Decadal phase shift of summertime Arctic dipole pattern and its nonlinear effect on sea ice extent

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Abstract
The rapid decline in Arctic sea ice during recent decades has been attributed to the combined influence of global warming and internal climate variability. Herein, we elucidate the process by which the decrease in sea ice is accelerated in association with the decadal phase shift of the Arctic dipole (AD), using observational data and Community Earth System Model (CESM1) simulations. The influence of the AD on Arctic sea ice varied according to its phase; in the negative-AD decades (1979–1998), atmospheric circulation during summers of positive phase AD acts to reduce the sea ice extent (SIE) in the Pacific sector but increases it in the Atlantic sector. In contrast, in the positive-AD decades (after 1999), the same atmospheric circulation pattern reduces the SIE in both sectors, resulting in enhanced sea ice melting across the entire Arctic region. A similar nonlinear relationship between the AD phase and SIE change is also observed in CESM1 Pre-Industrial simulations, which stem from altered background temperature conditions between periods, implying the significant role of internal variability, particularly over the Atlantic sector. However, contrary to the recently observed AD trend, CESM1 Large Ensemble experiments predicted a negative AD trend as global warming proceeded. This suggests that the recent positive AD phase may be naturally driven, but the current state of sea ice decline associated with AD could be altered in the near future because of enhanced global warming.

KEYWORDS
Arctic dipole pattern, Arctic sea ice extent, decadal variability

1 | INTRODUCTION

Since 1979, when satellite observations began, the Arctic sea ice extent (SIE) has been reduced considerably. The decline in sea ice has accelerated further since the early 2000s, even exceeding the speeds predicted by most models (Stroeve et al., 2007; Comiso et al., 2008; Stroeve et al., 2012). In particular, record-breaking SIE minimums during the melting season were recorded in 2007 and 2012, and these data are frequently mentioned to indicate a rapid transition to the ‘New Arctic’ (Duarte et al., 2012; Overland et al., 2012). The recurring sea ice minima are thought to be related to recurrent positive conditions of the Arctic dipole (AD) pattern during summer (Zhang et al., 2008; Wang et al., 2009; Overland and Wang, 2010; Overland et al., 2012), which is characterized by a
high-pressure anomaly over the eastern Arctic centred over Greenland and a low-pressure counterpart over the Eurasian sector (contours in Figures 1c,d). This anomalous pressure distribution facilitates sea ice melting over the Pacific sector through radiative and mechanical processes. It was revealed that adiabatic descent by anticyclonic circulation increases low-level clouds, allowing more downwards long-wave radiation to melt sea ice (Ding et al., 2017). In addition, associated meridional wind anomalies strengthen transpolar drift and sea ice export through the Fram Strait (Watanabe et al., 2006; J. A. Maslanik et al., 2007b; Wang et al., 2009; Wettstein and Deser, 2014; Smersrud et al., 2017). Enhanced oceanic heat flux into the Arctic Ocean via the Bering Strait also accelerates the lateral melting of sea ice (Wang et al., 2009; Peralta-Ferriz and Woodgate, 2017; Serreze et al., 2019).

In the context of sea ice reduction, the AD has been receiving attention since the early 2000s. As noted in previous studies, before the 2000s, the atmospheric variability that dominated sea ice loss during summer was the Arctic Oscillation (AO) (Deser et al., 2000; J. Maslanik et al., 2007a; Bi et al., 2019). However, the correlation between sea ice and AO then weakened (J. Maslanik et al., 2007a; Bi et al., 2019). Meanwhile, the AD became the principal atmospheric pattern governing sea ice variability, although the cause of this regime shift remains unclear (Zhang et al., 2008; Wang et al., 2009; Wei et al., 2019). Here, we explore the role of the summertime AD on Arctic sea ice variation by decade and investigate the reasons underlying the enhanced influence of the AD on the SIE during recent decades using observations and the pre-industrial (PI) run of the Community Earth System Model 1.0 (CESM1). Section 2 describes the data and methods employed in this study. The main results provided in Section 3 illustrate the processes through which internal climate variability affects Arctic sea ice, in conjunction with anthropogenic warming. In the subsequent discussion and conclusion sections, we discuss the implications of this study regarding the rapid decline in Arctic sea ice and predicted future changes, based on the analysis of CESM1 Large Ensemble (LE) experiments simulating the warming scenario.

