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Arctic Sea Ice Loss Weakens Northern Hemisphere Summertime Storminess but Not Until the Late 21st Century

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Key Points:

- Equilibrium and transient climate model simulations are used to quantify the summertime storminess response to Arctic sea ice loss
- The equilibrium response to mid-to-late 21st century Arctic sea ice loss involves weaker summertime storminess due to ocean coupling
- The transient weakening of present-day summertime storminess is not significantly affected by Arctic sea ice loss and Arctic Amplification

Supporting Information:

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

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Abstract Observations show Arctic sea ice has declined and midlatitude storminess has weakened during Northern Hemisphere (NH) summertime. It is currently unclear whether Arctic sea ice loss impacts summertime storminess because most previous work focuses on other seasons. Here we quantify the impact of Arctic sea ice loss on NH summertime storminess using equilibrium and transient climate model simulations. The equilibrium simulations show mid-to-late 21st century Arctic sea ice loss weakens summertime storminess, but only in the presence of ocean coupling. With ocean coupling, the equator-to-pole temperature and atmospheric energy gradients significantly weaken due to increased surface turbulent flux in the polar region following Arctic sea ice loss. The transient simulations show Arctic sea ice loss does not significantly weaken summertime storminess until the late 21st century. Furthermore, Arctic Amplification, which is dominated by Arctic sea ice loss in the present day, does not significantly impact the present-day weakening of summertime storminess.

Plain Language Summary Present-day summertime climate change in the NH is characterized by rapid Arctic sea ice loss and weakening of weather systems. While these trends are projected to continue throughout the 21st century, their connection is not well understood. Using climate model simulations, we show mid-to-late 21st century Arctic sea ice loss weakens the summertime weather system by decreasing the equator-to-pole energy (and temperature) difference. In addition, we demonstrate transient Arctic sea ice loss does not significantly contribute to weakening summertime weather system until the late 21st century. The results suggest that present-day Arctic sea ice loss and Arctic Amplification have not contributed significantly to the observed weakening of weather systems.

1. Introduction

Observations show Arctic sea ice area in late summer and early autumn is rapidly declining (Serreze & Stroeve, 2015), leading to a reduction of reflected shortwave at top of the atmosphere (Hartmann & Ceppi, 2014). Climate models project an ice-free summertime Arctic ocean within this century under a high-emission scenario (Notz & Community, 2020; Overland & Wang, 2013). Reanalysis data also show that storminess, as measured by eddy kinetic energy (EKE), has weakened significantly during the Northern Hemisphere (NH) summertime (Coumou et al., 2015; Gertler & O'Gorman, 2019). Consistently, the number of intense midlatitude cyclones has decreased significantly since 1979 (Chang et al., 2016). Summertime storminess in the NH is projected to further weaken throughout the 21st century (Harvey et al., 2020; Lehmann et al., 2014; O'Gorman, 2010; Priestley & Catto, 2022; Shaw & Voigt, 2015). Here we quantitatively investigate the connection between Arctic sea ice loss and summertime storminess weakening in the NH.

The impact of Arctic sea ice loss on the atmospheric circulation during winter is well documented using equilibrium and transient climate model simulations. The equilibrium simulations examined the response to future (mid-to-late 21st century) Arctic sea ice loss. In particular, Polar Amplification Model Intercomparison Project (PAMIP; Smith et al., 2019) simulations reported a weak but robust wintertime jet weakening and equatorward shift response to mid-21st century Arctic sea ice loss (Smith et al., 2022), consistent with earlier studies (Blackport & Kushner, 2017; Blackport & Screen, 2019; Peings & Magnusdottir, 2014; Screen et al., 2018; Sun et al., 2015). Future Arctic sea ice loss also weakens wintertime storminess in high latitudes (Murray & Simmonds, 1995; Oudar et al., 2017; Seierstad & Bader, 2009) and affects mean sea-level pressure (SLP) (Blackport & Kushner, 2017; Deser et al., 2016; Screen et al., 2018).

The transient simulations examined the response to present-day Arctic sea ice loss. Sun et al. (2018) showed the response of the large-scale circulations to present-day Arctic sea ice loss is insignificant during wintertime. The insignificant response might be due to large internal variability (Peings et al., 2021; Sun et al., 2022). Whether an impact of present-day Arctic sea ice loss on the wintertime circulation can be detected in observations is actively debated (Barnes & Screen, 2015; Cohen et al., 2020).

Previous work also showed that the atmospheric circulation response to Arctic sea ice loss in winter is sensitive to ocean coupling. The wintertime circulation response to Arctic sea ice loss, including the jet weakening, is larger with ocean coupling than without it (Deser et al., 2015, 2016). Ocean coupling also enhances the wintertime SLP response to Arctic sea ice loss (Deser et al., 2016; Tomas et al., 2016). The impact of ocean coupling is more important than the impact of different methods used to impose sea ice loss in coupled models (Screen et al., 2018; Simon et al., 2021; Sun et al., 2020).

