 2020), the Cowtan and Way (2014) update to HadCRUT4 referred to as HadCRUT4-hybrid, the ERA-20C reanalysis (Poli et al., 2016), and the ERA5 reanalysis (Hersbach et al., 2020). For ease of presentation, we focus on results from GISTEMPv4, which is based on NOAA-GHCN-v4 station data over land and ERSSTv5 over ocean (Huang et al., 2017). Note that only GISTEMPv4 and HadCRUT5 cover the entire period of interest: the HadCRUT4-hybrid dataset ends in 2018, ERA-20C ends in 2010, and ERA5 only starts in 1950. Lastly, we analyze the 200 members of the HadCRUT5 ensemble to assess the impacts of observational uncertainty, which arises from statistical infilling of sparsely observed areas, measurement uncertainty, and changes in SST measurement practices, among other factors. More information about these datasets is given in Table S1.

2.2 Climate model simulations

We utilize the 40 members of the Community Earth System Model v1 Large Ensemble (CESM1-LE), introduced by Kay et al. (2015). CESM1 is a CMIP5-class climate model, using the CAM5 atmospheric model and the POP2 ocean model. Each of the 40 members uses identical historical forcing (Lamarque et al., 2010) for the period 1920-2005 and future emissions under the RCP8.5 scenario from 2006 onwards (Meinshausen et al., 2011). The only difference between the members arises from chaotic fluctuations generated by round-off level (10^{-14} K) perturbations to the atmospheric initial temperature in 1920. As such, each ensemble member is a realization of the climate system over the past century, with the ensemble mean isolating the forced response to external forcing and the spread among the ensemble members being solely due to internal variability of the climate system. The CESM1-LE has been widely used to investigate the roles of anthropogenic forcing and internal variability in driving observed trends in Arctic SAT and sea ice (Ding et al., 2017; England et al., 2019; Ding et al., 2019; Landrum & Holland, 2020; Krishnan et al., 2020; Polvani et al., 2020).

To investigate the contributions of anthropogenic aerosols and greenhouse gases to observed SAT trends over the past century, we analyze two CESM1 single-forcing ensembles, each containing 20 members, introduced by Deser, Phillips, et al. (2020). The first, CESM1 x-aer, is identical to the CESM1-LE except that industrial aerosol concentrations are fixed at 1920 values. All other forcings evolve as in the CESM1-LE. In the same fashion, the second, CESM1 x-ghg, is identical to the CESM1-LE except that greenhouse gas concentrations are held fixed at 1920 values. Taking the difference between the ensemble mean of the CESM1-LE (which features all forcings) and either CESM1 x-aer or CESM1 x-ghg (which feature all but one forcing) isolates the roles of aerosols and greenhouse gases in driving historical temperature trends in CESM1. More details on the large ensembles analyzed here are given in Table S2.

We compare the results from the CESM1-LE with three other large ensembles which also participated in the recent CLIVAR large ensemble collection (Deser, Lehner, et al., 2020). Specifically, we analyse the 30 members of CSIRO-Mk3-6-0 (Jeffrey et al., 2013), the 20 members of GFDL-CM3 (Sun et al., 2018) and the 100 members of MPI-ESM (Maher et al., 2019). We focus on the results from the CESM1-LE because of the availability of single forcing ensembles with this model.

3 Prolonged periods of observed Arctic cooling during global warming

We begin by examining the timeseries of observed Arctic (60°N - 90°N) and global average SAT anomalies relative to a baseline period of 1951-1980, as shown in Figure 1. These show the much larger interannual variability and multi-decadal changes in the Arctic temperature (blue line) as compared to the global temperature (red line). As documented by previous studies (Johannessen et al., 2004; Gillett et al., 2008; Serreze et al., 2009; Semenov & Latif, 2012), the timeseries of Arctic surface temperatures can be characterized by a period of anomalous warmth in the 1930s and 1940s, and then a substantial period of cooling lasting until the 1980s, which was followed by four decades of rapid Arctic warming up to the present day. These results remain qualitatively unchanged if the domain is limited to either land or ocean regions only in the Arctic (Fig. S2). In contrast to the Arctic, global temperatures have generally risen throughout the past century, with muted warming for much of the mid-20th century and an increased rate of warming after approximately 1980.

The two timeseries in Figure 1 demonstrate that Arctic Amplification did not occur for large parts of the 20th century. To illustrate this, we focus on the 50-year period 1935-1984, indicated by the trendlines in Figure 1. During this period, the global-mean temperature showed a small warming trend of $0.03\,^{\circ}\mathrm{C/decade} \pm 0.02\,^{\circ}\mathrm{C/decade}$, yet the Arctic cooled at a rate of $-0.15\,^{\circ}\mathrm{C/decade} \pm 0.08\,^{\circ}\mathrm{C/decade}$, where the uncertainties represent the 95% linear regression confidence interval. These results from GISTEMPv4 are consistent with the other observational and reanalysis products analyzed here (Fig. S1).

