Title
Unraveling The Arctic Sea Ice Change Since The Middle Of The Twentieth Century

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UNRAVELING THE ARCTIC SEA ICE CHANGE SINCE THE MIDDLE OF THE TWENTIETH CENTURY

By

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ABSTRACT

Changes in Arctic sea ice since the middle of the last century are explored in this study. Both observations and climate model simulations show an overall sea ice expansion during the period of 1953–1970 but a marked sea ice decline afterward. Anthropogenic aerosols, natural forcing, and atmospheric ozone changes are found to contribute to the sea ice expansion in the early period. Their effects are generally strong in late boreal summer. On the other hand, greenhouse gas warming had a dominant effect on diminishing Arctic sea ice cover during 1971–2005, especially in September. Internal climate variability also plays a role in the Arctic sea ice change during 1953–1970. However, it cannot solely explain the Arctic sea ice decline since the 1970s.

ACKNOWLEDGEMENTS

I would like to acknowledge my mentor Dr. Wei Liu, who has guided me through this entire project completely. Without him, none of this would have been possible. His experience with the NCL programming language and deep knowledge relating to similar studies as well as the field in general has proven to be extremely insightful. His knowledge of related studies as well as previous research on this topic has been an invaluable resource in completing this research.

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INTRODUCTION

Satellite passive microwave data starting from 1979 has shown a very clear substantial decrease in the Arctic sea ice cover [2,30,36,37,40]. However, numerous observations and reconstructions from the 1950s to the 1970s point to an increase in sea ice extent prior to 1979 [12,15,24,27,29,33,35]. These changes in the Arctic sea ice have been well-simulated in historical experiments, which used a combination of anthropogenic and natural agents with climate models from the Coupled Model Intercomparison Project (CMIP) phase 3 (CMIP3) [28] and Coupled Model Intercomparison Project (CMIP) phase 5 (CMIP5) [12,29]. Understanding the underlying physical mechanisms that have been controlling the Arctic sea ice change over the past few decades is crucial because of the significant global and regional climate impacts [1,5,10,17,18,21,31,39] that it will and has already had.

External forcings [12,14,28,29,30] or internal climate variability [15,24,33] have been attributed to changes in the Arctic sea ice since the middle of the 20th century. External forcings could be something like human activities that cause variations in the levels of greenhouse gasses and aerosols in the air. Internal climate variability means naturally occurring variations in nature. A related study by Gagne et. al [12] used the CMIP5 model CanESM2 historical simulations and associated anthropogenic aerosols forcing only, well-mixed greenhouse gasses forcing only, and natural forcing only experiments to show that the expansion of Arctic sea ice cover from the period of 1950–1975 is mainly driven by anthropogenic aerosols. Anthropogenic aerosols meaning a suspension of either droplets or some fine solid particles in the air that originate from human activity, some examples being mist, smoke, dust, and steam, among others. Another related study by Mueller et al. [29] used historical, well-mixed greenhouse gasses and natural forcing-only experiments with eight CMIP5 models. The study found that the negative sea ice trend induced by well-mixed greenhouse gasses is partially offset by a weak positive trend induced by other anthropogenic forcings, which were mainly aerosols, between 1953 and 2012. Ployakov et al. [33], on the other hand, discovered that a multi-decadal oscillation dominated the sea ice variability in the Kara, Laptev, East Siberian, and Chukchi Seas during the twentieth century.

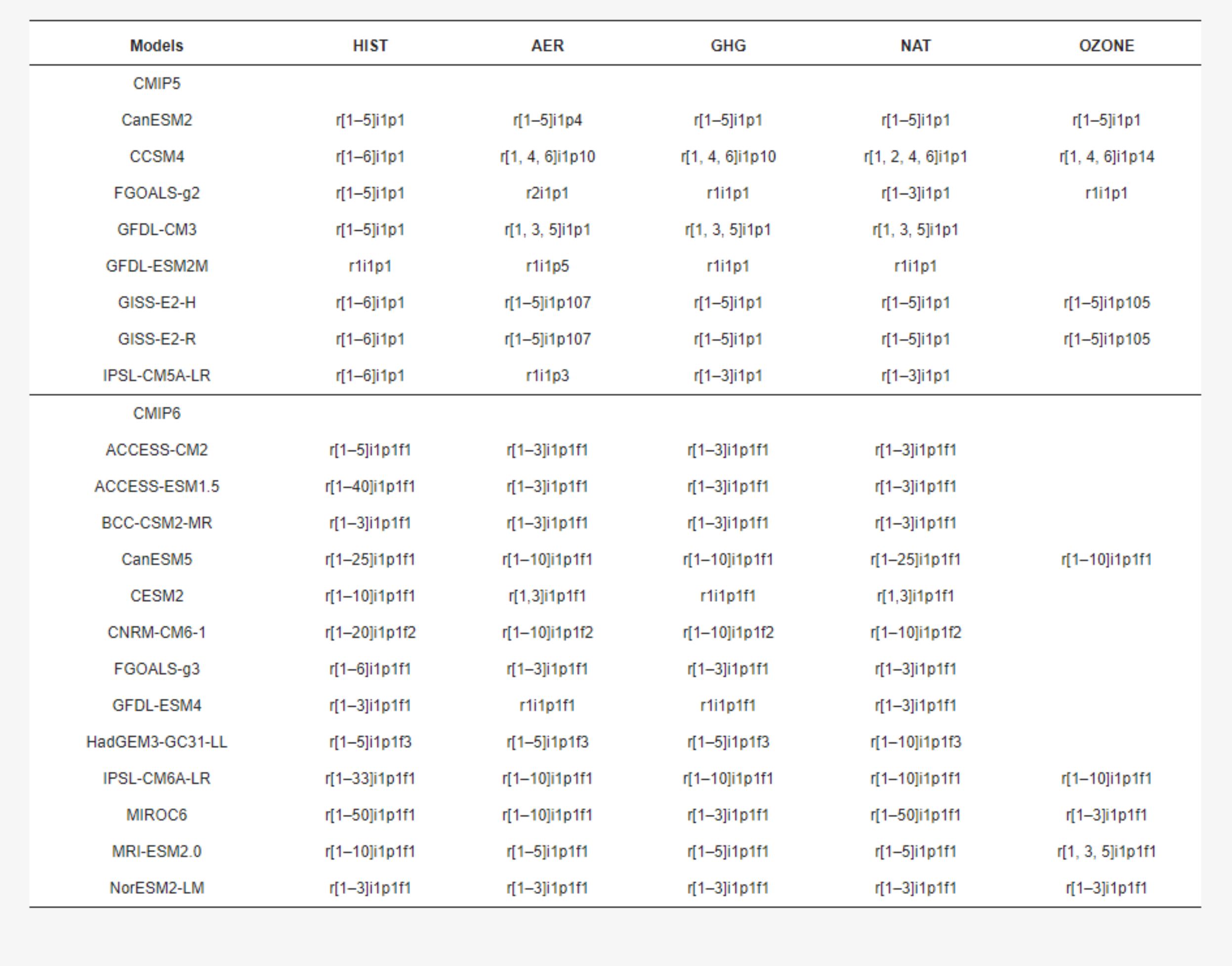
The scientific question we are answering is if the historical Arctic sea ice increase and decline can be accurately simulated, and what the mechanism is for this. Unlike previous studies, we will leverage state-of-the-art CMIP phase 6 (CMIP6) models [9] and their historical and single forcing experiments [13] to probe the roles of external forcings and internal climate variability in driving the Arctic sea ice change since the mid-twentieth century. Compared with the previous generations of climate models, CMIP6 models feature higher spatial resolutions, sophisticated aerosol-cloud physics, and additional biogeochemical processes. Our original hypothesis is that the observed cooling effect is mainly caused by anthropogenic aerosols while the warming effect is caused by greenhouse gasses. We believe that overall changes could be a mixture of external forcings and internal climate variability. We will explore the role of atmospheric ozone change, which has been seldom discussed in previous studies. We will also investigate the seasonal variations of Arctic sea ice, which has not previously been extensively discussed, in addition to annual mean change.

In our next section, we will address the materials we used in our analysis along with the methods employed on those materials. Subsequently, we will present our findings with a focus on the roles of external forcings and internal climate variability in historical Arctic sea ice changes. In our fourth and final section, we will conclude our study, along with further discussions.