In contrast, only a few studies have investigated the impact of Arctic sea ice loss on the summertime circulation. Some studies have documented a weaker summertime NH jet stream in response to future Arctic sea ice loss (England et al., 2018; Oudar et al., 2017), whereas others find no significant response (Sun et al., 2015). Furthermore, the summertime SLP and geopotential height only showed a limited significant response (Petrie et al., 2015; Screen et al., 2013). To our knowledge, there are no studies that examine the impact of future Arctic sea ice loss on summertime storminess (storm tracks) as measured by EKE or tracks of cyclones and anticyclones. Additionally, the importance of Arctic sea ice loss for the present-day weakening of summertime storminess has not been established.

But how does summertime storminess respond to Arctic sea ice loss? Understanding the mechanism underlying the impact of Arctic sea ice loss on summertime storminess is important for having confidence in climate model projections (Shaw, 2019) and proper understanding of present-day trends (Wallace et al., 2014). A recent study proposed an energetic mechanism, which relies on thermodynamic ocean coupling, that links polar sea ice loss to a weakened meridional atmospheric energy gradient and thereby weakened storminess (Shaw & Smith, 2022). It is currently unclear whether the energetic mechanism operates in summertime.

Here we address the following questions: (a) How does future Arctic sea ice loss impact summertime storminess? (b) Does Arctic sea ice loss significantly contribute to the present-day weakening of summertime storminess? Our approach to answering these questions follows that for wintertime. In particular, we use equilibrium climate model simulations to answer the first question and transient climate model simulations to answer the second question.

2. Data and Methods

2.1. Coupled and Uncoupled Equilibrium Sea Ice Loss Simulations

To answer the first question, we use ensembles of coupled and uncoupled climate model simulations of the equilibrium response to future Arctic sea ice loss (Table S1 in Supporting Information S1). The models used to create the ensembles are described below.

For the uncoupled simulations, we use PAMIP pdSST-pdSIC and pdSST-futArcSIC simulations which prescribe present-day and mid-21st century Arctic sea ice (Smith et al., 2019). The same present-day SST is prescribed in both simulations, except in regions of sea ice loss where mid-21st century SST is prescribed. To calculate the storminess response, seven models (AWI-CM-1-1-MR, CanESM5, CESM2, HadGEM3-GC31-MM, IPSL-CM6A-LR, MIROC6, and TaiESM1) and their ensemble members providing high-frequency (daily or higher) atmospheric winds are analyzed.

We also use uncoupled Whole Atmosphere Community Climate Model (WACCM4) simulations from Sun et al. (2015), hereafter called WACCM4-U, which prescribes present-day and late-21st century Arctic sea ice. As for PAMIP, the same present-day SST is prescribed in both simulations, except in regions of sea ice loss where late-21st century SST is prescribed.

For the coupled simulations, we do not consider PAMIP simulations since high-frequency atmospheric winds were unavailable. Instead, we use coupled WACCM4 simulations, hereafter called WACCM4-C, with present-day and late-21st century Arctic sea ice. The WACCM4-C simulations have similar sea ice as WACCM4-U, but with ocean coupling. In WACCM4-C simulations, sea ice is constrained using the ghost flux method of Deser et al. (2015), which involves specifying a seasonally varying longwave radiative flux to the ice model to match either present-day or future sea ice.

We also use existing coupled simulations. In particular, we use Community Earth System Model version 1 simulations from Blackport and Kushner (2017) (hereafter called BK17) with present-day and late-21st century Arctic sea ice imposed using the albedo method (artificially decreasing the ice albedo). We also use coupled WACCM4 simulations from England et al. (2020) with present-day and late-21st century sea ice imposed using the ghost flux method. The simulations from England et al. (2020) quantify the impact of sea ice loss in the Arctic (named E20-A) and both poles (named E20-A&AA). More details can be found in Blackport and Kushner (2017) and England et al. (2020).

The ensemble-mean climate response to future Arctic sea ice loss for coupled (WACCM4-C, BK17, E20-A, E20-A&AA) and uncoupled (WACCM4-U and seven PAMIP models) models are defined by the difference between future and present-day sea ice. As these Arctic sea ice loss experiments are generally uncoordinated (except for the PAMIP simulations) and have different amounts of Arctic sea ice loss (see Table S1 in Supporting Information S1), we normalize individual model responses by the amount of Arctic sea ice loss (see Table S1 in Supporting Information S1) following Screen et al. (2018).

