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Research Article

Keywords: Longwave cloud radiative effect, Arctic–Eurasian teleconnection, Barents–Kara Sea sea ice, Ural Mountains

Posted Date: September 28th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10973082/v1>

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Role of Winter Surface Longwave Cloud Radiative Effect over the Ural Mountains in the Arctic–Eurasian Teleconnection

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Abstract. Using ERA5 reanalysis data and sea ice sensitivity experiments, this study investigates the interannual variability of the winter surface longwave cloud radiative effect (LWCRE) and its role in Arctic–Eurasian climate variability. The leading mode of winter LWCRE variability exhibits pronounced anomalies over the Ural Mountains. Its associated circulation anomalies are closely related to the Arctic Oscillation (AO) and enhanced high-latitude anticyclonic circulation over Eurasia, accompanied by a Greenland warming–northern Eurasian cooling dipole. Negative LWCRE anomalies over the Urals are associated with enhanced surface radiative cooling and precede the development of regional anticyclonic circulation, accompanied by an eastward-propagating Rossby wave train and southward cold-air intrusion into northern Eurasia and downstream East Asia. The leading mode is significantly associated with autumn Barents–Kara Sea (BKS) sea ice anomalies, suggesting a potential modulating influence of sea ice on the LWCRE-related climate response. Atmospheric Model Intercomparison Project (AMIP) simulations and Community Atmosphere Model version 5 (CAM5) sensitivity experiments further support this modulation, showing that reduced autumn BKS sea ice enhances the LWCRE-related atmospheric circulation anomalies and northern Eurasian cooling. Prescribed BKS sea ice loss in CAM5 increases the regional-mean cooling by approximately 17% without fundamentally altering the dominant circulation pattern, indicating that autumn BKS sea ice acts primarily as a secondary modulator of LWCRE-related Arctic–Eurasian climate variability.

Keywords: Longwave cloud radiative effect, Arctic–Eurasian teleconnection, Barents–Kara Sea sea ice, Ural Mountains

1. Introduction

Rapid Arctic warming over recent decades has profoundly altered the Arctic climate system and has raised considerable interest in its potential impacts on midlatitude weather and climate. The Arctic has warmed at a rate substantially faster than the global mean, a phenomenon commonly referred to as Arctic amplification (AA) (Screen and Simmonds 2010; Serreze and Barry 2011; Goosse et al. 2018; Rantanen et al. 2022). Meanwhile, despite the continuous increase in global mean temperature, Eurasia has experienced recurrent winter cold extremes, including persistent cold spells, heavy snowfall events, and severe low-temperature anomalies (Thompson and Wallace 1998; Mori et al. 2014; Cohen et al. 2014; Gao et al. 2015; Cohen et al. 2020; Zhang et al. 2022; Ku et al. 2025). This apparent contrast between a warming Arctic and episodic Eurasian winter cooling has motivated extensive investigations into the mechanisms linking Arctic changes to midlatitude climate variability.

Among various Arctic processes, rapid sea ice decline has been considered an important factor in Arctic–midlatitude climate connections. In particular, reduced sea ice over the BKS has received considerable attention because of its close relationship with Eurasian winter climate anomalies (Screen 2017; Cosford et al. 2025). Observational studies have suggested that autumn and early winter sea ice loss in the BKS region can enhance local warming, weaken the meridional temperature gradient, and favor large-scale atmospheric circulation anomalies associated with Eurasian cold extremes (Honda et al. 2009; Francis et al. 2009; Screen 2017). However, the extent to which Arctic sea ice loss directly contributes to Eurasian winter cooling remains highly debated. Several modeling studies have indicated that the atmospheric response to sea ice forcing is sensitive to the magnitude, location, and temporal evolution of sea ice anomalies, resulting in substantial uncertainty in the simulated midlatitude response (Rinke et al. 2013; Pedersen et al. 2016; Ding et al. 2021; Ding and Wu 2021). Moreover, large-ensemble and numerical sensitivity experiments have suggested that Eurasian winter cooling events are often dominated by atmospheric internal variability, whereas the contribution of sea ice loss may be relatively weak (Chen et al. 2016; McCusker et al. 2016; Koenigk et al. 2019). For example, Blackport et al. (2019) argued that atmospheric circulation anomalies can simultaneously contribute to Arctic sea ice loss and Eurasian cold anomalies, challenging the interpretation that sea ice decline is the primary driver of midlatitude cooling. These studies indicate that the mechanisms responsible for Eurasian winter cooling remain unresolved, particularly regarding the relative roles of external Arctic forcing and internally generated atmospheric variability.