MATERIALS AND METHODS

In our research, we utilized two historical Arctic sea ice reconstructions, called observations. They are the Walsh and Chapman data set [41] (Walsh and Chapman thereafter) and the HadISST data set [34]. The Walsh and Chapman data provide a one-degree gridded monthly sea ice extent and concentration starting from 1850 and are a hybrid of satellite data with gridded data, including those from the Scanning Multichannel Microwave Radiometer/Special Sensor Microwave/Imager. The Met Office's Hadley Centre produces the HadISST data, which includes Hadley Centre sea ice and sea surface temperature. Starting from 1870, the HadISST observations consist of monthly concentrations of sea ice on a one-degree grid. Both Walsh and Chapman and HadISST data are in-filled data. The integral sum of all grid cells with a sea ice concentration of at least 15% is used to determine the sea ice extent. In the Walsh and Chapman data, a climatological infilling is used to close gaps in the historical record. In the HadISST data, Arctic sea ice concentrations present a data gap prior to 1953. As a result, we focus on the Arctic sea ice changes in both observational datasets from 1953 onward.

To investigate the mechanism by which Arctic sea ice has changed over time, we make use of eight CMIP5 [38] and thirteen CMIP6 [9] climate models (Table 1). We select these models since they provide single-forcing simulations under historical changes in anthropogenic aerosols only (AER), well-mixed greenhouse gasses only (GHG), natural sources such as solar and volcanic activity only (NAT), and atmospheric ozone only (OZONE), as well as the combined effects of all forcing (HIST). Because most of the CMIP5 and CMIP6 simulations end in 2005 and 2014, respectively, we focus on the period of 1953–2005, during which all the data are available from either observations or CMIP5 and CMIP6 model simulations. We utilize both CMIP5 and CMIP6 models due to their inherent differences, in that CMIP6 models contain different future scenarios, have a greater resolution, and are widely considered to be more accurate among other differences.



Models	HIST	AER	GHG	NAT	OZONE
CMIP5					
CanESM2	r[1–5]i1p1	r[1–5]i1p4	r[1–5]i1p1	r[1–5]i1p1	r[1–5]i1p1
CCSM4	r[1–6]i1p1	r[1, 4, 6]i1p10	r[1, 4, 6]i1p10	r[1, 2, 4, 6]i1p1	r[1, 4, 6]i1p14
FGOALS-g2	r[1–5]i1p1	r2i1p1	r1i1p1	r[1–3]i1p1	r1i1p1
GFDL-CM3	r[1–5]i1p1	r[1, 3, 5]i1p1	r[1, 3, 5]i1p1	r[1, 3, 5]i1p1	
GFDL-ESM2M	r1i1p1	r1i1p5	r1i1p1	r1i1p1	
GISS-E2-H	r[1–6]i1p1	r[1–5]i1p107	r[1–5]i1p1	r[1–5]i1p1	r[1–5]i1p105
GISS-E2-R	r[1–6]i1p1	r[1–5]i1p107	r[1–5]i1p1	r[1–5]i1p1	r[1–5]i1p105
IPSL-CM5A-LR	r[1–6]i1p1	r1i1p3	r[1–3]i1p1	r[1–3]i1p1	
CMIP6					
ACCESS-CM2	r[1–5]i1p1f1	r[1–3]i1p1f1	r[1–3]i1p1f1	r[1–3]i1p1f1	
ACCESS-ESM1.5	r[1–40]i1p1f1	r[1–3]i1p1f1	r[1–3]i1p1f1	r[1–3]i1p1f1	
BCC-CSM2-MR	r[1–3]i1p1f1	r[1–3]i1p1f1	r[1–3]i1p1f1	r[1–3]i1p1f1	
CanESM5	r[1–25]i1p1f1	r[1–10]i1p1f1	r[1–10]i1p1f1	r[1–25]i1p1f1	r[1–10]i1p1f1
CESM2	r[1–10]i1p1f1	r[1,3]i1p1f1	r1i1p1f1	r[1,3]i1p1f1	
CNRM-CM6-1	r[1–20]i1p1f2	r[1–10]i1p1f2	r[1–10]i1p1f2	r[1–10]i1p1f2	
FGOALS-g3	r[1–6]i1p1f1	r[1–3]i1p1f1	r[1–3]i1p1f1	r[1–3]i1p1f1	
GFDL-ESM4	r[1–3]i1p1f1	r1i1p1f1	r1i1p1f1	r[1–3]i1p1f1	
HadGEM3-GC31-LL	r[1–5]i1p1f3	r[1–5]i1p1f3	r[1–5]i1p1f3	r[1–10]i1p1f3	
IPSL-CM6A-LR	r[1–33]i1p1f1	r[1–10]i1p1f1	r[1–10]i1p1f1	r[1–10]i1p1f1	r[1–10]i1p1f1
MIROC6	r[1–50]i1p1f1	r[1–10]i1p1f1	r[1–3]i1p1f1	r[1–50]i1p1f1	r[1–3]i1p1f1
MRI-ESM2.0	r[1–10]i1p1f1	r[1–5]i1p1f1	r[1–5]i1p1f1	r[1–5]i1p1f1	r[1, 3, 5]i1p1f1
NorESM2-LM	r[1–3]i1p1f1	r[1–3]i1p1f1	r[1–3]i1p1f1	r[1–3]i1p1f1	r[1–3]i1p1f1

Table 1. The CMIP5 and CMIP6 models, simulations, and ensembles used in the current study.

In order to identify and quantify the effects of distinct external forcings on the alteration of Arctic sea ice, we examine the multi-model means (MMMs) of historical and single-forcing CMIP5/6 simulations. For either CMIP5 or CMIP6 models, we compute the multi-model means by first calculating the ensemble mean for each model and then averaging the mean values over all the models. In addition, the inter-model spread is calculated by using one standard deviation among the ensemble means of individual models.

To examine the effect of internal climate variability on Arctic sea ice change, we analyze large (>30) ensemble simulations with three CMIP6 climate models, ACCESS1-ESM1.5, IPSL-CM6A-LR, and MIROC6 (Table 1). Each individual ensemble member responds to anthropogenic forcing and contains a realization of internal climate variability of a different timing from the others, since the predictability horizon of climate models at most amounts to one to two decades [6,25]. Knowing this, we can obtain the model response to anthropogenic forcing by calculating the ensemble mean to average out the internal climate variability. After that, we will subtract the ensemble mean from each member to obtain the signals that represent internal climate variability.

Some important things to mention are that: i) The CMIP6 OZONE simulations are only forced by stratospheric ozone changes [13,22] while the CMIP5 OZONE simulations cover changes in tropospheric and stratospheric ozone levels. Unlike HIST, AER, GHG, and NAT simulations, only parts of the CMIP5 and CMIP6 models have OZONE simulations available (Table 1). ii) Two CMIP5 models, CSIRO-Mk3.6.0 and NorESM1-M, are excluded from analysis since CSIRO-Mk3.6.0 has an unrealistic simulation of Arctic sea ice and NorESM1-M includes not only well-mixed greenhouse gasses but also time-varying ozone changes in its GHG simulation [29]. iii) The method used by Gagne et al. [12], in contrast to Mueller et al.'s [29] method, is used in this study to directly estimate the aerosol effect on Arctic sea ice using AER simulations, in which HIST simulation signals are subtracted from GHG and NAT simulation signals to estimate the aerosol effect indirectly. iv) The amount of ocean ice changes in AER, GHG, NAT, and OZONE is not guaranteed to be equivalent to the ocean ice change in HIST because of other potential elements and/or the nonlinearity of reactions to single forcings.