2.2. Coupled Transient Climate Model Simulations

The second question is answered using transient simulations from the present day to the late 21st century of the climate response to total anthropogenic forcing with and without Arctic sea ice loss. Specifically, we use two transient Geophysical Fluid Dynamics Laboratory Coupled Model version 3 (CM3) simulations from Sun et al. (2018), each with five ensemble members. The first transient simulation, hereafter called RCP, simulates the transient climate response to total anthropogenic (historical and RCP8.5) forcing from 1970 to 2090. We compare the present-day (1980–2020) RCP simulation to three reanalysis datasets (ERA5, JRA55, and MERRA2; Hersbach et al., 2020; Kobayashi et al., 2015; Gelaro et al., 2017).

The other transient simulation, hereafter called RCP_ICE1990, simulates the climate response to anthropogenic forcing without Arctic sea ice loss from 1990 to 2090. In this simulation, the Arctic sea ice volume is artificially relaxed to a repeating seasonal cycle of 1990 sea ice conditions. The transient response to Arctic sea ice loss from 1990 to 2090 is quantified by the difference between the first and second transient simulations, hereafter called ΔICE = RCP−RCP_ICE1990. The last 30 years of ΔICE simulation are also added to the coupled equilibrium model ensemble (Section 2.1, Table S1 in Supporting Information S1). Additional details of the CM3 simulations can be found in Sun et al. (2018).

2.3. Methods

We quantify storminess using EKE and tracks of cyclones and anticyclones. For the reanalysis datasets, CM3, WACCM4-C, WACCM4-U, and PAMIP simulations, we calculate monthly-mean EKE as

$$\mathrm{EKE} = \left(\overline{u'^2} + \overline{v'^2}\right) \times 0.5, \tag{1}$$

where overbars denote monthly mean and u' and v' are daily anomalies from the monthly mean. For BK17, E20-A, and E20-A&AA simulations, daily data is unavailable, therefore EKE is calculated as,

$$\mathrm{EKE} = \left(\overline{u^2} - \overline{u}^2 + \overline{v^2} - \overline{v}^2\right) \times 0.5. \tag{2}$$

This method includes signals from frequency higher than daily, but the impact is expected to be small. We vertically integrate EKE from the surface to 200 hPa.

Individual cyclones and anticyclones are tracked using six-hourly SLP data from reanalysis datasets, CM3, and three PAMIP (CESM2, IPSL-CM6A-LR, and TaiESM1) simulations using the Hodges (1999) method. We spatially filter the SLP to retain total wavenumbers from 5 to 63. The summertime climatology for each year is also subtracted to reduce the signal from low-frequency circulations (Chang et al., 2016). The local minima or