Next, we examine all 50-year trends in observed Arctic (blue) and global (red) SAT over the past century (Fig. 2a) to investigate exactly when Arctic Amplification began. The red shading in Figure 2a shows the 50-year SAT trends that feature Arctic Amplification (i.e. where the rate of Arctic warming is greater than the rate of global warming), while the blue shading denotes 50-year SAT trends of simultaneous Arctic cooling and global warming. We highlight three important points: (i) the first occurrence of Arctic Amplification in the observed record was the years 1951-2000, (ii) during the past century, periods of Arctic cooling under global warming occurred approximately as frequently as periods of Arctic Amplification, and (iii) the switch from Arctic cooling to Arctic amplified warming (white shading) was rapid, transitioning in less than five years. The same broad features are found in the other observational and reanalysis datasets that we analyzed (Fig. S3a). In addition, the conclusions are robust to the impacts of observational uncertainty as represented by the 200 ensemble members of HadCRUT5 (Fig. S3b) and remain approximately unchanged if we examine the non-infilled version of HadCRUT5 (compare panels b and c in Fig. S3).

We turn to the 40 members of the CESM1-LE to examine the extent to which this observed behaviour is replicated by climate model simulations (Figs. 2b,c). There are individual ensemble members that largely capture the evolution of observed trends in Arctic and global SAT. As an example we show ensemble member #33 (Fig. 2b, crosses), which exhibits Arctic cooling for much of the early and mid 20th century followed by Arctic amplified warming thereafter. There are several differences between this ensemble member and the observations, namely that the Arctic cooling trends are approximately 30% smaller and the transition to Arctic Amplification occurs a few years earlier than observed. Overall, however, ensemble member #33 replicates the main features of the observed trends. But, the majority of ensemble members fail to simulate the observed trends in both Arctic and global-mean temperatures. As an example, ensemble member #31 exhibits Arctic-amplified surface warming trends throughout the past century (Fig. 2b, circles), which is inconsistent with the observations. The substantial differences in the running 50-year Arctic trends of the two members indicate the important role of internal variability in driving observed trends.

To separate the roles of the forced response and internal variability in contributing to the observed trends, we show the 50-year SAT trends of all 40 members of the CESM1-LE (Fig. 2c, dots) in addition to the ensemble mean (Fig. 2c, thick lines). The observed global-mean trends are roughly consistent with the forced trends in the CESM1-LE, with weakly positive trends over the early and middle-20th century, followed by more rapid warming in the second half of the century. In contrast, the observed 50-year Arctic cooling trends over the mid-20th century are at the edge of the CESM1-LE distribution (compare panels a and c of Fig. 2), suggesting that the observed trends are either a low probability trajectory of the climate system or that the CESM1-LE systematically underestimates the Arctic cooling during this period. More recently, the strong Arctic warming trends over the past 50 years are reproduced by the ensemble-mean of the CESM1-LE (compare panels a and c of Fig. 2).

Although most CESM1-LE members do not reproduce the Arctic cooling trends seen over much of the 20th century, the ensemble mean does show a slight Arctic cooling for trends centred in the 1940s and 50s, during a period in which the ensemble-mean global trend is positive. This indicates a potential role for the ensemble mean response alone to drive periods of Arctic cooling concurrent with global warming. Moreover, the majority of the members (31 out of 40) include at least some periods of Arctic cooling concurrent with global warming over the past century, suggesting that this observed phenomenon can be reproduced in part by climate models. The 50-year Arctic and global SAT trends simulated by the CESM1-LE are broadly consistent with the three other large ensembles we analyzed (Fig. S4) although we note that MPI-ESM does not simulate the periods of observed Arctic cooling and CSIRO-Mk3-6-0 and GFDL-CM3 do not replicate the observed global warming in the mid-20th century. In addition, GFDL-CM3 simulates Arctic warming trends over the second half of the 20th century which are much stronger than observed. Overall, we find that of the CESM1-LE performs the best at capturing the major characteristics of the observed trends. Next, we explore why there was no Arctic Amplification for much of the 20th century.

4 What caused the lack of Arctic Amplification?

In order to investigate what caused the opposing trends in observed Arctic and global SAT, we focus on three central potential drivers: industrial aerosols, greenhouse gases, and internal climate variability. We investigate the forced response to aerosols and greenhouse gases by analyzing the 20 member CESM1 single forcing ensembles with fixed aerosols (x-aer) and fixed greenhouse gases (x-ghg). Previous studies have shown the importance of industrial aerosols (Fyfe et al., 2013; Navarro et al., 2016; Gagne et al., 2017; Deser, Phillips, et al., 2020) and greenhouse gases (Gillett et al., 2008; Nafaji et al., 2015; Deser, Phillips, et al., 2020; Polvani et al., 2020) in contributing to the observed Arctic SAT trends over the past century. However, the contributions of greenhouse gases, aerosols and internal variability to the observed Arctic SAT trends have yet to be quantified.