RESULTS

The Role of External Forcing in Annual Mean Arctic Sea Ice Changes

We look at annual mean Arctic sea ice extents from both observations and CMIP5/6 historical simulations. According to the HadISST and Walsh and Chapman data, Arctic sea ice expanded between 1953 and 1970 (Figure 1), with a linear trend of 0.10 x 10^6 km^2/decade for the former and 0.19 x 10^6 km^2/decade for the latter (Figure 2). They also suggest an Arctic sea ice decline during 1971–2005, with linear trends of -0.41×10^6 km^2/decade and -0.40×10^6 km^2/decade, respectively. The CMIP5/6 models (Figure 1 and Figure 2a,f) have generally done a good job of simulating these observed increases and decreases in sea ice extent. The multi-model means of CMIP5 and CMIP6 historical simulations show Arctic sea ice increases in the trends of 0.17×10^6 km^2/decade and 0.18×10^6 km^2/decade over 1953–1970 but Arctic sea ice decreases in the trends of -0.19×10^6 km^2/decade and -0.31×10^6 km^2/decade over 1971–2005. It is also important to note that climate models have a lot of inter-model uncertainty when attempting to simulate the change in Arctic sea ice over time, especially CMIP5 models in the earlier periods. For a particular CMIP5 model, the linear trend of Arctic sea ice extent may fall to a negative value between 1953 and 1970 (Figure 3).

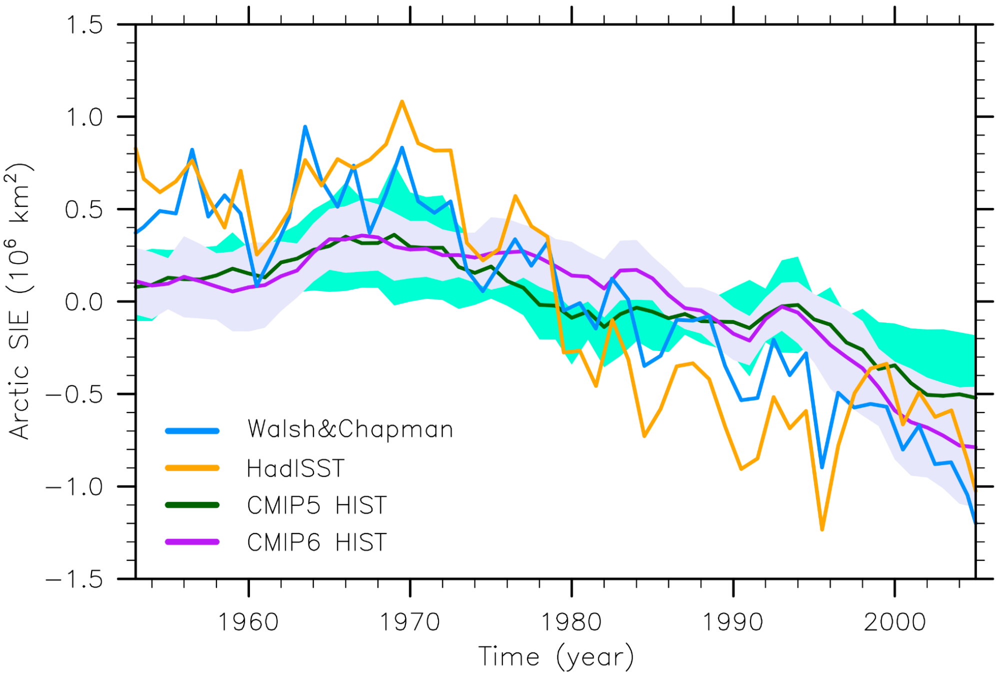


Figure 1. Annual mean Arctic sea ice extents (relative to the 1953–2005 average) from Walsh and Chapman (blue) and HadISST (orange) data and CMIP5 (MMM, green; inter-model spread, light green) and CMIP6 (MMM, purple; inter-model spread, light purple) historical simulations during 1953–2005. Sea ice extent is calculated as the integral sum of the areas of all grid cells with a sea ice concentration of at least 15%. The inter-model spread is calculated as one standard deviation among the ensemble means of individual models. The data is normalized relative to the entire period's mean.

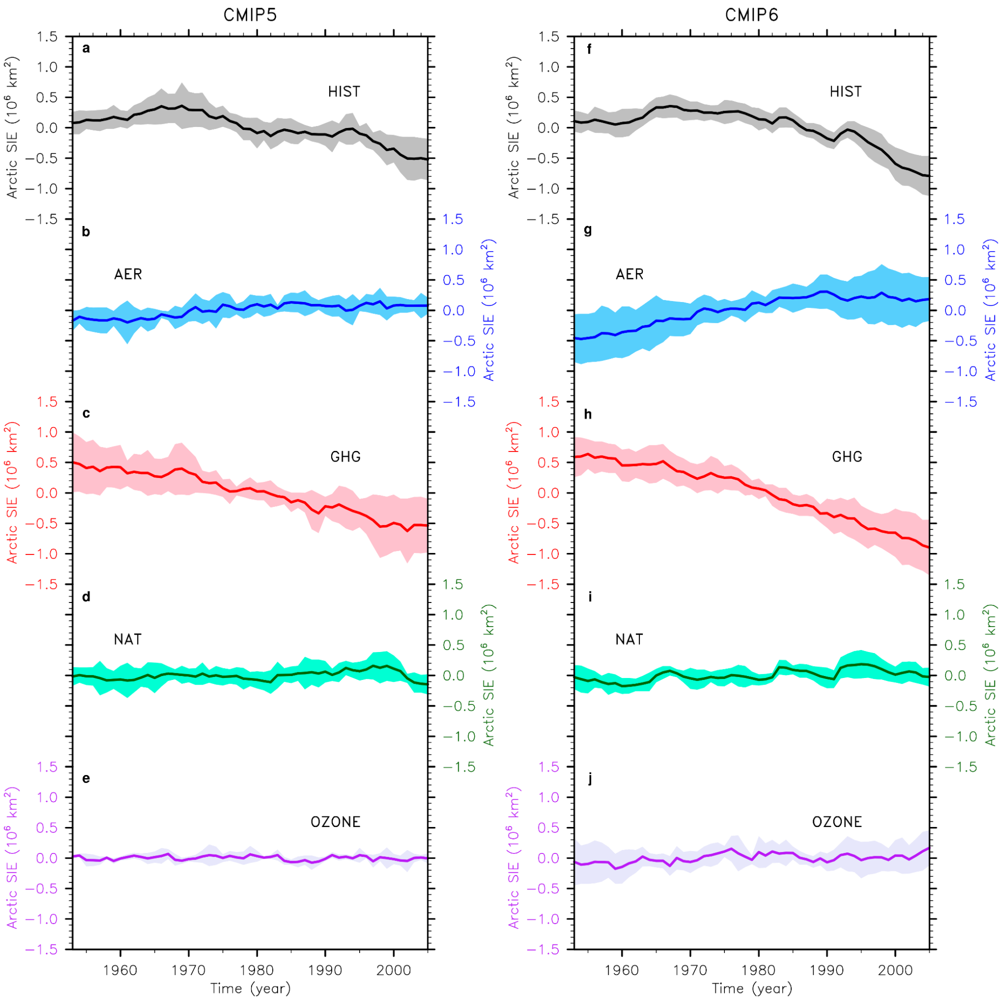


Figure 2. (**a**–**e**) Annual mean Arctic sea ice extents (relative to the 1953–2005 average) from CMIP5 historical (MMM, black; inter-model spread, gray), AER (MMM, blue; inter-model spread, light blue), GHG (MMM, red; inter-model spread, pink), NAT (MMM, green; inter-model spread, light green) and OZONE (MMM, purple; inter-model spread, light purple) simulations over 1953–2005. (**f**–**j**) Same as (**a**–**e**) but for CMIP6 simulations. Sea ice extent is calculated as the integral sum of the areas of all grid cells with a sea ice concentration of at least 15%. The inter-model spread is calculated as one standard deviation among the ensemble means of individual models.