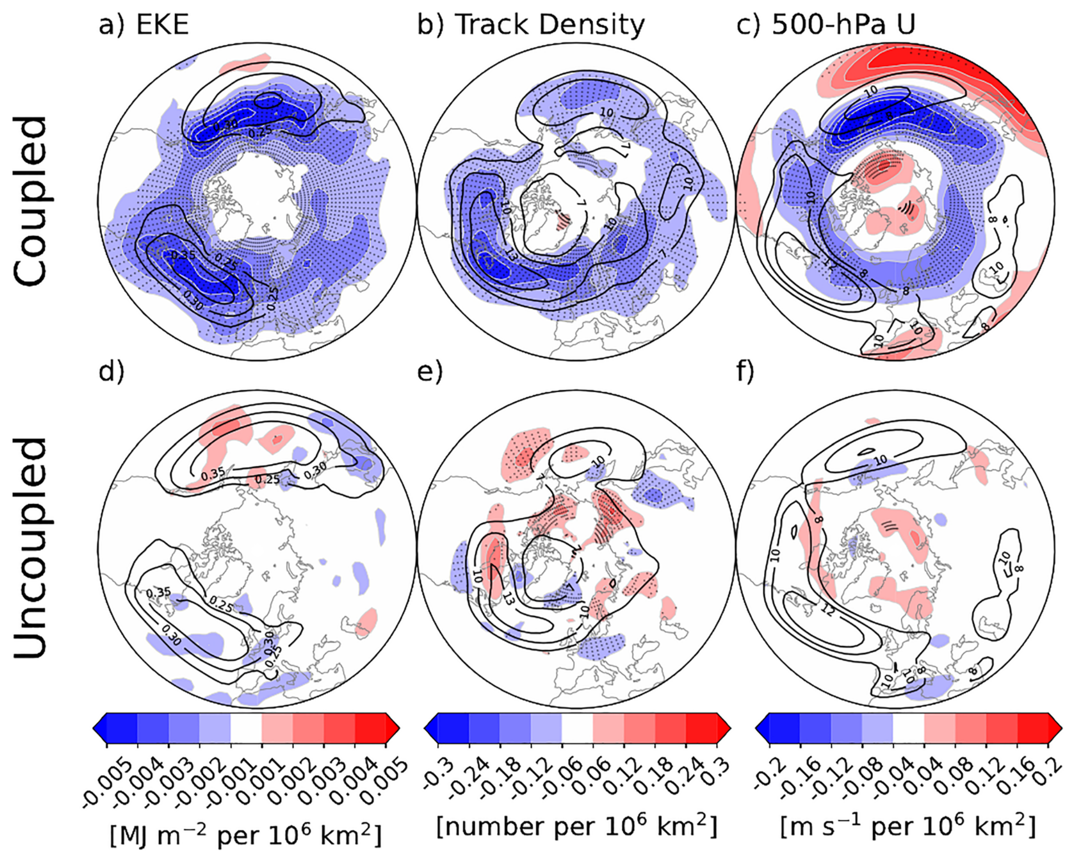

Figure 1. Response of summertime (a, d) vertically-integrated eddy kinetic energy, (b, e) track density, and (c, f) 500-hPa zonal wind to future Arctic sea ice loss in (a–c) coupled and (d–f) uncoupled climate model simulations. In all panels but (b), stipples indicate where all models agree in the sign of the response. In (b), stipples represent statistically significant responses at the 95% confidence level using a two-sided Student's *t*-test as track density response is calculated from a single model (CM3: 2061–2090). The summertime climatology is shown in black contours in units of (a, d) MJ m^{-2}, (b, e) number, and (c, f) m s^{-1}.

maxima from the filtered SLP field are labeled as cyclone or anticyclone tracks, and those that last longer than 2 days and travel farther than 1,000 km are analyzed.

We sample summertime cyclones and anticyclones that spend at least one time step in the summer months. With these selected weather systems, we calculate the track density (Hoskins & Hodges, 2002) defined as the number of summertime cyclones and anticyclones per ~10^6 km^2 (Kang & Son, 2021). For plotting purposes, we smooth the track density using a Gaussian filter with a standard deviation of 1.5°.

3. Results

3.1. Summertime Storminess Response to Future Arctic Sea Ice Loss

Summertime storminess measured by transient EKE weakens in response to future Arctic sea ice loss in coupled climate models (Figure 1a). The weakening occurs at all longitudes and pressure levels (Figure S1a in Supporting Information S1) and across all models (Figures S2a–S2e in Supporting Information S1). When averaged over midlatitudes (35°N–65°N), storminess weakens by ~4.6% (or ~1.0% per 10^6 km^2 of Arctic sea ice loss), which is about one-third of the EKE weakening at the end of the 21st century under a high-emission scenario (Lehmann et al., 2014). This robust summertime weakening in response to Arctic sea ice loss is consistent with the weakening reported in other seasons (Audette et al., 2021; Magnusdottir et al., 2004; Seierstad & Bader, 2009; Shaw & Smith, 2022). In particular, the wintertime EKE weakens by ~6.1% in our coupled simulations.

Summertime storminess quantified by the track density of individual cyclones and anticyclones also weakens in response to future Arctic sea ice loss (Figure 1b). The strongest weakening is found over the North Atlantic and

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North Pacific basins where track density decreases by ~1%–2% per 10^6 km^2 of Arctic sea ice loss. In addition, individual cyclones and anticyclones become weaker in response to Arctic sea ice loss (Figure S3 in Supporting Information S1). The decrease and weakening of the summertime weather systems are consistent with the wintertime response (Murray & Simmonds, 1995; Oudar et al., 2017).

Finally, the summertime zonal wind weakens on the poleward side of the jet in response to future Arctic sea ice loss (Figure 1c), consistent with previous work (England et al., 2018; Oudar et al., 2017). The weakening is robust over the North Pacific, but it is less robust in the North Atlantic across the models (Figure S4a–S4e in Supporting Information S1). In the zonal mean, the NH jet exhibits an equatorward shift (Figure S1c in Supporting Information S1), similar to the wintertime response to Arctic sea ice loss (Blackport & Kushner, 2017; Deser et al., 2016; Smith et al., 2022).

3.2. Importance of Ocean Coupling for Weakening Storminess

In contrast to the coupled simulations, summertime EKE does not change significantly in response to imposed future Arctic sea ice loss in the uncoupled simulations (Figure 1d). An insignificant response is seen across different models and pressure levels (Figures S1b and S2f–S2m in Supporting Information S1). Consistently, the summertime cyclone and anticyclone track density response is insignificant in the uncoupled simulations (Figure 1e). The small patches of sign agreement are likely related to the small number of models in the ensemble since individual models exhibit inconsistent responses (Figure S5 in Supporting Information S1). The summertime jet response to Arctic sea ice loss is also insignificant (Figure 1f) in the uncoupled simulations at all pressure levels (Figure S1d in Supporting Information S1) and for individual models (Figures S4f–S4m in Supporting Information S1). The different summertime responses in uncoupled versus coupled simulations illustrate the importance of ocean coupling for the summertime circulation response to Arctic sea ice loss.