## 2 MATERIALS AND METHODS

We analysed monthly Arctic SIE data from the Sea Ice Index Version 3 of the National Snow and Ice Data Center (NSIDC; Fetterer et al., 2017) and monthly sea ice concentration (SIC) data from National Oceanic and Atmospheric Administration (NOAA)/NSIDC, Climate Data Record of Passive Microwave Sea Ice Concentration, Version 3 (Peng et al., 2013), from 1979 to 2017. Monthly atmospheric variables of ERA-Interim Reanalysis data were used for 1979 to 2017 because it is known as a reliable reanalysis dataset for the Arctic region (Dee et al., 2011; Jakobson et al., 2012; Kapsch et al., 2013; Lindsay et al., 2014). To determine the statistical significance of the regression, we used the Student’s t-test. However, we used a corrected test by Paternoster et al. (1998) to determine significant differences between regression coefficients. Monthly sea level pressure (SLP) data from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 were also analysed to examine long-term variation in AD from 1948 (Kalnay et al., 1996). Monthly anomalies were computed by removing the monthly climatology. We removed linear trends over the entire period from the variables, except for defining the AD, as this study focuses on the long-term phase shift of the AD and consequent changes affecting sea ice. To examine the physical background of the sea ice decline that minimizes in September, we focused on atmospheric variability during the summer season (June to August; JJA; Ogi and Wallace, 2007; Ogi et al., 2008; Ogi et al., 2010; Blanchard-Wrigglesworth et al., 2011; Wettstein and Deser, 2014).

The horizontal AD pattern and its index were obtained from the leading empirical orthogonal function (EOF) over the Arctic (60–90°N) and the corresponding principal component (PC) time series, using JJA-mean monthly anomalies of the SLP, from which the zonal mean was removed (green contours in Figures 1c,d). The AD pattern captured by the leading EOF accounted for 29.6% of the total variance. In previous studies, the AD pattern was defined as the second EOF of the SLP anomaly, while the first EOF was the AO, without the zonal mean removed from the anomalies (Wu et al., 2006; Overland et al., 2012; Choi et al., 2019). Our alternative definition is nearly equivalent to the previous definition, as the anomalies of the AO are quite zonal (the pattern correlation between the two AD patterns is 0.88). This alternative definition has the advantage of detecting the AD pattern as it is less affected by the orthogonality constraint of the EOF analysis. Here, we assumed the spatial stationarity of the AD to define the prevalent pattern for the entire analysis period using the EOF. As reported in some studies (Zhang et al., 2008; Ding et al., 2017; Choi et al., 2019), observed AD patterns show slight changes in its horizontal structure over time. Although not shown, the influences of these horizontal changes are, to some extent, reflected in our results, as the regressed SLP patterns onto the new AD index also capture characteristic features of the AD for decades. However, horizontal variability of the AD is not a topic of interest in the present
FIGURE 1 Normalized summer (JJA) Arctic dipole (AD) index by one standard deviation (solid line) and its 13-year moving average (dotted line) obtained (a) from the observational data (1979 to 2017) and (b) pre-industrial (PI) experiment of Community Earth System Model 1 (CESM1). Positive-AD decades (1979–1998; P1) and negative-AD decades (1999–2017; P2) are separated by vertical line in (a). In the PI experiment, NEG and POS periods that mimic P1 and P2 are also obtained. NEG and POS periods are the composites of years where the 13-year running average exceeds ±0.5 standard deviations. Square and round dots in (b) indicate the years that are parts of NEG and POS periods, respectively. Regression maps of JIAS sea ice concentration (SIC) anomalies against JJA AD index (shading) from observational data for (c) P1 and (d) P2. Regression maps calculated in the same manner, obtained from PI experiments, for (d) NEG and (e) POS periods. Contour lines indicate the AD patterns, whereas solid and dotted lines represent positive and negative sea level pressure (SLP) anomalies, respectively. The box of thick line indicates the Barents-Kara Sea region (70–85°N, 20–80°E). The units of the regression maps are percentile, and the hatched region indicates significance at the 90% (observation) and 95% (model) confidence levels [Colour figure can be viewed at wileyonlinelibrary.com]
study because we obtained consistent results from the model analysis regardless of the horizontal pattern of the AD for the given periods.

To examine long-term variability in the AD, which cannot be readily assessed using an observational approach, we analysed fully coupled perpetual PI runs with a fixed radiative forcing of 1850 for a period of 201 years, and 40 LE experiments under the RCP8.5 scenario of CESM1 covering the 2006–2080 period (Kay et al., 2015). To define AD in PI simulations, we adopted the same methodology used for the observations and obtained an AD pattern similar to the observations (27.6% total variance; Figure 1e,f). Considering the identical model configuration, except for the forcing between PI and LE, the EOF1 pattern of the PI experiments was used to calculate the AD index of LE by projecting it onto the SLP anomalies of each LE component. In the model analysis, we used winds and air temperature at 936.198 hPa, which was the closest to 925 hPa, and the surface ice fraction was analysed instead of SIC.