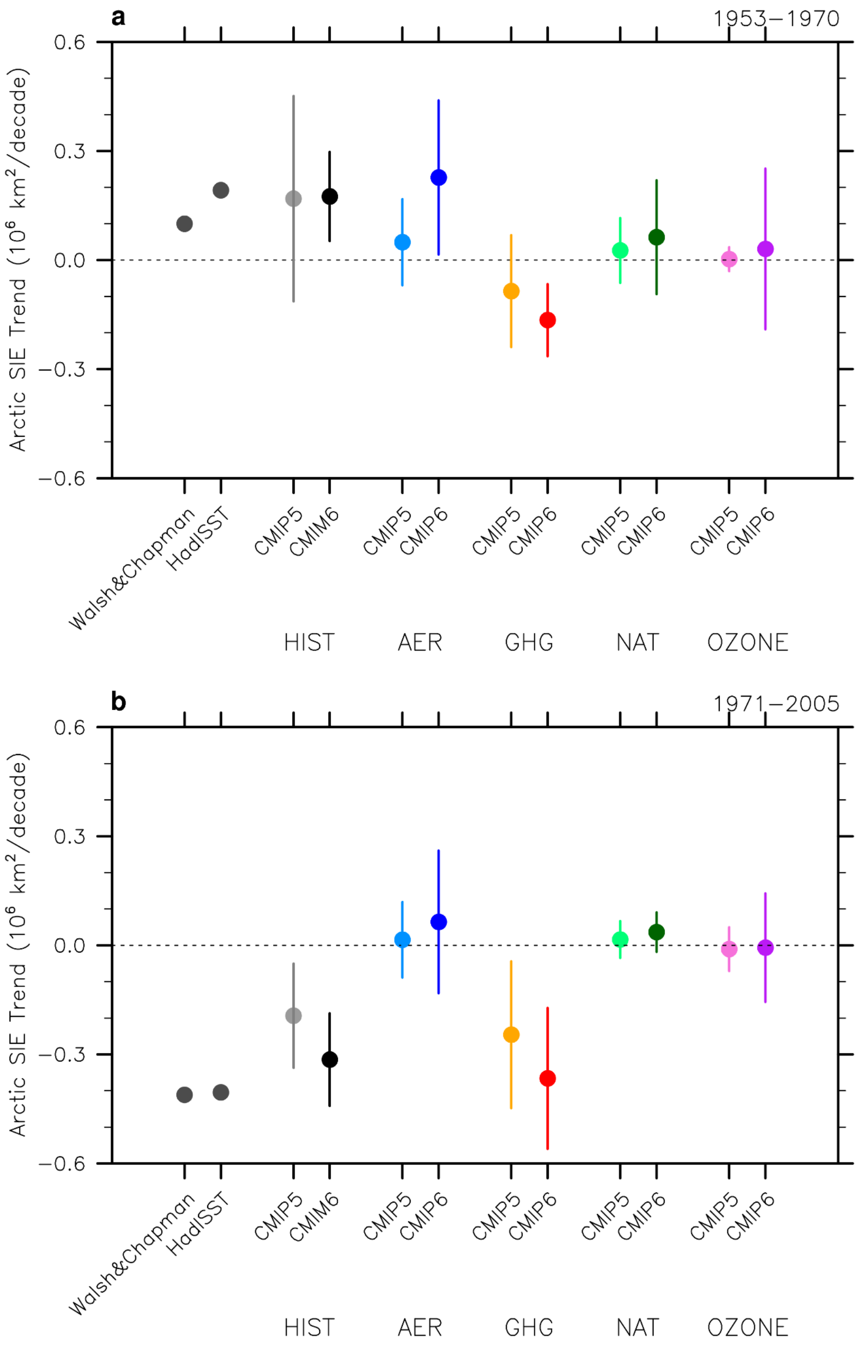


Figure 3. (**a**) Linear trends of annual mean Arctic sea ice extents from Walsh and Chapman and HadISST data (gray dots) and CMIP5 and CMIP6 historical (light gray and black), AER (light blue and blue), GHG (orange and red), NAT (light green and green) and OZONE (light purple and purple) simulations over 1953–1970. For the CMIP5/6 model's results, dots indicate MMMs, and bars indicate inter-model spreads. (**b**) Same as (**a**) but for trends over 1971–2005.

CMIP5/6 models successfully capture the observed Arctic sea ice extent increase over 1953–1970. However, their patterns of sea ice concentration change are different from those of observations (Figure 4a–d). In particular, the historical CMIP5/6 simulations demonstrate a general increase in sea ice in the seas surrounding the Arctic Ocean. Sea ice increases are especially strong in the Atlantic sector and in the Greenland and Barents Seas (Figure 4c,d). On the other hand, both observation datasets exhibit a strong sea ice increase in the Baffin Bay, the Greenland, Barents and Kara Seas but a strong sea ice decrease in the Chukchi and Bering Seas, and the Sea of Oshkosh (Figure 4a,b). These distinct regional sea ice changes are consistent with the previous results reported by Ployakov et al. [33] and Mahoney et al. [24].

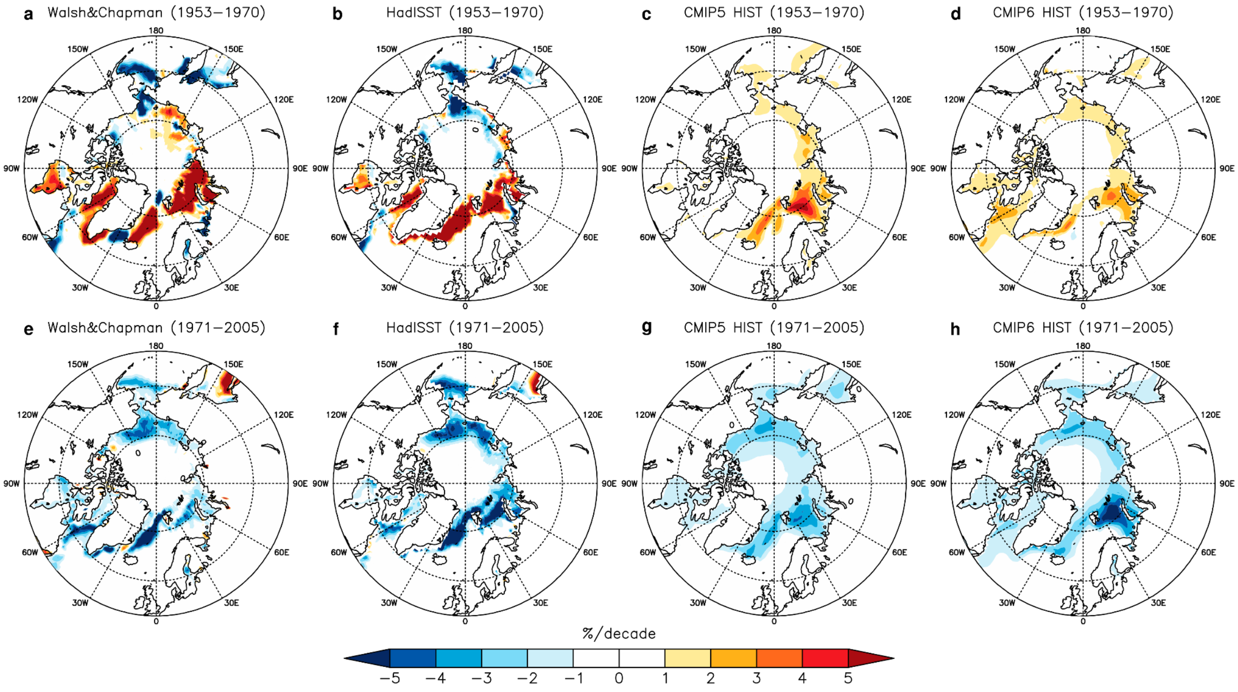


Figure 4. (**a**–**d**) Linear trends of annual mean sea ice concentrations (shading in percent/decade) from (**a**) Walsh and Chapman and (**b**) HadISST data and the MMMs of (**c**) CMIP5 and (**d**) CMIP6 historical simulations during 1953–1970. (**e**–**h**) Same as (**a**–**d**) but for the period of 1971–2005.

The observed pattern of sea ice concentration reduction from 1971 to 2005 is generally well simulated by the CMIP5/6 models (Figures 1 and Figure 4). Both observations and CMIP5/6 historical simulations suggest a broad sea ice decrease in most seas in and around the Arctic Ocean (Figure 4e–h). The only exception occurs in the Sea of Oshkosh where CMIP5/6 models simulate a sea ice decrease while observations indicate a sea ice increase.