The different summertime storminess responses to Arctic sea ice loss in the coupled and uncoupled simulations can be understood from the surface energy flux response. The surface energy flux response can be expressed as follows

$$\Delta TF + \Delta SW_s + \Delta LW_s = \Delta NA, \tag{3}$$

where ΔTF, ΔSW_s, ΔLW_s, and ΔNA are the change in surface turbulent flux, surface shortwave radiation, surface longwave radiation, and non-atmospheric fluxes including oceanic heat storage and transport, respectively (Shaw & Smith, 2022). In Equation 3, positive energy fluxes indicate energy gain in the atmosphere (loss to surface). Note that energy conservation (Equation 3) only holds in coupled simulations, and NA represents the non-conservation of energy in the uncoupled simulations.

In the coupled simulations, the surface turbulent flux into the high latitude (50°N–90°N) atmosphere increases (blue, Figure 2a), mostly balancing the increase in surface shortwave radiation into the ocean following the loss of Arctic sea ice (yellow, Figure 2a). In contrast, the high-latitude surface turbulent flux response is negligible in the uncoupled models. The uncoupled models underestimate the surface turbulent flux mostly over the previously ice-covered ocean due to weaker SST response but also over the land and adjacent ice-free ocean (Figures S6a and S6b in Supporting Information S1). As a result, the atmospheric meridional energy gradient weakens significantly in the coupled simulations due to surface turbulent flux (solid line, Figure 2b) and storminess weakens consistent with the energetic mechanism, which relies on ocean coupling (Shaw & Smith, 2022). The negative surface turbulent flux response around 42°N in the coupled simulations is likely related to weakened ocean heat transport in response to Arctic sea ice loss (Sévellec et al., 2017; Sun et al., 2018).

The different surface energy flux responses to future Arctic sea ice loss in coupled versus uncoupled simulations also manifest in summertime temperature (Figures 2c and 2d). The coupled models exhibit Arctic warming that extends to the free troposphere and lower latitudes (Figure 2c). In contrast, the Arctic warming is weak in the uncoupled simulations and confined near the surface (Figure 2d). This demonstrates that ocean coupling is important for summertime Arctic Amplification, extending previous work for the annual mean (Chemke et al., 2021; Deser et al., 2015). We note that Arctic warming is ~6 times larger during wintertime than summertime in the coupled simulations. Ocean coupling is also important for the SST response outside the regions of sea ice loss (Figures S6c and S6d in Supporting Information S1) consistent with previous work (Blackport & Kushner, 2018).

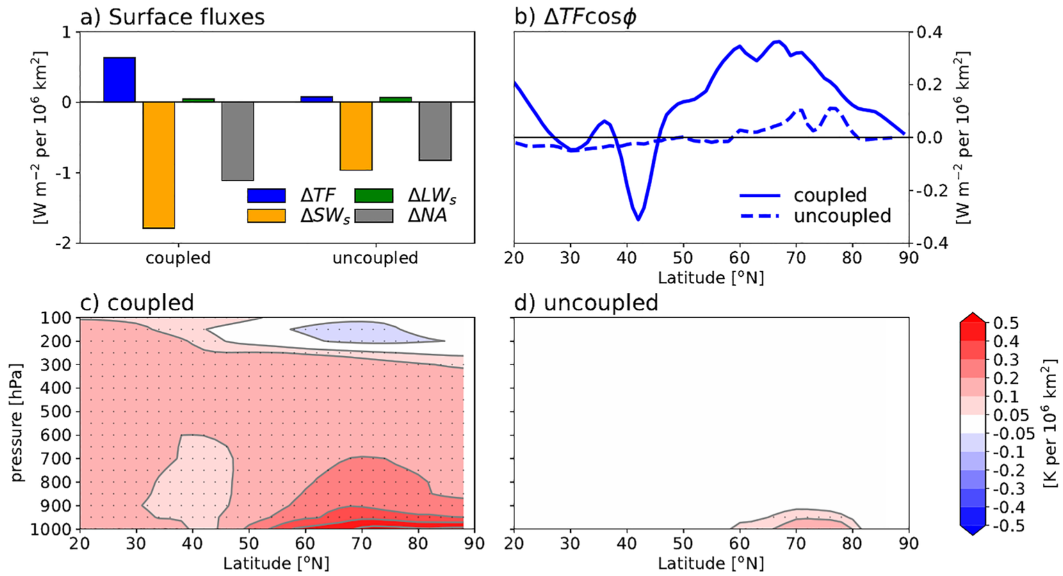

Figure 2. Response of summertime (a) high-latitude (50°N–90°N) surface energy flux (defined as positive upward), (b) zonal-mean surface turbulent flux (multiplied by the cosine of latitude), and (c, d) zonal-mean temperature to Arctic sea ice loss in the coupled and uncoupled climate model simulations. In (c, d), stipples indicate where all models agree in the sign of the response.