Figure 3a shows that in the absence of changes in the concentrations of industrial aerosols since 1920, CESM1 indicates that both Arctic and global SAT would have risen monotonically throughout the past century. Hence, in the absence of extra industrial aerosol emissions, the Arctic would not have experienced any 50-year cooling trends over the past century. In contrast, without the increase in greenhouse gases since 1920, CESM1 indicates that both the Arctic and the global mean surface would have cooled throughout the century (Fig. 3b). This suggests that greenhouse gases are necessary to explain the global surface warming throughout the century as well as the rapid Arctic warming since the second half of the 20th century, while aerosols are required to explain the Arctic cooling over much of the 20th century. It is important to note that in both ensembles, x-aer and x-ghg, Arctic Amplification is present in nearly every member throughout the entire century. Therefore it is the specific combination of greenhouse gas emissions and industrial aerosol emissions, and the extent to which their effects offset each other at a global and regional scale, that created the conditions for Arctic Amplification not to occur for much of the 20th century.

Next we focus again on the period 1935-1984 and quantify the contributions to the observed trends from aerosols, greenhouse gases, and internal variability (Fig 4). This 50-year period was chosen to broadly represent the Arctic and global mid-20th century SAT trends. Similar results are found for a decade earlier (1925-1974, Fig. S5). To calculate the contribution of aerosols (light blue bar) we take the difference between the ensemble mean of the CESM1-LE and the ensemble mean of the CESM1 x-aer ensemble and then calculate the trends over the period of interest. To calculate the contribution of greenhouse gases (light red bar), we repeat this process but with the CESM1 x-ghg ensemble rather than x-aer. The role of internal variability is estimated as the residual (orange bar) after the effects of aerosols and greenhouse gases have been subtracted from the observed trend. This is compared with the range of trends attributable to internal variability in the CESM1-LE (black bars), which is computed by subtracting the ensemble mean to remove the forced response and then calculating the central 95% range of the 50-year SAT trends across the 40-members (i.e. the difference between the 39th and 2nd member after ranking).

These results allow us to estimate what caused the observed Arctic cooling of -0.15°C/decade during 1935-1984. As shown in Figure 4a, CESM1 implies that industrial aerosols caused a cooling trend of -0.27°C/decade, and greenhouse gases caused a warming trend of +0.20°C/decade, which resulted in a net anthropogenic impact of -0.07°C/decade. Thus the residual needed to account for the observed trend is -0.08°C/decade. This is well within the range of 50-year SAT trends due to internal variability simulated by CESM1-LE [-0.14°C/decade, $+0.11$°C/decade], implying that the residual can be plausibly attributed to internal variability. The results therefore suggest that in the absence of internal variability, the observed Arctic cooling trend would have been half as large. In addition, some realizations of internal variability would have overcome the net anthropogenic cooling effect and resulted greater Arctic warming over this period than the observed global warming. That is to say, the lack of Arctic Amplification was not an inevitable response to the anthropogenic forcing.

We can similarly estimate what drove the observed global mean warming trend of +0.03°C/decade (Fig. 4b) during 1935-1984. We find that there is a near perfect cancellation between the aerosol cooling trend of -0.09°C/decade and the greenhouse gas induced warming trend of +0.09°C/decade. Thus the residual needed to account for the observed trend is +0.03°C/decade. This is at the edge of the range of internal variability simulated by CESM1-LE [±0.03°C/decade]. This suggests that we could have experienced global mean cooling during this period under a different realization of internal variability, and as such we could have experienced a period of Arctic amplified cooling. We note that the Arctic Amplification factor, commonly defined as the Arctic SAT trend divided by the global SAT trend, is only 2.2 for greenhouse gases (a driver of Arctic and global warming) over this period, but 3.0 for industrial aerosols (a driver of Arctic and global cooling). This difference likely arose because aerosol emissions primarily occurred over North America and Northern Europe (Navarro et al., 2016; Deser, Phillips, et al., 2020; Krishnan et al., 2020). This helps to explain why the simulated (i.e. the CESM1-LE ensemble mean) features a small cooling trend in the Arctic SAT and a weak warming trend in the global SAT (compare ensemble mean lines in Fig. 2c).

5 Conclusions

In this study we have investigated the extent to which Arctic Amplification occurred over the past century in the observed record. We found that Arctic Amplification is a relatively recent phenomenon during this period, first occurring in 50-year trends centered in the second half of the 20th century. We showed that 50-year periods with Arctic cooling concurrent with global warming occurred as frequently as periods with Arctic amplified warming during the past century. We then used CESM1 to investigate why Arctic Amplification was not ubiquitous throughout the past century. We showed that CESM1 single forcing experiments imply that without historical changes in greenhouse gases or aerosols, Arctic Amplification would have consistently occurred. We found that it is the cancellation of these two forcings, with aerosols having an outsized effect on the Arctic compared to the global mean, that created the conditions for Arctic cooling during global warming. Lastly we used CESM1 results to estimate the contributions of aerosols, greenhouse gases, and internal variability to the observed SAT trends during 1935-1984. These results imply that the lack of Arctic Amplification during this period, which is reproduced by many members of the CESM1-LE, was made more likely due to anthropogenic forcing, and that internal variability also played a key role. Different realizations of internal variability could have caused the global mean or Arctic SAT trend to switch sign, and thus the lack of Arctic Amplification was not inevitable under the anthropogenic forcing.