Focusing on the decadal phase of AD and its influence on sea ice, we separately examined two observational periods, namely 1979–1998 (P1) and 1999–2017 (P2), as performed by Bi et al. (2019), considering distinct variabilities in sea ice and the AD between the two periods. As shown in Figure 1a, a negative-to-positive phase shift of the AD occurred between P1 and P2. In addition, to investigate the altered climatic influence of the AD according to decadal phase shift in PI experiments, we selected two representative groups of periods with negative (NEG) and positive (POS) decadal phases, based on 13-year running averages of the AD index (dotted line in Figure 1b). When the running average index exceeded the threshold (i.e., ±0.5 standard deviations of the running average AD index), consecutive years within the exceeding range were regarded as belonging to either a POS or NEG period (denoted by round and square dots in Figure 1b). Consequently, 61 years of POS and 50 years of NEG periods were compiled, corresponding to the P2 and P1 observational counterparts, respectively. We found that the variabilities of the AD within the POS and NEG periods tended to be weaker than those of the observations. However, the influence of different variabilities on sea ice response was not crucial, and overall results were not highly sensitive to the criteria for selecting model periods.

3 | RESULTS

The relationship between the summertime AD and September SIE showed a marked change between periods P1 and P2. Based on the two detrended indices of the AD and SIE over the entire Arctic, the correlation was −.08 in P1, while it increased sharply to −.60 in P2, which is significant at the 99% confidence level based on a two-tailed Student’s t-test. As the indices are all detrended, this change in correlation reveals that the influence of the AD on Arctic sea ice was enhanced after the late 1990s (e.g., Choi et al., 2019). Regarding the intensified correlation, Bi et al. (2019) also mentioned a stronger correlation between the AD index and sea ice area over the Pacific sector (70–80°N, 120°W–120°E) since 1999 than before. The increase of sea ice melting related to AD in the Pacific sector is also illustrated in Figure 1c,d, which show regression maps of June to September (JJAS)-averaged SIC anomalies against the JJA AD index. In contrast to P1 results, the SIC anomaly during P2 exhibited more pronounced declines for positive-AD summers, consistent with the results of Bi et al. (2019).

Meanwhile, the relationship of the Atlantic sector with the AD differed between P1 and P2, contrary to the Pacific sector. In contrast to the negative anomalies over the Pacific sector during positive-AD summers in P1, the sea ice over the Barents–Kara Seas (red box) increased (Figure 1c). The positive-SIC anomaly in P1 stems from the transpolar drift that flushes sea ice out of the central Arctic and Pacific sectors into Greenland and the Barents Seas during the positive phase of the AD (Watanabe et al., 2006; Wu et al., 2006; Bi et al., 2019). The PI experiments also revealed consistent features for the NEG periods (Figure 1e). Significant increases in sea ice were observed over the Atlantic sector, while declines were observed over coastal regions of the Pacific sector, such as the Beaufort and East Siberian Seas. In contrast, during the P2 observational period (Figure 1d), the positive anomaly over the Barents–Kara Seas largely disappeared. This may reflect the influence of global warming and increased oceanic heat transport through Atlantic inflow that facilitate earlier development of open water, favouring easier export of sea ice through the Fram Strait during positive-AD summers (Árthun et al., 2012; Smedsrud et al., 2013; Stroeve et al., 2014). However, anthropogenic forcing may not be the only cause of the reversed sea ice anomaly because the decadal phase shift of the AD presumably contributes to the change. The POS periods in the PI experiments also showed consistent changes over the Barents–Kara Seas in comparison to the NEG periods (Figure 1f), showing a pronounced turning point from positive to negative sea ice anomalies. The results suggest that the strengthened influence of the AD in P2, observed in the increased correlation with SIE between P1 and P2, may be partly accounted for by the weakened sea ice increase over the Atlantic sector during the positive-AD decades, in conjunction with the enhanced decrease in sea ice over the Pacific sector.
Notably, the decline in sea ice over the Pacific sector in POS periods was not as pronounced as that in observational P1. The sea ice over the central Arctic Ocean (north of 80°N) also showed different patterns between PI and observation. These discrepancies may allude to the prevailing influence of long-term internal variability over the Atlantic sector, while the anthropogenic contribution is more dominant over the Pacific sector than over the Atlantic sector. Different sea ice climatology and spatial structure of the AD would also affect the difference between the observation and PI results.

