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Key Points:
• Climate model MRI-ESM2.0 reproduces the Arctic surface air temperature rising and associated sea ice loss observed in the early 20th century
• MRI-ESM2.0 results indicate that the natural forcings and the internal variability are main contributors to Arctic warming during 1920–1940
• Multimodel analyses suggest the Arctic warming response to natural forcings in 1911–1940 is comparable to the unforced internal variability

Correspondence to:
T. Aizawa,
s1230210@gmail.com

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Abstract During the early 20th century, the Arctic experienced a period of remarkable warming, often called the early 20th century warming (ETCW). However, the degree of the response to external climate forcing on the Arctic surface air temperature is not well understood. Climate simulations using a state-of-the-art climate model of Meteorological Research Institute (MRI-ESM2.0) and multimodel analyses were conducted to better understand ETCW. The MRI-ESM2.0 historical simulations successfully reproduced the observed ETCW and the corresponding decreases in sea ice extent. Detection and attribution experiments using MRI-ESM2.0 suggest that internal climate variability and natural forcings to ETCW. Multimodel analyses indicate that the Arctic warming trend during 1911–1940 induced by natural forcings is comparable to the unforced multidecadal internal variability, suggesting major contributions of the internal dynamics and natural forcings to ETCW.

Plain Language Summary Instrumental records show that there was significant warming in the Arctic during the first half of the 20th century, known as the early 20th century warming (ETCW). Climate simulations using a state-of-the-art climate model of Meteorological Research Institute (MRI-ESM2.0) suggest that external natural forcings, i.e., long-lasting quiet volcanic activity and increased solar activity, influenced the model-simulated ETCW and associated sea ice decrease. Multimodel analyses indicate the robustness of the MRI-ESM2.0 results and suggest that the climatic response of Arctic surface air temperature to external natural forcings in the ETCW period is comparable to the unforced multidecadal internal variability of the models, suggesting a major contribution of unforced multidecadal internal variability and natural forcings to ETCW.

1. Introduction

Instrumental records show that, except for a hiatus in the 1960s, the globally averaged surface air temperature (SAT) has risen rapidly in the latter half of the 20th century (IPCC, 2007, 2013). According to Bindoff et al. (2013), more than half of the global warming during this period can be explained by anthropogenic forcings. This warming is even more remarkable in the Arctic; Arctic SATs have risen more than twice as fast as the global average in recent decades. Satellite observations reveal that Arctic sea ice has rapidly decreased in all seasons accompanying a rapid Arctic temperature amplification in recent decades (e.g., Johannessen et al., 2004). The rapid warming and associated sea ice reduction are primarily due to enhanced anthropogenic effects (Gillett et al., 2008).

Furthermore, specifically in the first half of the 20th century, instrumental records show that there was a significant warming period, called the early 20th century warming (ETCW), which was comparable to the present-day warming (Bengtsson et al., 2004; Hegel et al., 2018; Johannessen et al., 2004; Yamanouchi, 2011). This warming was observed only in the Pan-Arctic regions (Serreze & Francis, 2006; Shindell & Faluvegi, 2009). Observational historical sea ice data indicate a downward trend in summer sea ice extents during 1920–1940 synchronous with the Arctic SAT increase (Walsh et al., 2017). External anthropogenic forcings (i.e., greenhouse gases and aerosols), external natural forcings (i.e., solar irradiation and volcanic activity), and internal climate variabilities, or a combination of some of these, could all have contributed to ETCW.
Previous studies suggested that the ETCW could have had an intrinsic origin within the climate system. Particularly, Beitsch et al. (2014) showed that internal climate variability occurring in the Northern Hemisphere is sufficient to reproduce warm events matching the observed ETCW in a 3000-year unperturbed climate simulation using a coupled ocean-atmosphere climate model. In another study using a coupled ocean-atmosphere climate model, ETCW appeared in one member out of five ensemble simulations (Delworth & Knutson, 2000) suggesting that ETCW was controlled by low-frequency internal climate variability (Polyakov & Johnson, 2000; Polyakov et al., 2003) or decadal-to-multidecadal variabilities of the Atlantic and the Pacific Oceans (Bengtsson et al., 2004; Chylek et al., 2009; Svendsen et al., 2018; Tokinaga et al., 2017).