We further look into the role of external forcings in driving annual mean sea ice change during different time periods. Anthropogenic aerosols help enlarge Arctic sea ice extent (Figure 2b,g), with linear trends of 0.05×10^6 km^2/decade and 0.23×10^6 km^2/decade for the multi-model means of CMIP5 and CMIP6 models (Figure 3a) from 1953 to 1970. Sea ice increases over most of the sea in the Arctic but is especially strong in the Barents Sea in CMIP6 models (Figure 5f). In CMIP5 models, sea ice increases mainly occur in the Chukchi, Beaufort and Bering Seas. Nature forcings and ozone changes cause sea ice to increase but are very weak (Figure 2, Figure 3, Figure 5) compared to anthropogenic aerosols. However, all of these increases in sea ice are heavily offset by greenhouse gasses (Figure 2). The declines of greenhouse-gas-induced Arctic sea ice extent are at a rate of -0.09×10^6 km^2/decade and 0.16×10^6 km^2/decade for the multi-model means of CMIP5 and CMIP6 models, respectively (Figure 3b). On average, the sea ice response to the aerosols forcing is stronger in CMIP6 models compared to CMIP 5 models. This could possibly be due to stronger aerosol cooling [7] and higher climate sensitivity [26,43] in CMIP6 models compared to CMIP5 models (Figure 3a). Another possibility is that the aerosols forcing causes a sea ice decrease in the Greenland Sea in CMIP5 models (Figure 5a), which partially offsets the sea ice increases in other regions and slows down the overall expansion of the Arctic sea ice cover.

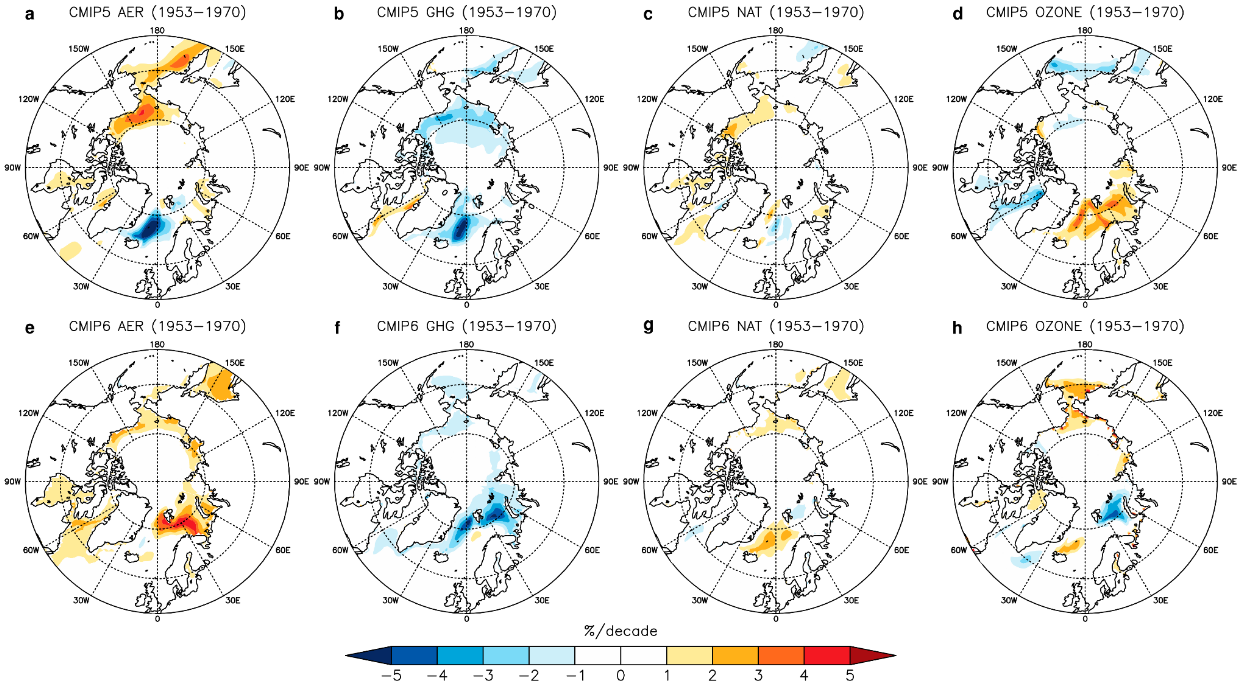

a CMIP5 AER (1953–1970)
b CMIP5 GHG (1953–1970)
c CMIP5 NAT (1953–1970)
d CMIP5 OZONE (1953–1970)
e CMIP6 AER (1953–1970)
f CMIP6 GHG (1953–1970)
g CMIP6 NAT (1953–1970)
h CMIP6 OZONE (1953–1970)

Figure 5. (**a**–**d**) Linear trends of annual mean sea ice concentrations (shading in percent/decade) for the MMMs of CMIP5 (**a**) AER, (**b**) GHG, (**c**) NAT, and (**d**) OZONE simulations during 1953–1970. (**e**–**h**) Same as (**a**–**d**) but for CMIP6 simulations.

The effect of greenhouse gasses strengthens from 1971 to 2005. This leads to declining Arctic sea ice extents at rates of -0.25×10^6 km^2/decade and 0.37×10^6 km^2/decade for the multi-model means of CMIP5 and CMIP6 models, respectively (Figure 3b). Anthropogenic aerosols and natural forcings work to increase sea ice extent (Figure 2, Figure 6), but the effects of greenhouse gasses completely overpower their effects. The ozone effect on Arctic sea ice change is meanwhile neglectable. In summary, greenhouse gas warming completely dominates the Arctic sea ice decline during 1971–2005, and other external forcings are overwhelmed by greenhouse gasses.

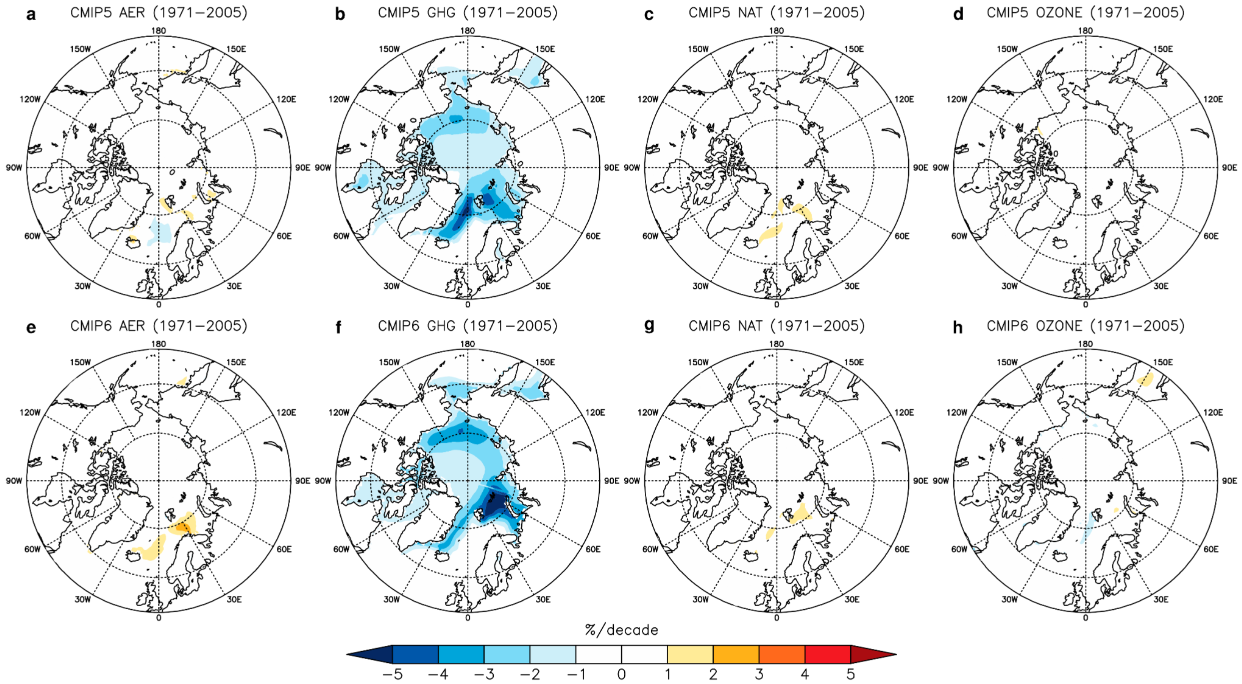


Figure 6. (**a**–**d**) Linear trends of annual mean sea ice concentrations (shading in percent/decade) for the MMMs of CMIP5 (**a**) AER, (**b**) GHG, (**c**) NAT, and (**d**) OZONE simulations during 1971–2005. (**e**–**h**) Same as (**a**–**d**) but for CMIP6 simulations.