We then focused on the autumn season to assess how the recovery of sea ice is altered by the summertime AD. While the observed decrease in sea ice attributable to the AD was the greatest over the Pacific during summer, the sea ice anomaly during late autumn (October–November) was marked over the Atlantic sector (Figure 2). During the observational P1 and simulated

![Regression maps of sea ice concentration (SIC) anomalies during October-November (ON) against AD index (shading) from observational data for (a) 1979–1998 (P1) and (b) 1999–2017 (P2). Equivalent regression maps obtained through PI experiments of CESM1 for (c) NEG and (d) POS periods. The box indicates the Barents–Kara Sea region (70–85°N, 20–80°E), as in Figure 1. The units of the regression maps are percentile, and the hatched region indicates significance at the 90% (observation) and 95% (model) confidence levels.](https://wileyonlinelibrary.com)
NEG periods (Figure 2a,c), positive sea ice anomalies were found over the Atlantic sector, as shown in Figure 1. During the P2 and POS periods (Figure 2b,d), in contrast, the sign was reversed, and significant negative anomalies became dominant over the Kara Sea. Notably, a wide range of negative sea ice anomalies over the Pacific sector observed in the preceding month recovered rapidly in late autumn, but this recovery was markedly slower in the Atlantic sector. Considering the importance of late autumn sea ice conditions for the mid-latitude cold season weather (Kim et al., 2014; Sung et al., 2016), this distinct recovery pattern of the sea ice and the precursory AD conditions deserve attention. The delayed recovery over the Atlantic sector is related to the intrinsic characteristics of sea ice, such as mean thickness and age (Kay et al., 2008; Stroeve et al., 2012; Stroeve and Notz, 2018). Sea ice over the Barents–Kara Seas is younger and thinner than that of the Pacific sector, and therefore, it tends to melt easily, while freezing begins later because of the contiguous Atlantic Ocean. It appears that the positive decadal shift in the AD enhances the vulnerability of sea ice to warming by hindering the thickening of the ice and subsequently facilitating melting in the following summer.

The factors that caused these changes over the Atlantic sector between P1 and P2 remain to be determined. Thus, we thoroughly investigated the summertime thermodynamic processes covariant with the AD, represented by the net surface heat flux \(Q_{\text{net}}\); sum of net shortwave radiation (SW), net longwave radiation (LW), latent heat flux (LH), sensible heat flux (SH)), and atmospheric temperature advection \((-\vec{V} \cdot \nabla T)\). A positive value of \(Q_{\text{net}}\) denotes a direction of atmosphere-ocean. Quantitative changes between P1 and P2 were examined with the differences in the regression coefficients against the AD index for each period, which revealed the changes in AD-related thermodynamic processes (Figure 3a,b). In the Atlantic sector (red box in Figure 3a), AD-related \(Q_{\text{net}}\) increased between P1 and P2, especially over the area where the AD-related sea ice anomaly showed distinct changes (see Figure 1). Specifically, SW anomalies showed the largest change among the variables over the Atlantic sector, implying the crucial role of surface albedo feedback in the changes in sea ice (see Figure S1). This result contrasts the features observed over the Beaufort Sea and the ocean to the north of Greenland, wherein pronounced increases in LW were exhibited along with an increase in SW associated with the decadal phase shift of AD, consistent with the results of Ding et al. (2017).

Temperature advection exhibited positive anomalies over the area of the negative sea ice anomalies, similar to the trends in \(Q_{\text{net}}\) (Figure 3b). We also obtained similar results for temperature advection, and \(Q_{\text{net}}\) over the Atlantic sector increased during POS periods (Figure S2). These findings suggest that the distinct relationships between the AD and sea ice over the Atlantic sector by decade have resulted from altered feedback processes due to radiative and thermodynamic changes. The results of PI experiments support the role of temperature advection in altering the influence of the AD on the autumn season (ON) sea ice, as shown in Figure 3d, in which scattered points denote temperature advection related to the summer (JJA) AD index over the Atlantic sector (70°–85°N, 20°–80°E; boxed area in Figure 3b). Each value was computed for a 19-year moving window, corresponding to the P1/P2 observational periods. Noticeably, negative sea ice anomalies corresponding to the AD tended to be accompanied by warm atmospheric advection, as can be inferred from an overall linear distribution of regression coefficients \(r = −0.48\), significant at the 99% confidence level). These results demonstrate how the decadal phase shift of the AD reduces sea ice over the Atlantic sector, as observed in Figure 3c \(r = −0.46\), significant at the 99% confidence level), though previous studies have focused more on the radiative effect or influence of sea ice export than on the role of temperature advection (Wu et al., 2006; Hegyi and Taylor, 2017; Choi et al., 2019).