3.3. Insignificant Impact of Present-Day Arctic Sea Ice Loss on Storminess

The equilibrium simulations show future Arctic sea ice loss has a significant impact on summertime storminess in the presence of ocean coupling. Next, we use transient simulations to investigate the impact of present-day Arctic sea ice loss on summertime storminess. The RCP simulation captures present-day summertime Arctic sea ice loss (Figure S7a in Supporting Information S1). The summertime EKE in the RCP simulations involves a significant weakening (black, Figure 3a) that slightly overestimates trends in reanalysis datasets (green, Figure 3a) possibly due to stronger global warming (Figure S7b in Supporting Information S1). To account for this, we compare the RCP and reanalysis trends of EKE weighted by trends of global-mean near-surface temperature, which leads to better agreement between the model and reanalysis ensembles (Figure 3b).

The summertime trend in number of cyclones and anticyclones in the RCP simulations involves a significant weakening (black, Figure 3c), consistent with the reanalysis ensemble (Figure 3d). The significant decrease in cyclone and anticyclone numbers in reanalysis datasets extends the findings of Chang et al. (2016), who reported a significant decrease in intense cyclones. The summertime jet trend in the RCP simulations also features a significant weakening (black, Figure 3e), consistent with the reanalysis ensemble (Figure 3f). Thus we find that the RCP simulation reasonably reproduces the present-day summertime trends in storminess and jet per degree of global-mean warming.

How much of the present-day storminess weakening is due to Arctic sea ice loss? According to the transient simulations, the trend in EKE from 1990 to 2020 due to Arctic sea ice alone (blue, Figure 3a) is statistically insignificant (p-value > 0.05) for all ensemble members (blue bar, Figure 4a, Figure S8a in Supporting Information S1). Similarly, Arctic sea ice loss does not lead to a statistically significant trend in the number of cyclones and anticyclones (blue, Figure 3c, Figure S8b in Supporting Information S1) or in the jet strength (blue, Figure 3e, Figure S8c in Supporting Information S1). Consistently, the temperature trend due to Arctic sea ice loss involves weak surface-trapped warming in the Arctic (Figure S9a in Supporting Information S1), and thus it does not affect the meridional temperature gradients throughout the depth of the troposphere. A negligible wintertime circulation response to present-day Arctic sea ice loss was also found using the same transient simulations (Sun et al., 2018).

If Arctic sea ice loss does not dominate the present-day weakening of summertime storminess then what does? The simulations suggest the response to anthropogenic forcing without Arctic sea ice loss (RCP−ΔICE) dominates the weakening of present-day storminess (compare black and red bars in Figure 4a). The temperature response to anthropogenic forcing without Arctic sea ice loss involves warming aloft and hence an increase in vertical