Arctic Amplification is thought to be one of the most robust features of global warming. Yet, we have shown that the emergence of this phenomenon in the observed record has only occurred relatively recently. We reconciled this by demonstrating that the lack of Arctic Amplification over much of the early and mid 20th century arose from a particular combination of factors: a cancellation between the forced response to greenhouse gases and aerosols, the stronger Arctic amplified response to aerosols than to greenhouse gases over this time period, and the specific trajectory of internal variability. Moving forward, it is unlikely that this set of factors will manifest at any point in the 21st century for three main reasons: (i) the overall aerosol burden is expected to decrease over this century (Szopa et al., 2013; Fiedler et al., 2019) and so the forced response to increasing greenhouse gas concentrations will dominate, (ii) if increases in aerosol emissions do occur then it is expected they will originate from low latitudes (Fiedler et al., 2019) and thereby have limited cooling effects on the Arctic, and (iii) the levels of internal variability simulated by the four large ensembles studied here are not large enough to overcome the forced Arctic amplified warming response to projected increases in greenhouse gas concentrations. Hence, Arctic Amplification is likely to be a robust and persistent feature of climate change over the coming century, despite not occurring for much of the past century.

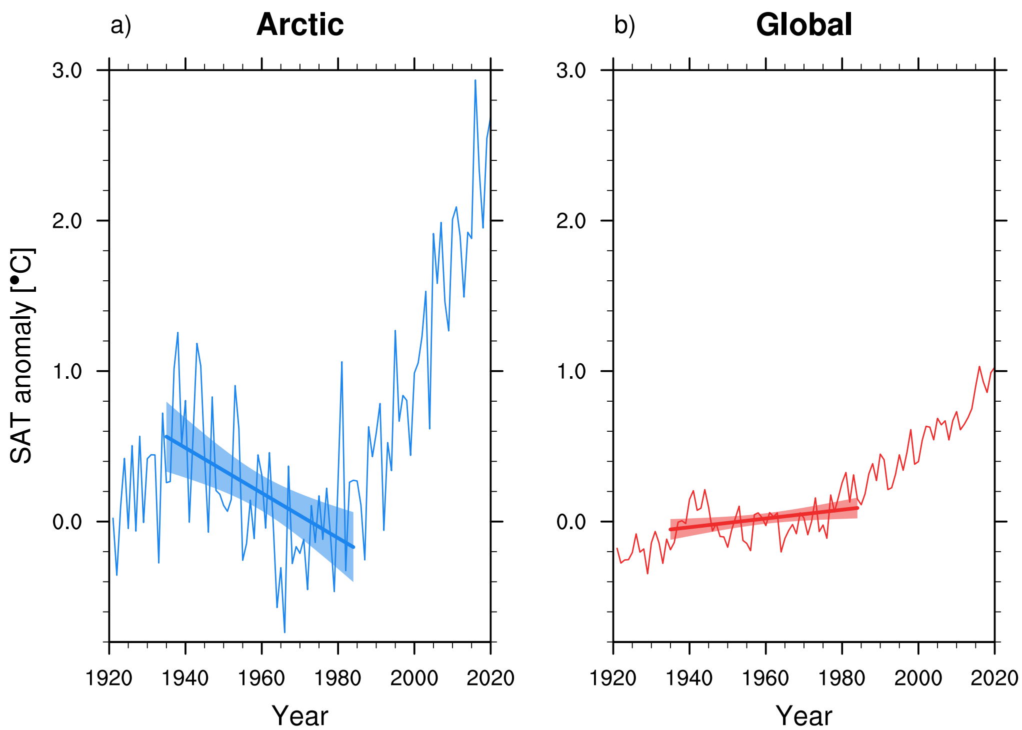

Figure 1. Timeseries of (a) Arctic and (b) global annual mean surface air temperature anomalies, relative to the mean temperature during the period 1951-1980, from GISTEMPv4. The trends during 1935-194 are indicated with shading to represent the 95% linear regression confidence interval.

Acknowledgments

The authors declare that they have no competing interests. Support for this work came from the National Science Foundation. The GISTEMPv4 observational dataset can be downloaded from https://data.giss.nasa.gov/gistemp/. The HadCRUT5 observational dataset can be download form https://www.metoffice.gov.uk/hadobs/hadcrut5/. The HadCRUT4-hybrid observational dataset can be downloaded from https://www-users.york.ac.uk/ kdc3/papers/coverage2013/series.html. ERA20C and ERA5 reanalysis data can be downloaded from the Copernicus Climate Change Service Data Store at https://cds.climate.copernicus.eu/. The multiple large ensemble archive can be found at http://www.cesm.ucar.edu/projects/community-projects/MMLEA/. The CESM1-CAM5 single forcing runs are accessible via the NCAR Climate Data Gateway.