However, it remains unclear how much internal climate variability contributed to the observed ETCW because of the difficulties in extracting internal climate variability alone from the observed climate changes. Detection and attribution studies using climate models have been conducted to understand external factors for the climate changes observed in the 20th century (e.g., Meehl et al., 2003; Nozawa et al., 2005; Shiogama et al., 2006; Stott et al., 2000). Because the influence of greenhouse gasses on SATs in the first half of the 20th century was smaller than at present, greenhouse gasses alone cannot fully account for ETCW (Bindoff et al., 2013). Gradual increases in emissions of anthropogenic aerosols and their precursors, which generally cause negative radiative forcing owing to the scattering of solar radiation, during that period cannot explain ETCW. In the period between the 1912 Novarupta eruption and the 1963 Agung eruption, there were no explosive volcanic eruptions (Robock, 2000). Generally, such long-term quiet volcanic activity periods are expected to impact both global and Arctic warming positively owing to decreases in negative radiative effects of volcanic stratospheric aerosols, compared to high-volcanic activity periods. The total solar irradiance was generally increasing in the first half of the 20th century (Lean et al., 1995). A portion of ETCW may be explained by the superposition of an increase in solar activity and a decrease in volcanic activity, in addition to gradual increases in the greenhouse gases concentrations and other anthropogenic forcings (Nozawa et al., 2005; Shiogama et al., 2006; Tett et al., 2002). Note that external natural forcings, such as large volcanic eruptions and solar activity, likely modulate the internal climate variabilities (e.g., Otterå et al., 2010; Pausata et al., 2015; Sławinska & Robock, 2018; Zanchettin et al., 2013). Quantifications of the internal climate variability and responses to external natural and anthropogenic climate forcings on ETCW and associated sea ice reduction are not sufficient because of the uncertainties in the forcings and the responses to the forcings in the models, as well as inadequate observational coverage.

We developed the state-of-the-art climate model of Meteorological Research Institute Earth System Model version 2.0 (MRI-ESM2.0; Yukimoto et al., 2019) and participated in the Detection and Attribution Model Intercomparison Project (DAMIP; Gillett et al., 2016), which is conducted as part of the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016). DAMIP was proposed to understand how external climate forcings can explain historical climate changes that have occurred since the Industrial Revolution; therefore, it is suitable for evaluating the contributions of external climate factors to ETCW. This study examines the factors controlling the Arctic SAT changes during ETCW period using DAMIP outputs generated by MRI-ESM2.0 and 11 other CMIP6 models. We quantitatively estimate the signal of the model response to the external climate forcings on the simulated ETCW and the associated sea ice reduction compared to the magnitude of the unforced multidecadal internal climate variability using MRI-ESM2.0. In addition, we conduct the multimodel analyses to verify the validity of the MRI-ESM2.0 results.

2. Model Experiments and Analysis Method

MRI-ESM2.0 consists of the following component models. The atmospheric component is MRI-AGCM3.5, whose spatial resolution and model top are T159L80 (1.125° in longitude and in latitude, and 80 vertical levels) and 0.01 hPa, respectively. The oceanic component is the MRI Community Ocean Model version 4 (MRI.COMv4; Tsujino et al., 2017), which has a tripolar grid with a nominal horizontal resolution of 1° in longitude and 0.5° in latitude (0.3° between 10°S and 10°N) and 61 vertical levels. An aerosol chemical transport model and an atmospheric chemistry model are included in MRI-ESM2.0, which enables the estimation of forcing effects from gasses and aerosols on the climate (Oshima et al., 2020).