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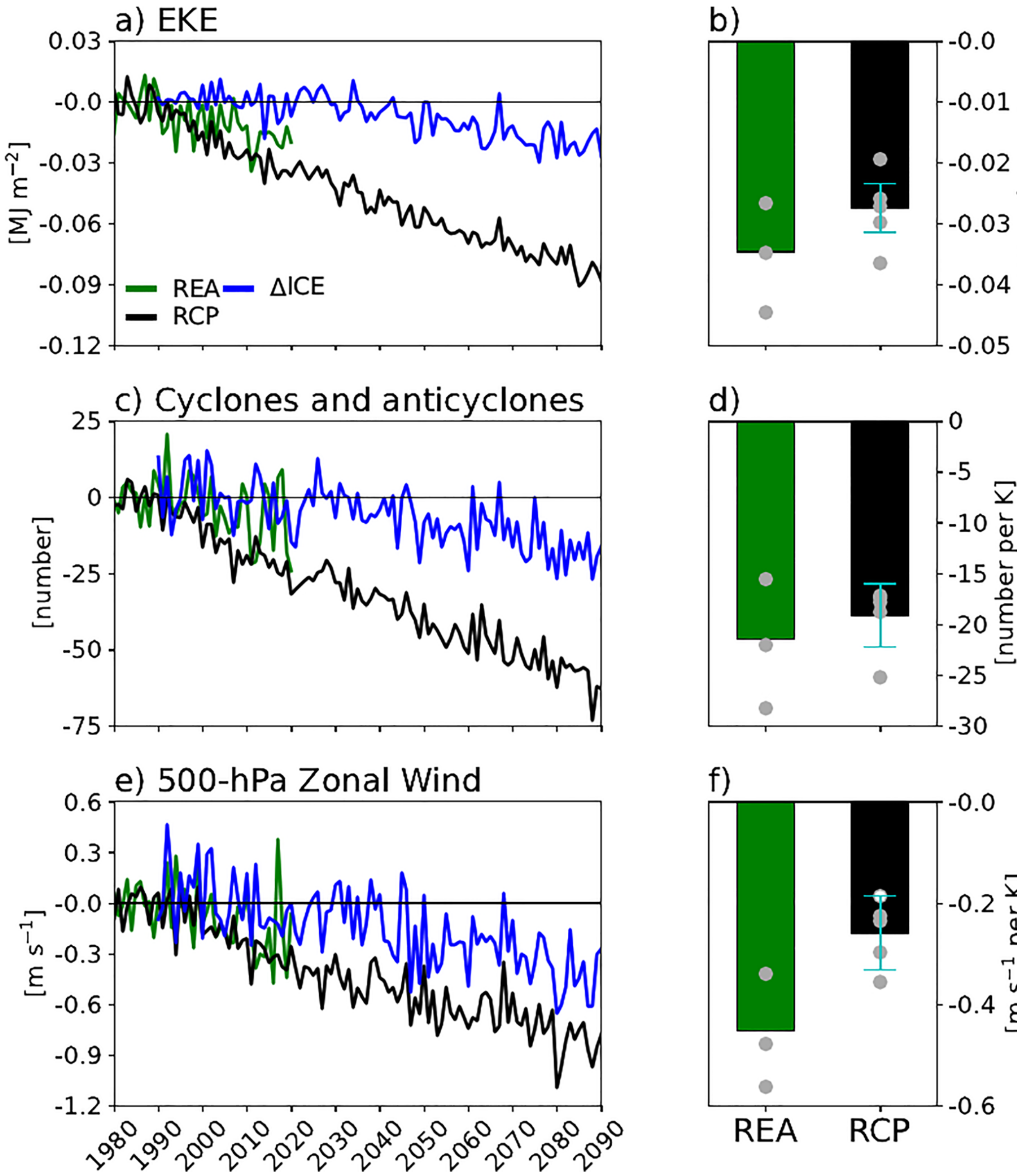

Figure 3. Time series of (a) eddy kinetic energy (EKE) (20°N–70°N) for ensemble mean of reanalysis datasets (REA, green) and ensemble-mean RCP (black) and ΔICE (blue) simulations with respect to the 1980–1990 climatology. (b) Linear trends from 1980 to 2020 per degree K of global-mean warming for EKE for ensemble mean of reanalysis datasets (REA, green) and ensemble mean of RCP simulations (black). Statistically significant trends at the 95% confidence level for individual reanalysis datasets and RCP simulation ensemble members are shown in filled gray circles. The error bars indicate the 95% confidence interval for the ensemble-mean trend. Similar results to (a, b) are shown for (c, d) cyclones and anticyclones (30°N–70°N) and (e, f) 500 hPa zonal wind (35°N–70°N).

stability and maximum warming around 45°N which weakens the meridional temperature gradient throughout the depth of the troposphere (Figure S9b in Supporting Information S1). A similar transient summertime temperature response to anthropogenic forcing without Arctic sea ice loss was reported in Dai et al. (2019) (see their Figure 9e). This warming response may be related to direct radiative forcing (Shaw & Voigt, 2015, 2016) and/or changes in aerosol forcing (Dong et al., 2022).

It is also interesting to note that the RCP simulation features significant Arctic Amplification but it is not dominated by anthropogenic forcing without Arctic sea ice loss (compare black and red bars in Figure 4b). Instead, summertime Arctic Amplification is dominated by Arctic sea ice loss (compare black and blue bars in Figure 4b), consistent with previous work (compare Figures 7a and 8a in Dai et al., 2019). Thus the transient simulations

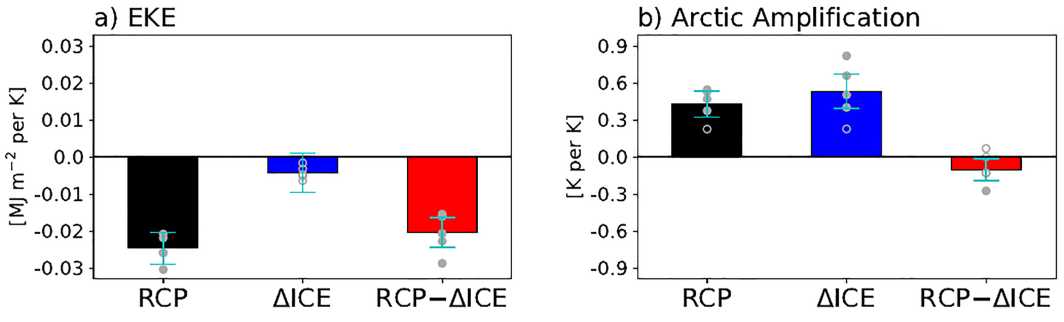

Figure 4. Linear ensemble-mean trends from 1990 to 2020 per degree K of global-mean warming of (a) eddy kinetic energy (20°N–70°N) and (b) Arctic Amplification defined as the difference between Arctic (65°N–90°N) and Northern Hemisphere (0°N–90°N) near-surface temperature following Blackport and Screen (2020) for RCP (black), ΔICE (blue), and RCP−ΔICE (red) simulations. Statistically significant trends at the 95% confidence level for individual ensemble members are shown in filled gray circles. The error bars indicate the 95% confidence interval for the ensemble-mean trend.

suggest present-day Arctic sea ice loss and Arctic Amplification do not significantly affect the present-day weakening of summertime storminess.