The Role of External Forcing in Seasonal Arctic Sea Ice Variations

We compare the trends of monthly Arctic sea ice extent between observations and CMIP5/6 historical simulations over different time periods. Walsh and Chapman and HadISST observations display a downward trend of Arctic sea ice extent in the late spring from April to May and an upward trend of sea ice extent from July to December (Figure 7a,c) from 1953 to 1970. On the other hand, the multi-model means from CMIP5 and CMIP6 historical simulations show an upward trend throughout the season. In CMIP5 models, the peak of the trend occurs in August (Figure 7e) while the peak of CMIP6 models occurs in September (Figure 7g). HadISST, Walsh and Chapman data sets, CMIP5, and CMIP6 all show downward trends in the Arctic sea ice extent throughout the year from 1971 to 2005. It is also notable that the sea ice decline is extraordinarily strong during the late boreal summer (Figure 7b,d,f,h).

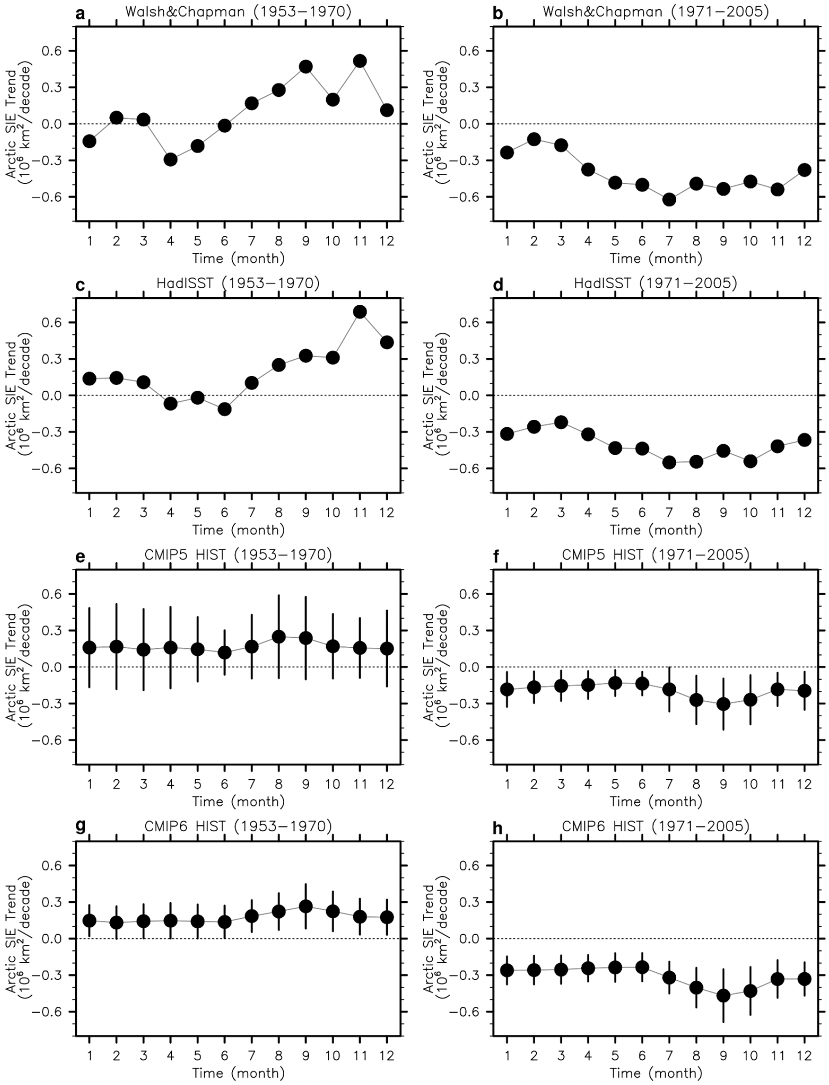


Figure 7. (**a**,**c**,**e**,**g**) Linear trends of monthly mean Arctic sea ice extents from (**a**) Walsh and Chapman and (**c**) HadISST data and (**e**) CMIP5 and (**g**) CMIP6 historical simulations over 1953–1970. For the CMIP5/6 model's results, dots indicate MMMs, and bars indicate inter-model spreads. (**b**,**d**,**f**,**h**) Same as (**a**,**c**,**e**,**g**) but for trends over 1971–2005.

We also look into how seasonal sea ice changes at different times and how they are influenced by external forcings. CMIP5 and CMIP6 models both consistently display an aerosol induced sea ice increase and greenhouse gas induced sea ice decrease through all seasons from 1953 to 1970. In September, we can see a small sea ice increase for aerosols, natural forcings, and ozones, and a decrease in sea ice for greenhouse gasses. CMIP5 and CMIP6 models also both consistently display a very strong greenhouse gas induced sea ice decrease through all seasons from 1971 to 2005, especially in September from 1971 to 2005. It is also notable that anthropogenic aerosols, natural forcings, and atmospheric ozone changes drive small upward trends of Arctic sea ice extent in the early boreal spring (Figure 9).

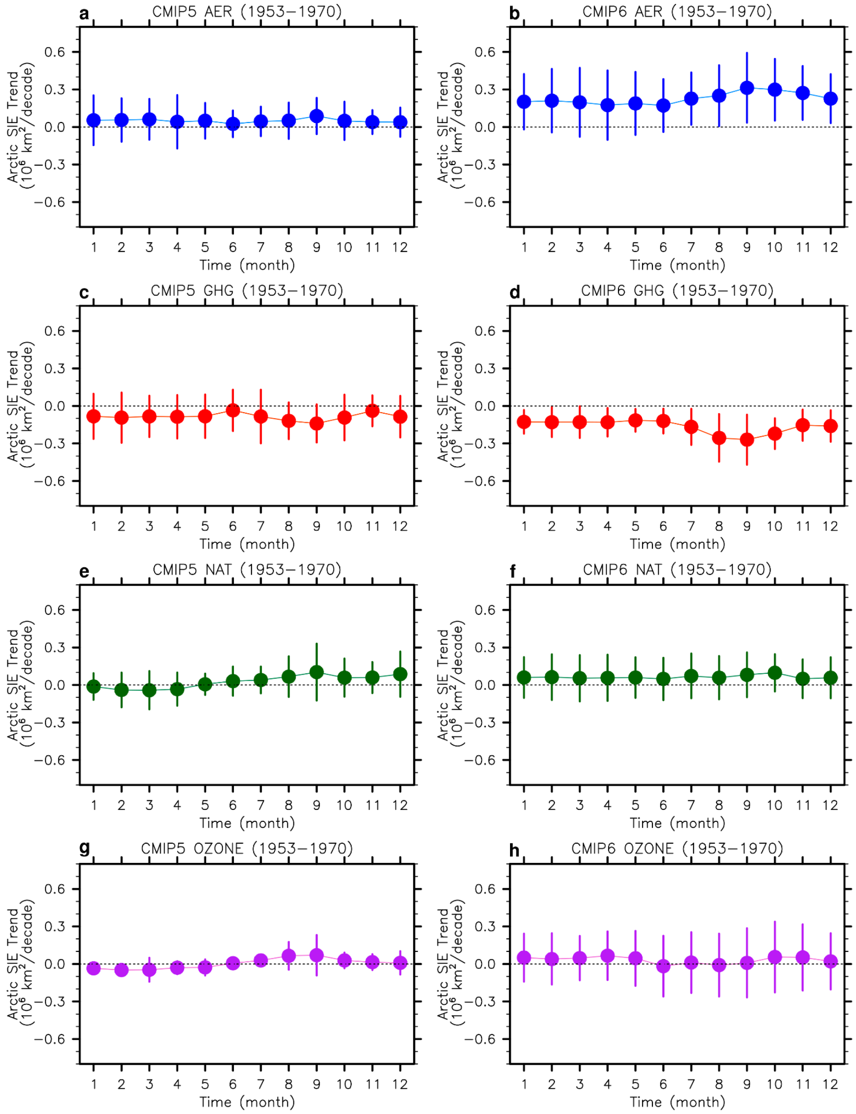


Figure 8. (**a**,**c**,**e**,**g**) Linear trends of monthly mean Arctic sea ice extents from CMIP5 (**a**) AER, (**c**) GHG, (**e**) NAT, and (**g**) OZONE simulations over 1953–1970. Dots indicate MMMs and bars indicate inter-model spreads. (**b**,**d**,**f**,**h**) Same as (**a**,**c**,**e**,**g**) but for CMIP6.