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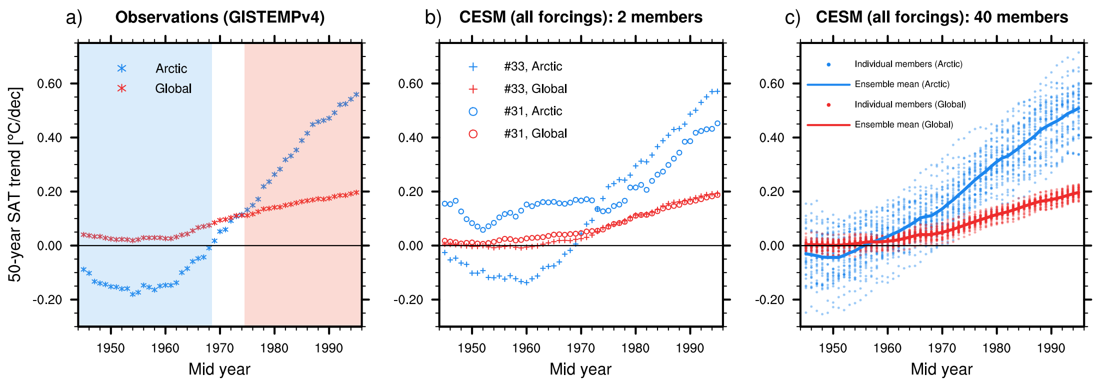

Figure 2. 50-year trends in Arctic (blue) and global (red) SAT over the years 1921-2020, with the mid-year shown on the horizontal axis. (a) The observed trends using GISTEMPv4, with blue shading indicating periods of concurrent Arctic cooling and global warming and red shading indicating periods of Arctic amplified warming. (b) The trends of two individual ensemble members from the CESM1-LE: ensemble member #31 (circles) and ensemble member #33 (crosses). (c) The dots show the trends for all 40 members of the CESM1-LE and the solid lines shows the ensemble mean trends.

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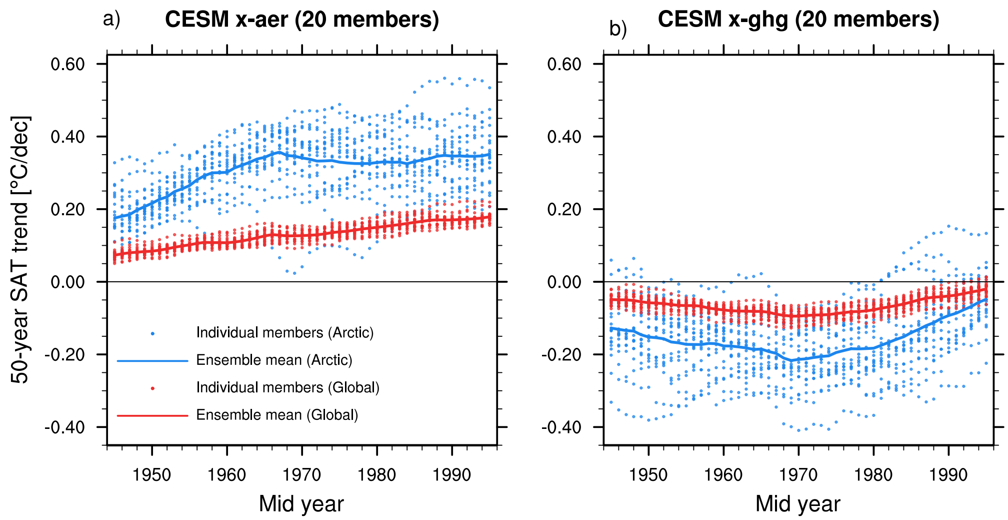

Figure 3. As in Fig. 2c, but for (a) the 20 members of the CESM1 x-aer ensemble and (b) the 20 members of the CESM1 x-ghg ensemble.

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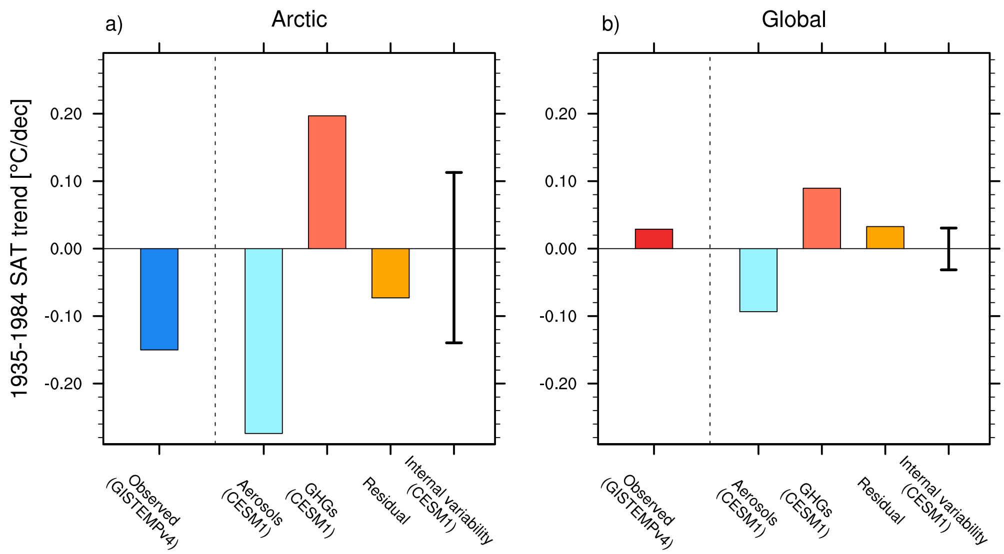

Figure 4. Decomposition of the observed (a) Arctic and (b) global SAT trends during 1935-1984 into contributions from aerosols, GHGs, and internal variability. The forced responses to aerosols and GHGs are calculated using the CESM1 ensembles. The residuals after the aerosol and GHG forced responses are subtracted from the observed trends are also indicated. The black bars indicate the 95% confidence intervals for the trends which could be explained by internal variability according to the CESM1-LE.