The altered temperature advection that changed between P1 and P2 stemmed largely from the warming in the background climate conditions. Figure 3e shows the climatological mean differences in the summertime air temperature at 925 hPa between P1 and P2 (P2 – P1). Overall warming was observed within the Arctic, but the strongest warming was found near the dateline over the Pacific sector, which can change the contiguous horizontal temperature gradient. As the atmospheric temperature during summer was horizontally homogeneous in the Arctic, the decadal change could be substantial for the temperature advection corresponding to the cross-Arctic wind accompanied by the AD. Indeed, the difference in temperature advection patterns between periods P1 and P2, as seen in Figure 3b, was primarily due to the differential warming in the background temperature field \((-\vec{V} \cdot \nabla T)\); see Figure S3). This result is consistent with those of Serreze et al. (2011), which showed that considerable changes in temperature by northerly and easterly wind advection over the Kara Sea became influential after 2000, which was concurrent with the mean change. Likewise, the PI experiments (Figure 3f) results showed that during positive-AD decades, Arctic temperatures tended to rise primarily over the Pacific sector. Therefore, the intense warming in the Pacific sector observed during P2 was inferred to be a result of the combined influence of global warming and the decadal shift of the AD.
4 | SUMMARY AND DISCUSSIONS

In this study, we examined decadal phase shift of summertime AD and its influence on the Arctic SIE, mainly focusing on the Atlantic sector. Before 1999, that is, the negative-AD decades, the SIE over the Pacific sector decreased under positive seasonal AD conditions, while SIE over the Atlantic sector increased. However, after
1999, that is, the positive-AD decades, the same atmospheric circulation of the AD reduced the SIE in both sectors. This reversed sign of the sea ice response to the AD over the Atlantic sector contributed to an increase in the correlation between AD and SIE, indicating a strengthened influence of the AD on sea ice during the past few decades. The altered influence of the AD could be due to the net surface heat flux and atmospheric temperature advection. When the decadal phase of the AD shifts negative-to-positive, it changes the thermal distribution of the mean temperature within the Arctic, consequently altering the seasonal effect of temperature advection accompanied by the AD, particularly over the Atlantic sector. Ice-albedo feedback would then act to amplify the response. These distinct thermodynamic processes according to the decadal condition of the AD are similarly found in CESM1 Pre-Industrial experiment, suggesting that recent changes in the AD and intensified sea ice response are, to some extent, attributable to the internal variability.

Although we focused on the negative-to-positive phase shift of the AD within an observational period beginning in 1979, one may wonder if such a phase shift of the AD had occurred due to global warming. To address this, long-term observations and future global warming scenario experiments were analysed. A long-term observational AD index beginning in 1948 showed a positive-to-negative phase shift in the 1960s (dotted line in Figure 4a), implying that recurrent positive-AD summers in the recent decade should not be simply interpreted as being global warming-induced but likely explained by internal variability. Furthermore, CESM1 LE simulations revealed a pronounced negative trend of the AD as global warming proceeded (Figure 4b). Although future changes using model experiments should be predicted with caution, the negative trend of the AD produced in CESM1 is noteworthy because its spatial structure and decadal variability are markedly consistent with the observations, as shown in Figure 1. Furthermore, Cai et al. (2018) showed a negative trend of AD in the RCP8.5 scenario using a multi-model ensemble from Phase 5 of the Coupled Model Intercomparison Project (CMIP5). These results suggest that the recent positive phase shift of the AD is likely to be ascribed to natural variability, which may be associated with the Atlantic Multidecadal Oscillation or tropical Pacific sea surface temperature (SST) impact (Ding et al., 2014; Wettstein and Deser, 2014; Yu and Zhong, 2018; Castruccio et al., 2019).