We conducted a preindustrial control experiment (hereafter, CNTL) and historical experiments (HIST) using MRI-ESM2.0. HIST consists of five ensemble members with different initial conditions taken from the
600-year CNTL at 50-year intervals from the first year. The integration period of HIST is from 1850 to 2014, and the official CMIP6 forcing data set version 6.2.1 was used in the experiments. A detailed description of CNTL and HIST is given in Yukimoto et al. (2019). To confirm the reproducibility of the SATs and September sea ice extents in HIST, we used CRUTEM4 (Jones et al., 2012), HadCRUT4 (Morice et al., 2012) for SAT observation, and Walsh et al. (2017) for sea ice observation. Walsh et al. (2017) is a historical observational data set of gridded sea ice concentrations extending back to 1850 released by the National Snow and Ice Data Center.

We conducted the following DAMIP experiments for the period of 1850–2020 using MRI-ESM2.0; well-mixed greenhouse-gas-only historical simulations (GHG); anthropogenic-aerosol-only historical simulations (AER); natural solar irradiance forcing and volcanic forcing-only historical simulations (NAT); natural solar irradiance forcing-only historical simulations (SOL); and natural volcanic forcing-only historical simulations (VOLC) (Gillett et al., 2016). These simulations were driven by changes only in the forcing of interest, while all other forcings were held at preindustrial values. Each experiment consisted of five ensemble members starting with the same initial conditions as those of HIST.

Taking ensemble averages can substantially reduce the internal climate variations, even though portions of the internal climate variability remain even after ensemble averaging owing to the small number of ensemble members. To show the significant 10-year SAT anomalies resulting from each forcing, we calculated the estimation errors due to the decadal internal variability of the model-simulated SAT, which were estimated as twice the standard deviation of the zonally averaged 10-year running mean values for ensemble mean SATs randomly sampled five 165-year-long series taken from the 600-year CNTL using a bootstrap method. We used these errors to detect externally forced signals in 10-year SAT anomalies that were greater than the estimation errors for HIST, GHG + AER, NAT, SOL, and VOLC.

We evaluated the 30-year linear trends in the ensemble mean SATs and the sea ice extents for the period from 1911 to 1940 for HIST, GHG, AER, and NAT. To compare these signals with the unforced multidecadal internal variability in the simulations, we calculated the standard deviations of the 30-year linear trends for the spatially averaged SAT and sea ice extent for all 30-year-long samples taken from the 600-year CNTL. The 5-year moving average was applied to both the SATs and the sea ice extents to remove the interannual variabilities, prior to the trend calculations. In addition, SATs were spatially averaged over latitudes from 70°N to 90°N. This approach enabled quantitative evaluations of the magnitude of the responses to external forcings in the ETCW period in comparison to the magnitude of the unforced multidecadal internal variability in the MRI-ESM2.0 simulations.

We conducted multimodel analyses using a set of DAMIP experiments performed by CMIP6 models. We chose 12 available models for CNTL, HIST, GHG, and NAT, and 11 models for AER. MRI-ESM2.0 is included as one of ensemble members. To enable quantitative comparisons of the Arctic SATs simulated by the DAMIP models with the observations, the simulated SATs were interpolated to the same grid as that of CRUTEM4 and were masked at the grid points missing observations. We calculated the 30-year linear trends and the intermodel spreads for SATs during 1911–1940 for HIST, GHG, AER, and NAT to detect the responses to each type of climate forcings. To evaluate the unforced multidecadal internal variability in the multimodel analyses, we calculated the individual model standard deviations of the 30-year linear trend for the spatially averaged SAT taken from each 500-year CNTL. Then, we calculated the ensemble mean of the 12-model standard deviations, which is regarded as the unforced multidecadal internal variability in the multimodel analyses. The simulated SATs for CNTL, HIST, GHG, AER, and NAT were averaged temporally by 10-year running mean and spatially over latitudes from 60°N to 90°N, prior to the trend calculations. Note that we expanded the region to lower latitudes in the multimodel analyses because of the low number of gridded data points in the sea ice region at 70°N–90°N in CRUTEM4.