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Figure 1.

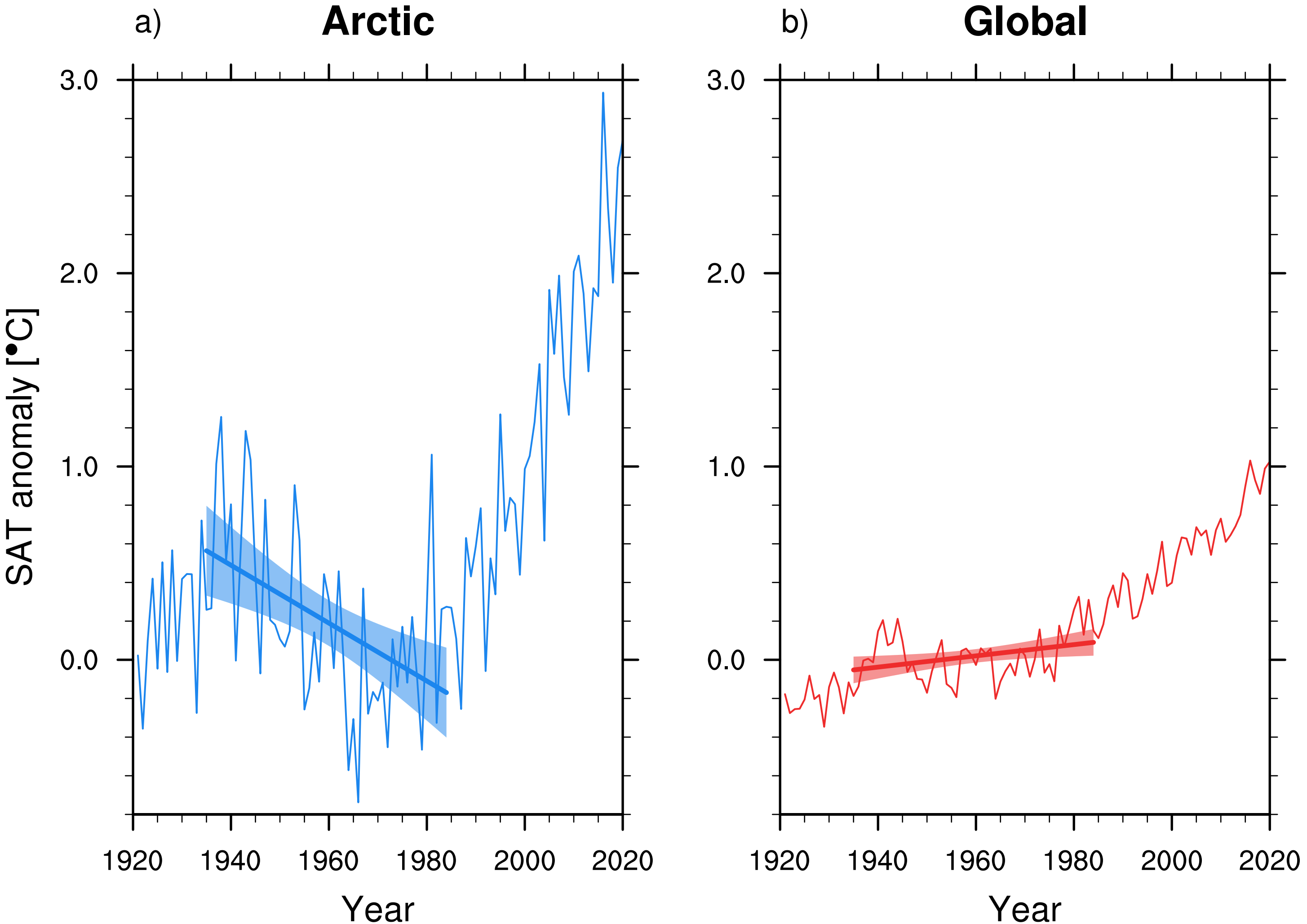

a)
Arctic
b)
Global
3.0
2.0
1.0
0.0
SAT anomaly [•C]
1920
1940
1960
1980
2000
2020
Year

Figure 2.