However, the negative trend of the AD predicted in both LE and CMIP5 experiments suggests that the long-term variability of the AD can be modulated by anthropogenic influence as warming intensifies. Although we showed that the positive decadal shift of AD accelerated sea ice loss, its projected negative trend does not imply that sea ice reductions in the Arctic will slow down. As shown in Figure 2, sea ice recovery over the Atlantic sector has been delayed to late autumn in P2, accompanied by warming in the central Arctic, thereby increasing the vulnerability of the ice to warming (Kay et al., 2008; Stroeve et al., 2012). While the influence of positive seasonal AD conditions causes more severe melting over the Pacific sector than over the Atlantic sector, negative seasonal AD conditions tend to increase melting over the Atlantic sector. Therefore, the decadal shift of the AD towards the negative phase can increasingly accelerate sea ice reductions in the Atlantic sector. This implies that the current aspect of sea ice decline may be substantially altered as global warming continues.
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REFERENCES
Árthun, M., Eldevik, T., Smedsrud, L.H., Skagseth, Ø. and Ingvaldsen, R.B. (2012) Quantifying the influence of Atlantic heat on barents sea ice variability and retreat. Journal of Climate, 25, 4736–4743. https://doi.org/10.1175/JCLI-D-11-00466.1.
Bi, H., Yang, Q., Liang, X., Zhang, L., Wang, Y., Liang, Y. and Huang, H. (2019) Contributions of advection and melting processes to the decline in sea ice in the Pacific sector of the Arctic Ocean. Cryosphere, 13, 1423–1439. https://doi.org/10.5194/tc-13-1423-2019.
Blanchard-Wrigglesworth, E., Bitz, C.M. and Holland, M.M. (2011) Influence of initial conditions and climate forcing on predicting Arctic sea ice. Geophysical Research Letters, 38(18), L18503. https://doi.org/10.1029/2011GL048807.
Cai, L., Alexeev, V.A., Walsh, J.E. and Bhatt, U.S. (2018) Patterns, impacts, and future projections of summer variability in the arctic from CMIP5 models. Journal of Climate, 31, 9815–9833. https://doi.org/10.1175/JCLI-D-18-0119.1.
Castruccio, F.S., Ruprich-Robert, Y., Yeager, S.G., Danabasoglu, G., Msadek, R. and Delworth, T.L. (2019) Modulation of Arctic Sea ice loss by atmospheric teleconnections from Atlantic multidecadal variability. Journal of Climate, 32, 1419–1441. https://doi.org/10.1175/JCLI-D-18-0307.1.
Choi, N., Kim, K.M., Lim, Y.K. and Lee, M.I. (2019) Decadal changes in the leading patterns of sea level pressure in the Arctic and their impacts on the sea ice variability in boreal summer. Cryosphere, 13, 3007–3021. https://doi.org/10.5194/tc-13-3007-2019.
Comiso, J.C., Parkinson, C.L., Gersten, R. and Stock, L. (2008) Accelerated decline in the Arctic sea ice cover. Geophysical Research Letters, 35, L01703. https://doi.org/10.1029/2007GL031972.
Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balseleda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Holm, E. V., Isaksen, L., Källberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.J., Park, B.K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.N. and Vitart, F. (2011) The ERA-interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137, 553–597. https://doi.org/10.1002/qj.828.
Deser, C., Walsh, J.E. and Timlin, M.S. (2000) Arctic sea ice variability in the context of recent atmospheric circulation trends. Journal of Climate, 13, 617–633. https://doi.org/10.1175/1520-0442(2000)013<0617:ASIVIT>2.0.CO;2.
Ding, Q., Schweiger, A., L’Heureux, M., Battisti, D.S., Poreda, S., Johnson, N.C., Blanchard-Wrigglesworth, E., Harms, K., Zhang, Q., Eastman, R. and Steig, E.J. (2017) Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. Nature Climate Change, 7, 289–295. https://doi.org/10.1038/nclimate3241.
Ding, Q., Wallace, J.M., Battisti, D.S., Steig, E.J., Gallant, A.I.E., Kim, H.J. and Geng, L. (2014) Tropical forcing of the recent rapid Arctic warming in northeastern Canada and Greenland. Nature, 509, 209–212. https://doi.org/10.1038/nature13260.
Duarte, C.M., Lenton, T.M., Wadhams, P. and Wassmann, P. (2012) Abrupt climate change in the Arctic. Nature Climate Change, 2, 60. https://doi.org/10.1038/nclimate1386.
Fetterer, F., Knowles, K., Meier, W., Savoie, M., and Windnagel, A. (2017) Sea Ice Index, Version 2. Boulder, CO: National Snow and Ice Data Center. doi: https://doi.org/10.7265/N5736NV7.
Hegyi, B.M. and Taylor, P.C. (2017) The regional influence of the Arctic oscillation and Arctic dipole on the wintertime Arctic surface radiation budget and sea ice growth. Geophysical Research Letters, 44, 4341–4350. https://doi.org/10.1002/2017GL073281.
Jakobson, E., Vihma, T., Palo, T., Jakobson, L., Keernik, H. and Jaagus, J. (2012) Validation of atmospheric reanalyses over the central Arctic Ocean. Geophysical Research Letters, 39(10), L10802. https://doi.org/10.1029/2012GL051591.
Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R. and Joseph, D. (1996) The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society, 77, 437–471.
Kapsch, M.L., Graversen, R.G. and Tjernström, M. (2013) Spring-time atmospheric energy transport and the control of Arctic summer sea-ice extent. Nature Climate Change, 3, 744–748. https://doi.org/10.1038/nclimate1884.
Kay, J.E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J.M., Bates, S.C., Danabasoglu, G., Edwards, J., Holland, M., Kushner, P., Lamarque, J.F., Lawrence, D., Lindsay, K., Middleton, A., Munoz, E., Neale, R., Oleson, K., Polvani, L. and Vertenstein, M. (2015) The community earth system model (CESM) large ensemble project: a community resource for studying climate change in the presence of internal climate variability. Bulletin of the American Meteorological Society, 96, 1333–1349. https://doi.org/10.1175/BAMS-D-13-00255.1.
Kay, J.E., L’Ecuyer, T., Gettelman, A., Stephens, G., O’Dell, C. (2008) The contribution of cloud and radiation anomalies to the 2007 Arctic sea ice extent minimum. Geophysical Research Letters, 35(8). http://dx.doi.org/10.1029/2008gl034351.