3. External Factors Affecting ETCW and Associated Sea Ice Reduction According to MRI-ESM2.0

HIST, as simulated by MRI-ESM2.0, shows a peak in the zonal mean SAT warming around 1940 and a subsequent cooling from the 1940s to the 1970s, which corresponds well to the observations (Figure 1a and 1b). We also compared the sea ice extent in HIST to the historical sea ice observations compiled by...
Walsh et al. (2017). The SAT warming around 1940 and the subsequent cooling during 1940–1970 caused decreases and increases in the sea ice extent, respectively, in HIST, even though the magnitudes in the model are smaller than the observation (Figure 1c). Even though MRI-ESM2.0 reproduced smaller September sea ice extents than the observation throughout the entire period, the decadal-to-multidecadal variations qualitatively agreed well between the model simulation and the observation (Figure 1c).

We compared the spatial distributions of July-August-September (JAS) SAT anomalies during 1935–1945 in HIST with observational data HadCRUT4. Anomalies are defined as deviations from the climatology, which was defined according to the mean values from 1941 to 1970. The observation data show the warm anomalies over northern Europe, the Barents-Kara Seas and the coastal regions of the Eurasian continent (Figure 2a). Good agreement with the observations is confirmed in the simulated summer Arctic SATs with high statistical significance in northern Europe, the Barents-Kara Seas and the coastal regions of the

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**Figure 1.** Latitude-time cross sections of zonal mean SAT anomalies (°C) in (a) HIST, as simulated by MRI-ESM2.0 (ensemble member: 5), and (b) CRUTEM4. The values are temporally averaged using the 10-year moving average. The climatology in (a and b) was calculated as an average for the period from 1941 to 1970. (c) Time series of the 5-year running mean September sea ice extent in HIST using MRI-ESM2.0 (black) and the observations (red). The shading in panel (c) indicates the ranges of one standard deviations of the five-member ensemble. Note that the averaged SATs in (a) are not masked by the missing grid point in CRUTEM4. SAT, surface air temperature; HIST, historical experiments.
Eurasian continent (Figure 2b), except some mismatches over the central Siberian and the Canadian archipelago (Figure 2a and 2b). The simulated summer sea surface temperatures are significantly high in the coastal region in association with the high SATs (Figure 2b and 2c). The simulated September sea ice concentration is significantly small on along the continental coasts consistent with the high temperatures (Figures 2a–2d). Those high SATs and ocean temperatures appear to provide favorable conditions for sea ice melting. Because these simulated ETCW patterns include some internal climate variabilities and the response to all external climate forcings, we quantitatively estimate the responses of the simulated ETCW to each external climate forcing separately.

Figures 3a–3e show the latitude-time cross sections of the 10-year running and zonal mean SAT anomalies for each DAMIP experiment simulated by MRI-ESM2.0 relative to the climatology. The climatology for each experiment is the same as that defined above (i.e., the 1941–1970 mean). Figures 3f–3g show time series of the carbon dioxide (CO2) concentrations and total solar irradiances. Figure 3h shows time series of the simulated optical depths of the volcanic sulfate aerosols and the total aerosols (except the volcanic aerosols) averaged over latitudes from 60°N to 90°N. GHG, as simulated by MRI-ESM2.0, exhibits a consistent warming trend accompanying interdecadal variations on a 20-year time scale. The forcing of well-mixed greenhouse gases, such as CO2 (Figure 3f), contributed to the increase in the Arctic SAT throughout the entire 20th century. By contrast, AER yields a cooling trend in SAT for the same period. Therefore, the warming in GHG
Geophysical Research Letters

was largely offset by the cooling in AER (Figure 3b). The weak warming signal in GHG + AER indicates that the simulated ETCW in HIST cannot be fully accounted for by anthropogenic effects alone.