While Arctic sea ice loss does not significantly impact the present-day summertime storminess trend, it does impact the storminess trend in the late 21st century. More specifically, starting in 1990, the trend of summertime storminess, as measured by EKE, in response to Arctic sea ice loss (ΔICE) becomes statistically significant for all ensemble members in 2068 (Figure S8a in Supporting Information S1), consistent with the response in the equilibrium simulations (Section 3.1). Arctic sea ice loss contributes about a fourth of the weakening by the end of the century. Following a similar approach, the impact of Arctic sea ice loss on the number of cyclones and anticyclones and the jet becomes significant in 2078 and 2087, respectively (Figures S8b and S8c in Supporting Information S1). Consistent with the significant weakening of storminess and jet in the late 21st century, Arctic sea ice loss induces a summertime warming trend from 1990 to 2090 that involves Arctic amplification extending into the free troposphere weakening the meridional temperature gradients throughout the depth of the troposphere (Figure S10 in Supporting Information S1).

4. Discussions

Here we investigate the connection between Arctic sea ice loss and summertime storminess for the first time using equilibrium and transient climate model simulations. Our approach follows previous work in other seasons. The results answer the two questions posed in the introduction. (a) Future (mid-to-late 21st century) Arctic sea ice loss significantly weakens summertime storminess but only in the presence of ocean coupling. (b) Present-day Arctic sea ice loss has not contributed significantly to the present-day weakening of summertime storminess. Altogether our results show Arctic sea ice loss does not matter very much for present-day weakening of summertime storminess but it will contribute about a fourth to the total weakening by the end of the century. Our results demonstrate the importance of examining the transient and equilibrium responses to climate change because mechanisms can operate on different time scales (Shaw, 2019).

The answer to our first question highlights the importance of ocean coupling for the summertime circulation response to Arctic sea ice loss, which is consistent with other seasons (Deser et al., 2016). Similarly, ocean coupling enhances summertime Arctic Amplification, consistent with previous work (Chemke et al., 2021; Deser et al., 2015). We find the summertime circulation response is generally insensitive to different methods used to impose sea ice loss in coupled simulations consistent with results from other seasons (Simon et al., 2021; Sun et al., 2020).

The answer to our second question comes from a single model. Nevertheless, the summertime temperature responses to anthropogenic forcing with and without Arctic sea ice loss in our simulations are similar to those in previous work using different models (Dai et al., 2019; Oudar et al., 2017). Moreover, our results are consistent with previous work that showed negligible summertime geopotential response from present-day Arctic sea ice loss (Screen et al., 2013) and a negligible impact of present-day Arctic sea ice loss on wintertime circulation trends (Sun et al., 2018).

Our results clarify the impact of transient Arctic sea ice loss on the present-day weakening of summertime storminess. Previous studies linked the present-day weakening of summertime storminess to temperature trends, including Arctic Amplification, via thermal wind (Coumou et al., 2015, 2018) and mean available potential energy (Gertler & O'Gorman, 2019). However, our transient simulations show Arctic sea ice loss and Arctic Amplification do not have a significant impact on the weakening of present-day summertime storminess in the NH. The temperature trend in response to present-day Arctic sea ice loss involves weak surface trapped warming in the Arctic and thus it does not significantly affect the meridional temperature gradients throughout the depth of the troposphere. Instead, our results point to the importance of the response to anthropogenic forcing in the absence of Arctic sea ice loss that may be related to direct radiative forcing (Shaw & Voigt, 2015, 2016) and/or aerosol forcing (Dong et al., 2022).

Data Availability Statement

The PAMIP data are downloadable from the CMIP6 data search interface https://esgf-node.llnl.gov/search/cmip6/. ERA5 reanalysis data are available from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form and https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form. JRA-55 reanalysis data can be obtained from https://rda.ucar.edu/datasets/ds628.0/. MERRA-2 reanalysis data can be downloaded from https://disc.gsfc.nasa.gov/datasets?project=MERRA-2. Post-processed model outputs and reanalysis data supporting the conclusions of this study are available at https://doi.org/10.5281/zenodo.7391819.

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