Kim, B.M., Son, S.W., Min, S.K., Jeong, J.H., Kim, S.J., Zhang, X., Shim, T. and Yoon, J.H. (2014) Weakening of the stratospheric polar vortex by Arctic Sea-ice loss. Nature Communications, 5, 4646. https://doi.org/10.1038/ncomms5646.

Lindsay, R., Wensnahan, M., Schweiger, A. and Zhang, J. (2014) Evaluation of seven different atmospheric reanalysis products in the arctic. Journal of Climate, 27, 2588–2606. https://doi.org/10.1175/JCLI-D-13-00014.1.

Maslanik, J., Drobot, S., Fowler, C., Emery, W. and Barry, R. (2007a) On the Arctic climate paradox and the continuing role of atmospheric circulation in affecting sea ice conditions. Geophysical Research Letters, 34, 10.1029/2006GL028269.

Maslanik, J.A., et al. (2007b) A younger, thinner Arctic ice cover: increased potential for rapid, extensive sea-ice loss. Geophysical Research Letters, 34, L24501. https://doi.org/10.1029/2007GL032043.

Ogi, M. and Wallace, J.M. (2007) Summer minimum Arctic Sea ice extent and the associated summer atmospheric circulation. Geophysical Research Letters, 34, L12705. https://doi.org/10.1029/2007GL029897.

Ogi, M., Yamazaki, K. and Wallace, J.M. (2010) Influence of winter and summer surface wind anomalies on summer Arctic Sea ice extent. Geophysical Research Letters, 37(7), L07701. https://doi.org/10.1029/2009GL042356.

Ogi, M., et al. (2008) Summer retreat of Arctic Sea ice: role of summer winds. Geophysical Research Letters, 35, L24701. https://doi.org/10.1029/2008GL035672.

Overland, J.E., Francis, J.A., Hanna, E. and Wang, M. (2012) The recent shift in early summer Arctic atmospheric circulation. Geophysical Research Letters, 39, L19804. https://doi.org/10.1029/2012GL053268.

Overland, J.E. and Wang, M. (2010) Large-scale atmospheric circulation changes are associated with the recent loss of Arctic Sea ice. Tellus, Series A: Dynamic Meteorology and Oceanography, 62, 1–9. https://doi.org/10.1111/j.1600-0870.2009.00421.x.

Paternoster, R., et al. (1998) Using the correct statistical test for the equality of regression coefficients. Criminology, 36, 859–866. https://doi.org/10.1111/j.1745-9125.1998.tb01268.x.

Peng, G., et al. (2013) A long-term and reproducible passive microwave sea ice concentration data record for climate studies and monitoring. Earth System Science Data, 5, 311–318. https://doi.org/10.5194/essd-5-311-2013.

Peralta-Ferriz, C. and Woodgate, R.A. (2017) The dominant role of the east Siberian Sea in driving the oceanic flow through the Bering Strait—conclusions from GRACE Ocean mass satellite data and in situ mooring observations between 2002 and 2016. Geophysical Research Letters, 44, 11472–11481. https://doi.org/10.1002/2017GL075179.

Serreze, M.C., Barrett, A.P. and Cassano, J.J. (2011) Circulation and surface controls on the lower tropospheric air temperature field of the Arctic. Journal of Geophysical Research Atmospheres, 116, D07104. https://doi.org/10.1029/2010JD015127.