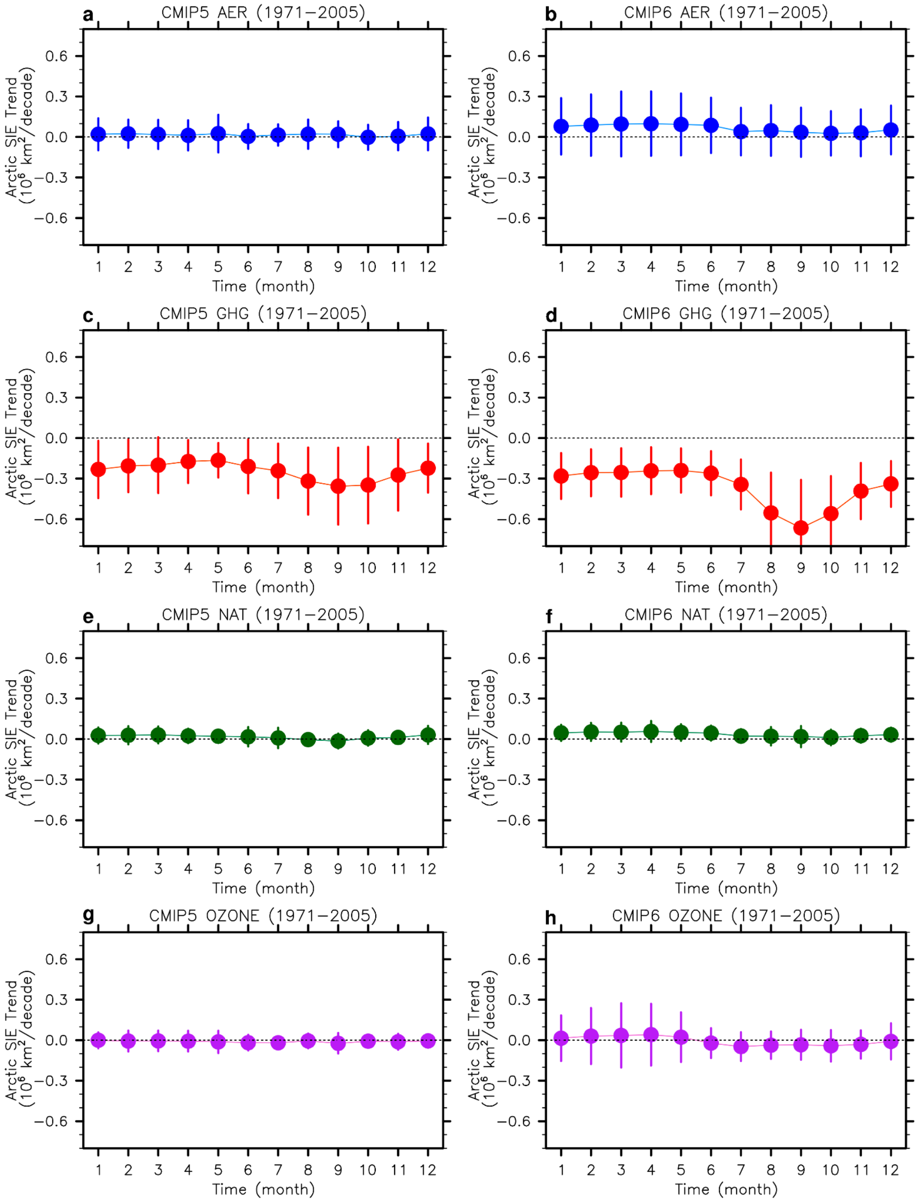


Figure 9. (**a**,**c**,**e**,**g**) Linear trends of monthly mean Arctic sea ice extents from CMIP5 (**a**) AER, (**c**) GHG, (**e**) NAT, and (**g**) OZONE simulations over 1971–2005. Dots indicate MMMs and bars indicate inter-model spreads. (**b**,**d**,**f**,**h**) Same as (**a**,**c**,**e**,**g**) but for CMIP6.

The Role of Internal Climate Variability in Historical Arctic Sea Ice Changes

We first removed the ensemble mean of the Arctic sea ice extent trend from the trends of individual ensemble members for ACCESS-ESM1.5, IPSL-CM6A-LR, and MIROC6, and compared these trends with those of Walsh and Chapman and HadISST observations for either period to illuminate the role of internal climate variability in the historical Arctic sea ice changes (Figure 10). We have chosen those three CMIP6 models due to their large individual ensemble members sizes, which is helpful when compared to the observations. The fact that the observed trend for the Arctic sea ice extent from 1953 to 1970 falls within the inter-member spread of the three models suggests that internal climate variability may have played a role in Arctic sea ice change during this time [15,24,33]. On the contrary, the observed trend of the Arctic sea ice extent from 1971 to 2005 is outside the inter-member spread of the three models. This suggests that the decline in the Arctic sea ice extent during this period cannot be solely explained by internal climate variability. Suggesting another factor is causing the sea ice decline. This result is consistent with previous studies [12,14,28,29,30] and highlights the importance of external forcings to the recent Arctic sea ice decline.

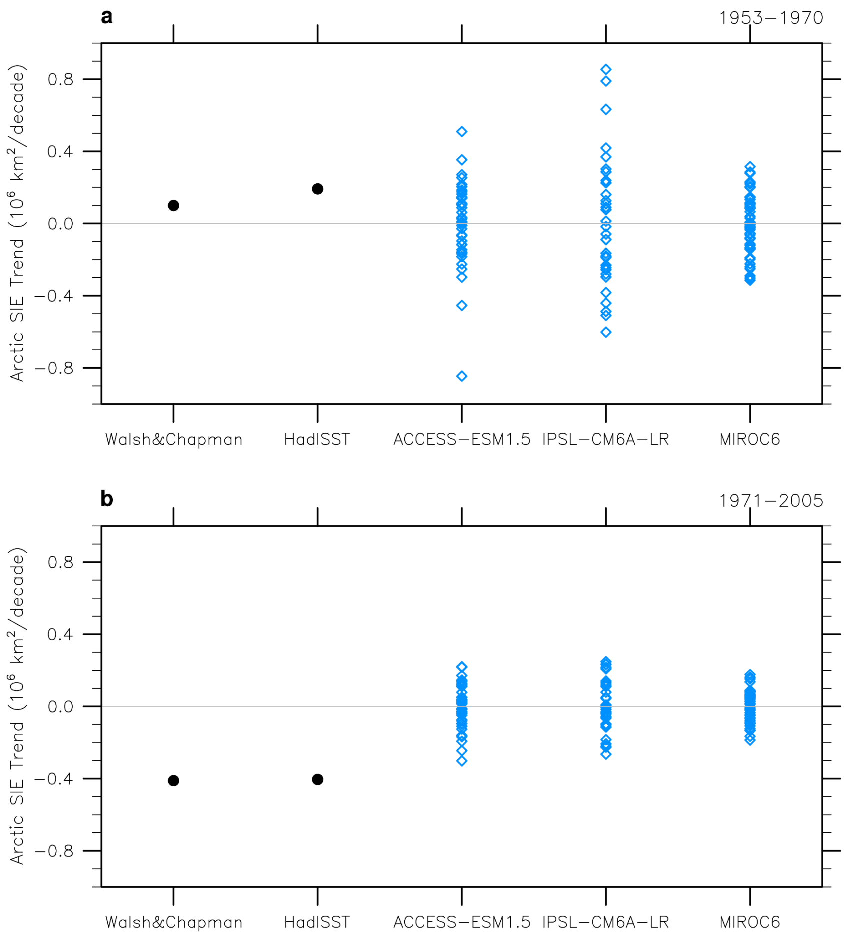


Figure 10. (**a**) Linear trends of annual mean Arctic sea ice extents from Walsh and Chapman and HadISST data (black) and ensemble members of ACCESS1-ESM1.5, IPSL-CM6A-LR, and MIROC6 (blue) over 1953–1970. For each model, the ensemble mean of the trend is removed. (**b**) Same as (**a**) but for trends over 1971–2005.