NAT exhibits a recognizable warm anomaly from 1920 to 1940 in the sea ice region north of 70°N. The response of Arctic SAT to natural forcings only (NAT) is smaller than that to all forcings (HIST). The strong SAT response in HIST is likely caused by interactions between the various forcings. Moreover, some disagreements in the SAT patterns between NAT and HIST may be owing to the difference in phase of the internal climate variations. We examined individual contributions from solar and volcanic forcings to the Arctic warm anomaly in the mid-20th century in HIST. Even though SOL shows a negative SAT anomaly around the 1920s, a positive Arctic SAT trend is evident during the entire first half of the 20th century in response to a consistent increase in the solar activity (Figure 3d and 3g). In SOL, there is a 0.10°C difference in the temporary averaged Arctic SATs between the relatively active 31 years of 1930–1960 and the less-active 31 years of 1883–1913. The Arctic SAT in VOLC appears to have a positive trend in the mid-20th century with quiet volcanic activity after the Novarupta eruption in 1912 as a reaction to the preceding high volcanic

Figure 3. Latitude-time cross sections of the five-member ensemble mean SAT anomalies (°C) in (a) HIST, (b) GHG + AER, (c) NAT, (d) SOL, and (e) VOLC calculated by MRI-ESM2.0. The climatology in (a–e) was calculated as an average for the period from 1941 to 1970. The values represent the 10-year running mean to remove interannual variability. The shadings in (a–e) show significant signals that are greater than the estimation errors that were obtained by MRI-ESM2.0 CNTL. Time series of (f) the CO₂ concentrations (ppmv), (g) the total solar irradiance (W/m²), and (h) the spatially averaged (60°N–90°N) simulated optical depths of the volcanic sulfate aerosols (red) and the total aerosols except the volcanic aerosols (black) at a wavelength of 550 nm. The red line in panel (g) indicates the 10-year running mean. Note that the averaged SATs in (a–e) are not masked by the grid points missing observations to look at high latitudes where are observation missing. SAT, surface air temperature; HIST, historical experiments.
activity (Figure 3e and 3h). In fact, the temporary averaged Arctic SATs in VOLC for the 31-year (1930–1960) low-volcanic activity period is 0.11°C greater than that for the 31-year (1883–1913) high volcanic activity period.

We quantitatively estimated the magnitudes of the model responses to external forcings during the ETCW period compared to the magnitude of the unforced multidecadal internal variability. Figure 4 shows the 30-year (1911–1940) linear trends for the September sea ice extent and spatially averaged SATs. The model responses of Arctic SAT to all forcings and to each forcing are estimated to be 0.52°C in HIST, 0.30°C in GHG, −0.58°C in AER, and 0.28°C in NAT, while the magnitude of the unforced multidecadal internal variability estimated by MRI-ESM2.0 CNTL is estimated to be 0.68°C. Therefore, the response of Arctic SATs to natural forcing is 0.4 times that of the unforced multidecadal internal SAT variability, supporting the significant effect of the natural forcing. Natural forcing also appears to influence the reduction of the sea ice extent synchronously with the Arctic SAT increase. The sea ice extent response to natural forcing is estimated to be −0.24 × 10⁶ km², which is 0.4 times the value of 0.55 × 10⁶ km² of the unforced multidecadal internal variability in the sea ice extent. The sea ice response to natural forcings is comparable to the anthropogenic forcings in GHG and AER and is smaller than the magnitude of the unforced multidecadal internal variability. The 30-year (1911–1940) sea ice response to all forcings in HIST is estimated to be −0.31 × 10⁶ km², which is 0.3 times that of the observation (Walsh et al., 2017) likely owing to the smaller warming signal in SAT in the models (Figure 1a and 1b).

4. External Factors in Arctic SAT Changes Based on Multimodel Analyses

Figures 5a–5c show time series of the DAMIP multimodel ensemble mean (MMM) SATs and their intermodel spreads (±1 standard deviation). The MMM Arctic SATs for the linear sum of each forcing experiment (GHG + AER + NAT) reproduces the observed ETCW and the subsequent long-lasting cooling from 1940 to 1970 well (Figure 5a), even though the amplitude of the simulated ETCW is approximately half as large as the observed ETCW. Note that the disagreement between MMM GHG + AER + NAT (the sum of the responses to the individual forcings) and MMM HIST (with all forcings combined) appears to be caused by the differences in internal climate variabilities and the nonlinear interactions between each forcing. MMM for GHG + AER cannot reproduce the Arctic SAT variations prior to 1950, indicating that external anthropogenic forcings alone cannot explain ETCW. However, the MMM Arctic SAT variations for NAT show a better correspondence with the CRUTEM4 observations from 1910 to 1970, suggesting a major contribution of natural forcings to the Arctic SAT changes. As pointed out by Otterå et al. (2010), external natural forcing also functions as a metronome for internal climate variabilities.