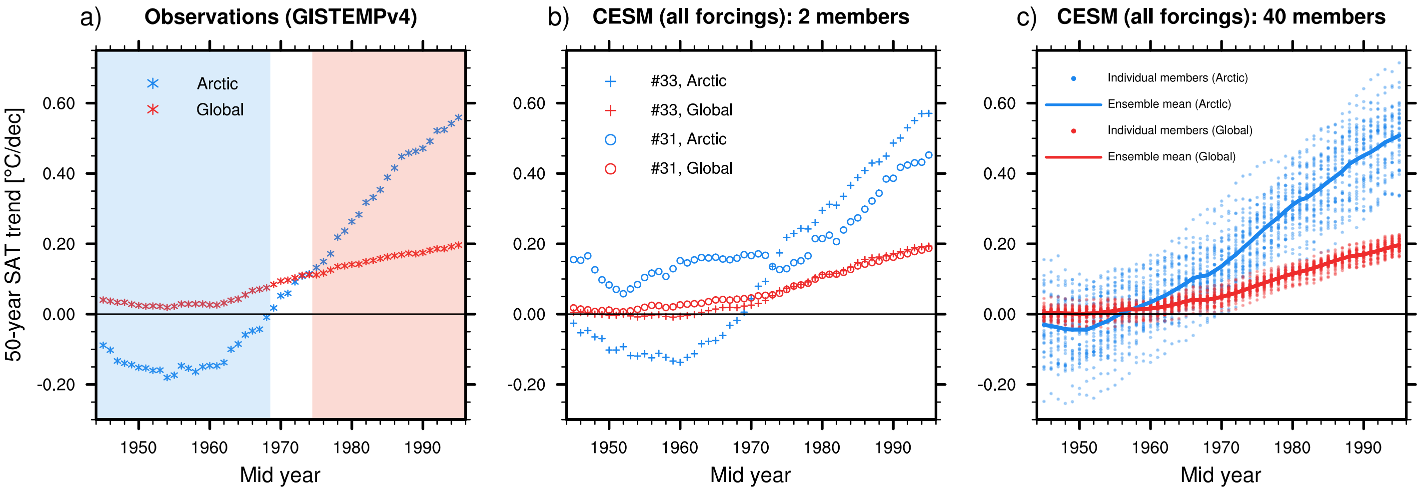

a)
Observations (GISTEMPv4)
Arctic
Global
50-year SAT trend [°C/dec]
0.60
0.40
0.20
0.00
-0.20
1950
1960
1970
1980
1990
Mid year
b)
CESM (all forcings): 2 members
#33, Arctic
#33, Global
#31, Arctic
#31, Global
c)
CESM (all forcings): 40 members
Individual members (Arctic)
Ensemble mean (Arctic)
Individual members (Global)
Ensemble mean (Global)

Figure 3.