Correlations between Surface Air Temperature and Sea Ice Area

We have also taken a look at the relationship between surface air temperature and sea ice area on both poles (Figure 10). Surface air temperature looks near the surface, usually at two meters air temperature. We have utilized the preindustrial control simulation with over 40 CMIP6 models in calculating correlation points. Correlation looks at the two poles and compares them. A positive correlation indicates both poles were changing at the same pace, that is, both poles losing or gaining ice at the same rate, along with surface cooling or heating at the same rate. The underlying physics is that a negative correlation indicates one pole receiving or losing ice more than the other, and accordingly, having cooler or warmer surface temperatures. Above changes in surface air temperature and sea ice are inherently related due to the ice-albedo feedback. This feedback loop is a process where the change in the sea ice amount affects the surface temperature and albedo of the planet. Ice is reflective in nature so the loss of sea ice results in increases in temperature and vice versa. Overall, we can see most models exhibiting a positive correlation (Figure 10).

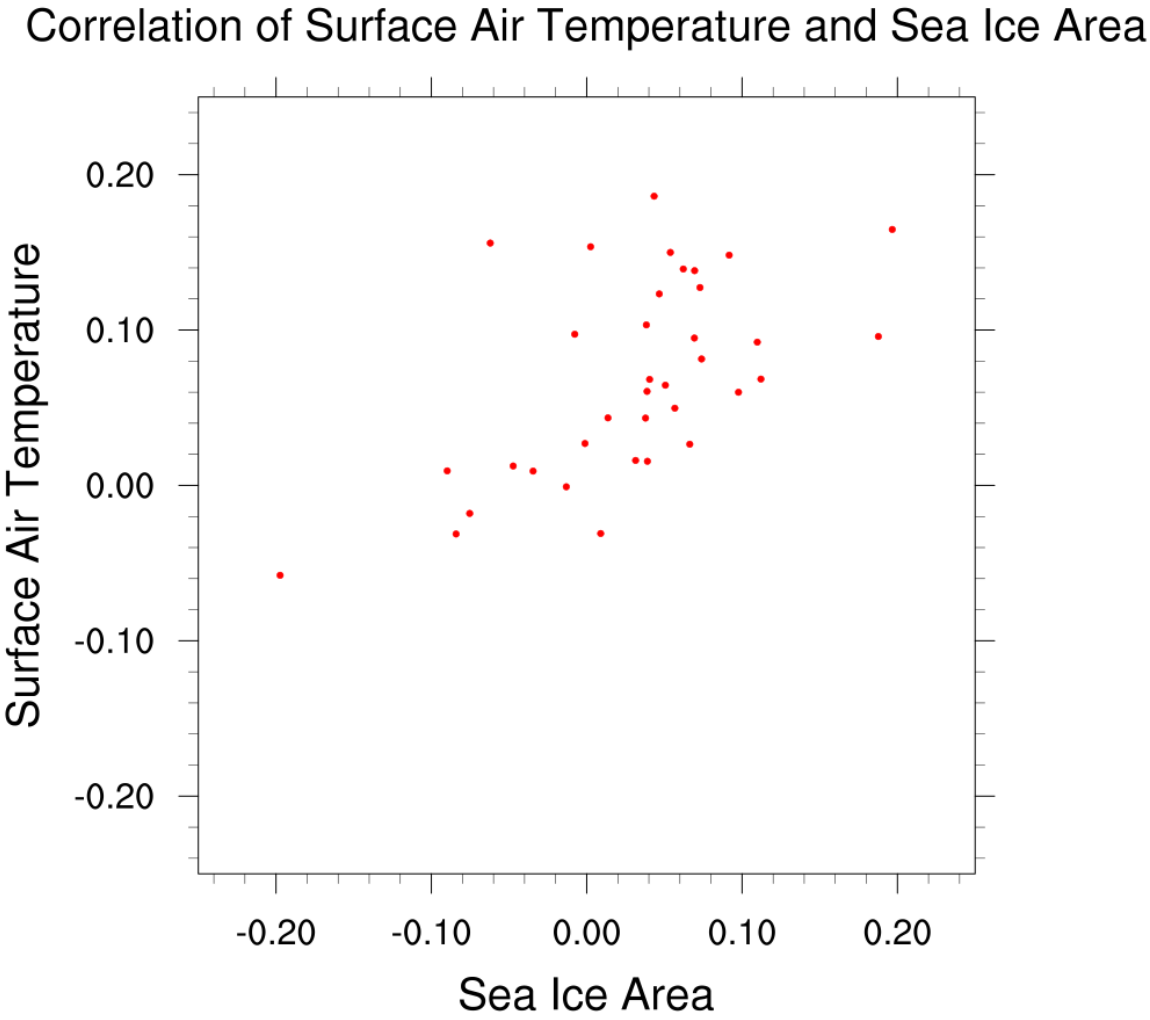


Figure 10. Correlation between surface air temperature (poleward than 60^o) and sea ice area between both poles the preindustrial control simulation with over 40 CMIP6 models. A 9-year running mean is applied to the surface air temperature and sea ice data to eliminate the ENSO influence before the calculation of correlation. Each dot represents a model.

CONCLUSIONS AND DISCUSSIONS

Using the Walsh and Chapman observations, HadISST observations, and CMIP5 and CMIP6 climate models, we have investigated the physical mechanisms underlying the shifts in Arctic sea ice that have occurred since the middle of the last century in this study. Both observations and model simulations show consistent changes in sea ice extent, which are an increase over 1953–1970 and a decrease over 1971–2005, but distinct patterns of the change in sea ice concentration within the early period. Specifically, CMIP5/6 models simulate a general increase in sea ice in the seas in and surrounding the Arctic Ocean, while observations indicate a significant increase in sea ice in the Baffin Bay, Greenland, Barents, and Kara Seas. Additionally, observations indicate a significant decrease in sea ice in the Chukchi and Bering Seas, as well as the Sea of Oshkosh. Based on CMIP5/6 single forcing experiments, we further find that anthropogenic aerosols, nature forcing and ozone changes contribute to the sea ice expansion over 1953–1970, with marked effects generally during late boreal summer. From 1971 to 2005, the effect of greenhouse gas warming becomes dominant, which leads to a pronounced decline in Arctic sea ice from 1971–2005, especially in September. Using large ensemble simulations of three CMIP6 models, we also find that although internal climate variability may have played a role in the expansion of Arctic sea ice from 1953 to 1970, it cannot fully explain the decline of Arctic sea ice from 1971 to 2005. In more recent times, we have seen that the role of external forcings has greatly outweighed the role of internal climate variability. We believe that if things do not change and continue on their current trajectory in regard to external forcings, the role of climate internal variability will remain small and will be unlikely to regain its previous more prevalent role. In addition, we find a tight relationship between surface air temperature and sea ice area on both poles, which is primarily due to the ice-albedo feedback.

Changes in ocean circulation, such as those in the Atlantic Meridional Overturning Circulation (AMOC), which is a system of circulations in the Atlantic Ocean that carry cold water southwards and warm water northwards, have been found to have a significant impact on the Arctic sea ice under either climate change [20] or variability [4,8,11,33]. The strength of the Atlantic Meridional Overturning Circulation and its induced poleward heat transport significantly anti-correlates with Arctic sea ice extent [3,23,44]. Relatedly, Liu and Fedorov [19] recently reported a two-way interaction between the changes in Arctic sea ice and the Atlantic Meridional Overturning Circulation. Particularly, an Arctic sea ice decline can lead to a weakened Atlantic Meridional Overturning Circulation with a multi-decadal delay through a downstream propagation of positive, sea-ice-induced buoyancy anomalies to the subpolar North Atlantic suppressing deep convection and deep-water formation there [18]. On the other hand, the weakened Atlantic Meridional Overturning Circulation could possibly diminish oceanic northward heat transport [42], therefore promoting an Arctic sea ice expansion within a few years. As a result, further research on the physical processes by which the atmospheres and the ocean's individual external forcings and internal climate variability influence historical Arctic sea ice changes is expected in future studies.

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