Figure 5d shows MMM for the 30-year Arctic SAT linear trends in the period of 1911–1940 for, HIST, GHG, AER, and NAT. The range of the unforced multidecadal internal variability estimated from CNTLs is shown.
in Figure 5d for comparison with the externally forced responses. The responses to increasing greenhouse gases and anthropogenic aerosols were very weak compared to those of natural forcings during the ETCW period, indicating that the solar and volcanic natural forcings play a major role in MMM SAT increases in the ETCW. The magnitude of the MMM response to natural forcings is estimated to be 0.60 ± 0.42°C in the period of 1911–1940, whereas that of the MMM unforced multidecadal internal variability is estimated to be 0.54°C (0.38–0.87°C, Figure 5d), indicating that the externally forced response of Arctic SATs to natural forcing in the MMM is a robust signal. This result also indicates that the magnitude of the response of the Arctic SAT linear trend to natural forcings estimated from the MRI-ESM2.0 results lies within the intermodel spread estimated from the multimodel analyses. The unforced multidecadal internal variability in MRI-ESM2.0 is also located within the intermodel spread.
5. Conclusions

We conducted a series of DAMIP experiments using MRI-ESM2.0 and identified the external climate factors in the historical Arctic SAT and sea ice changes during the first half of the 20th century. HIST, as simulated by MRI-ESM2.0, reproduced the historical changes in the Arctic SATs and the associated changes in the sea ice extent well, including the ETCW period, even though HIST underestimates the September sea ice extents throughout the entire period. The decrease in the model-simulated sea ice extents during 1911–1940 is likely owing to the Arctic warming. Comparison between HIST and the observation also showed a good reproduction of the Arctic warming pattern in summer between 1935 and 1945, except some mismatches.

The DAMIP experiments using MRI-ESM2.0 suggest that the simulated ETCW cannot be explained by anthropogenic effects alone (GHG + AER) and that external natural forcings play an important role in the model-simulated ETCW, rather than the sum of the anthropogenic forcings. We further quantitatively examined individual contributions from solar and volcanic forcings and found that solar and volcanic activities each have a subsidiary effect on the model-simulated Arctic warm anomaly during the mid-20th century. However, the magnitude of Arctic SAT signal in the ETCW period owing to the natural forcings is 0.4 times that of the unforced multidecadal internal variability, suggesting relative importance of the internal dynamics to ETCW.

The DAMIP multimodel analyses show that the model-simulated ETCW is primarily affected by natural forcings, rather than anthropogenic forcings. The climatic response of Arctic SATs to natural forcings is comparable to the unforced multidecadal internal variability during the ETCW period, supporting the robust model response to natural forcings. This result suggests that, if the observed ETCW is influenced by a certain internal variability, its magnitude is likely comparable to the natural forcing response.

Data Availability Statement

The DAMIP data used in this study are available on the Earth System Grid Federation (ESGF) website (https://esgf-node.llnl.gov/search/cmip6/) with digital object identifiers (doi). If readers want to access the data, please register with ESGF and search by selecting the appropriate activity (DAMIP), source ID (model name), and experiment ID (hist-aer, hist-GHG, hist-nat, hist-sol, and hist-volc) on the website. The observational data set CRUTEM.4.4.0.0.anomalies.nc and https://crudata.uea.ac.uk/cru/data/temperature/CRUTEM.4.4.0.0.anomalies.nc and https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT.4.6.0.0.median.nc, respectively.

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