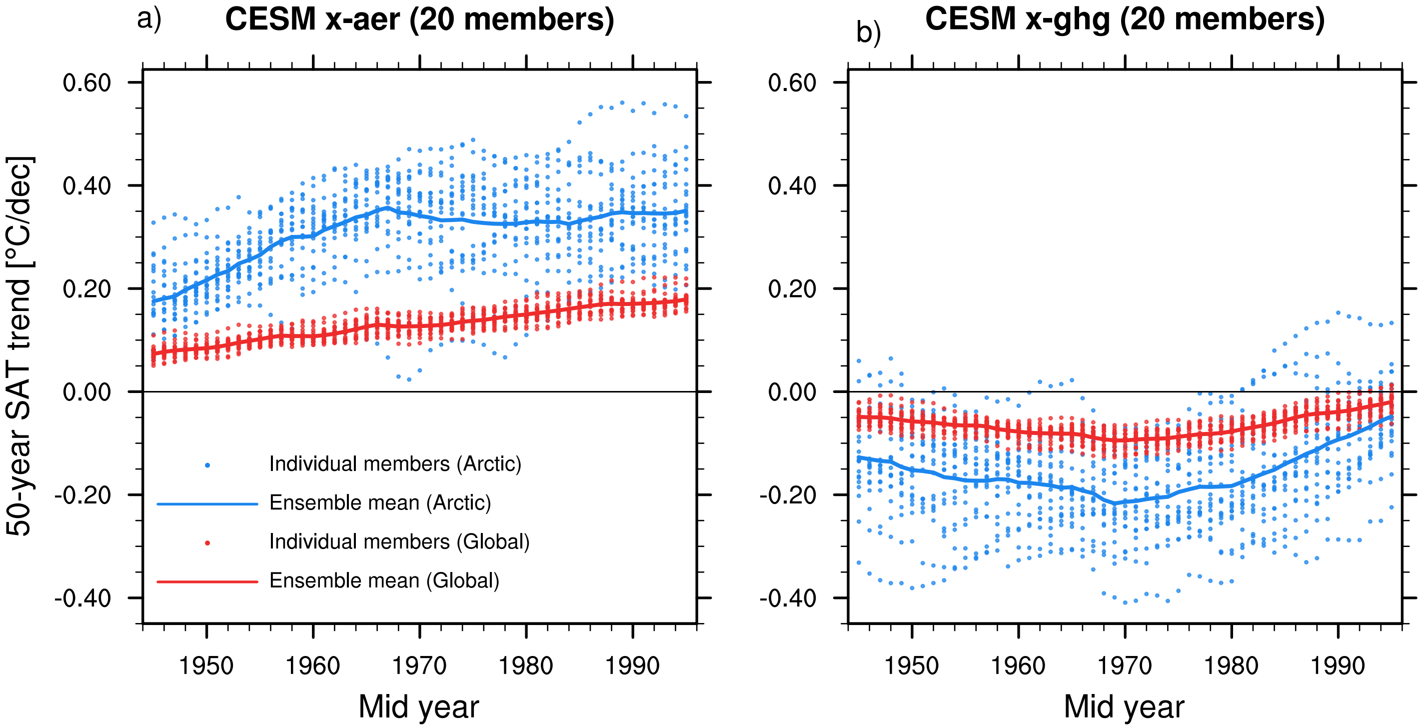
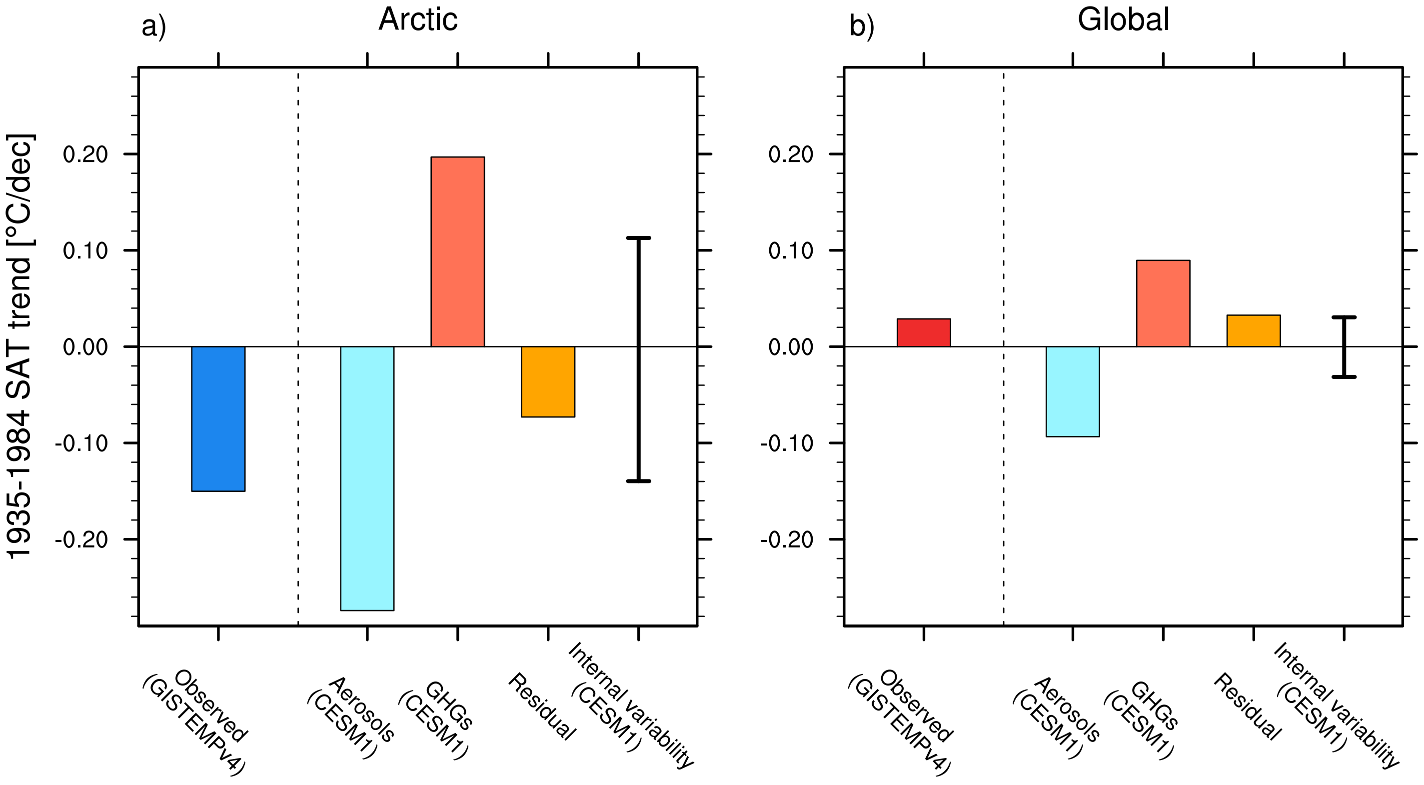

a)
CESM x-aer (20 members)
b)
CESM x-ghg (20 members)
0.60
0.40
0.20
0.00
-0.20
-0.40
50-year SAT trend [°C/dec]
Individual members (Arctic)
Ensemble mean (Arctic)
Individual members (Global)
Ensemble mean (Global)
1950
1960
1970
1980
1990
Mid year

Figure 4.


a)
Arctic
b)
Global
1935-1984 SAT trend [°C/dec]
0.20
0.10
0.00
-0.10
-0.20
Observed (GISTEMPv4)
Aerosols (CESM1)
GHGs (CESM1)
Residual
Internal variability (CESM1)