Serreze, M.C., Barrett, A.P., Crawford, A.D., Woodgate, R.A. (2019) Monthly Variability in Bering Strait Oceanic Volume and Heat Transports, Links to Atmospheric Circulation and Ocean Temperature, and Implications for Sea Ice Conditions. Journal of Geophysical Research: Oceans, 124(12), 9317–9337. http://dx.doi.org/10.1029/2019jc015422.

Smelth, L.H., Essai, I., Ingvaldsen, R.B., Eldevik, T., Haugan, P. M., Li, C., Lien, V.S., Olsen, A., Omar, A.M., Otterå, O.H., Risebrobakken, B., Sando, A.B., Semenov, V.A. and Sorokina, S.A. (2013) The role of the Barents Sea in the Arctic climate system. Reviews of Geophysics, 51, 415–449. https://doi.org/10.1002/rog.20017.

Smelth, L.H., Halvorsen, M.H., Stroeve, J.C., Zhang, R. and Kloster, K. (2017) Fram Strait sea ice export variability and September Arctic sea ice extent over the last 80 years. Cryosphere, 11, 65–79. https://doi.org/10.5194/tc-11-65-2017.

Stroeve, J. and Notz, D. (2018) Changing state of Arctic Sea ice across all seasons. Environmental Research Letters, 13, 103001. https://doi.org/10.1088/1748-9326/aae56.

Stroeve, J., et al. (2007) Arctic Sea ice decline: faster than forecast. Geophysical Research Letters, 34, L09501. https://doi.org/10.1029/2007GL029703.

Stroeve, J.C., Markus, T., Boisvert, L., Miller, J. and Barrett, A. (2014) Changes in Arctic melt season and implications for sea ice loss. Geophysical Research Letters, 41, 1216–1225. https://doi.org/10.1002/2013GL058951.

Stroeve, J.C., Serreze, M.C., Holland, M.M., Kay, J.E., Malanik, J. and Barrett, A.P. (2012) The Arctic’s rapidly shrinking sea ice cover: a research synthesis. Climatic Change, 110(3–4), 1005–1027. https://doi.org/10.1007/s10584-011-0101-1.

Sung, M.K., Kim, B.M., Baek, E.H., Lim, Y.K. and Kim, S.J. (2016) Arctic-North Pacific coupled impacts on the late autumn cold in North America. Environmental Research Letters, 11, 084016. https://doi.org/10.1088/1748-9326/11/8/084016.

Wang, J., Zhang, J., Watanabe, E., Ikeda, M., Mizobata, K., Walsh, J.E., Bai, X. and Wu, B. (2009) Is the dipole anomaly a major driver to record lows in arctic summer sea ice extent? Geophysical Research Letters, 36(5), L05706. https://doi.org/10.1029/2008GL036706.

Watanabe, E., Wang, J., Sumi, A. and Hasumi, H. (2006) Arctic dipole anomaly and its contribution to sea ice export from the Arctic Ocean in the 20th century. Geophysical Research Letters, 33, L23703. https://doi.org/10.1029/2006GL028112.

Wei, J., Zhang, X. and Wang, Z. (2019) Reexamination of Fram Strait sea ice export and its role in recently accelerated Arctic Sea ice retreat. Climate Dynamics, 53, 1823–1841. https://doi.org/10.1007/s00382-019-04741-0.

Wettstein, J.J. and Deser, C. (2014) Internal variability in projections of twenty-first-century Arctic sea ice loss: role of the large-scale atmospheric circulation. Journal of Climate, 27, 527–550. https://doi.org/10.1175/JCLI-D-12-00839.1.

Wu, B., Wang, J. and Walsh, J.E. (2006) Dipole anomaly in the winter Arctic atmosphere and its association with sea ice motion. Journal of Climate, 19, 210–225. https://doi.org/10.1175/JCLI3619.1.

Yu, L. and Zhong, S. (2018) Changes in sea-surface temperature and atmospheric circulation patterns associated with reductions in Arctic Sea ice cover in recent decades. Atmospheric Chemistry and Physics, 18, 14149–14159. https://doi.org/10.5194/acp-18-14149-2018.

Zhang, X., Sroteberg, A., Zhang, J., Gerdes, R. and Comiso, J.C. (2008) Recent radical shifts of atmospheric circulations and
rapid changes in Arctic climate system. *Geophysical Research Letters*, 35, L22701. https://doi.org/10.1029/2008GL035607.

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