Regardless of the origin of Arctic anomalies, atmospheric circulation provides a critical bridge connecting Arctic variability with Eurasian climate responses. Previous studies have emphasized the role of the Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and associated planetary-scale wave patterns in mediating Arctic–midlatitude interactions. Negative AO/NAO conditions are often accompanied by weakened westerly flow, enhanced meridional exchange, and increased southward transport of Arctic air masses into Eurasia (Honda et al. 2009; Cohen et al. 2014; Nakamura et al. 2019). Among these circulation features, Ural blocking has been identified as a particularly important pathway contributing to persistent Eurasian cold anomalies. Anomalous anticyclonic circulation over the Ural region can induce downstream trough development over eastern Eurasia, enhancing northerly cold-air advection and promoting severe winter cooling events (Petoukhov et al. 2013; Kug et al. 2015). Recent studies have further highlighted the importance of stratosphere–troposphere coupling and planetary wave propagation in regulating the persistence of Eurasian winter climate anomalies. Changes in Arctic conditions may influence the upward propagation of planetary waves, stratospheric polar vortex variability, and subsequent tropospheric circulation responses, thereby affecting the persistence of cold extremes (Cohen et al. 2021; Kretschmer et al. 2020). Although substantial progress has been made in understanding the dynamical pathways connecting Arctic anomalies to Eurasian climate, the radiative processes that may modulate these circulation responses remain insufficiently explored.

While previous studies have primarily focused on the dynamical impacts of Arctic sea ice variability, considerably less attention has been paid to the role of cloud radiative processes in Arctic–midlatitude climate interactions. Clouds influence Earth’s radiation budget by reflecting incoming solar radiation and trapping outgoing longwave radiation, thereby exerting both shortwave and longwave cloud radiative effects (Ramanathan et al. 1989). Under Arctic winter conditions, however, the absence of incoming solar radiation makes the longwave cloud radiative effect (LWCRE) the dominant cloud-radiative process in the surface energy budget. Extensive low-level clouds are frequently embedded within strong temperature inversions during the polar night, substantially enhancing downward longwave radiation and suppressing surface radiative cooling (Shupe and Intrieri 2004; Curry et al. 1996; Wendisch et al. 2019). Consequently, LWCRE is regarded as an important contributor to winter Arctic amplification (Graversen and Wang 2009; Palm et al. 2010). Variations in LWCRE can therefore modify surface radiative cooling and lower-tropospheric thermal conditions, which may interact with regional atmospheric circulation and large-scale planetary wave activity. Such radiative–

dynamical coupling provides a potential pathway through which regional LWCRE variability may be linked to downstream climate anomalies over Eurasia. Nevertheless, whether and how interannual LWCRE variability is involved in such Arctic–midlatitude climate linkages, and how this variability interacts with Arctic sea ice to influence Eurasian winter climate, remain largely unexplored.

In this study, we investigate the role of winter surface LWCRE variability in Arctic–Eurasian climate interactions using ERA5 reanalysis and numerical experiments. We first characterize the dominant mode of winter LWCRE variability and examine its associated moisture, cloud, and radiative processes. We then investigate the corresponding atmospheric circulation and planetary wave anomalies and their links to Eurasian winter climate variability. Finally, we assess the relationship between LWCRE variability and autumn Barents–Kara Sea sea ice variability and examine their respective roles in Eurasian winter cooling, with particular emphasis on the potential modulating role of autumn BKS sea ice.

2. Data and Methods

2.1 Data and model experiments

The meteorological fields used in this study are obtained from the ERA5 reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The analyzed variables include surface net longwave radiative fluxes under all-sky and clear-sky conditions, total cloud cover, 2-m air temperature, sea-level pressure, precipitation, geopotential height, zonal wind, meridional wind, and specific humidity at multiple pressure levels. All variables are interpolated onto a common horizontal grid with a resolution of $2.5^{\circ} \times 2.5^{\circ}$. Sea ice concentration (SIC) data are obtained from the Hadley Centre sea ice dataset at a horizontal resolution of $1^{\circ} \times 1^{\circ}$. The analysis period spans 45 winters from 1979/80 to 2023/24. Boreal winter is defined as December–February (DJF), with the winter year referring to the calendar year of December, whereas autumn is defined as September–November (SON).

The Coupled Model Intercomparison Project Phase 6 (CMIP6) Atmospheric Model Intercomparison Project (AMIP) simulations are analyzed to assess the robustness of the observed relationships. The AMIP simulations cover the period 1979–2014. Given the different native horizontal resolutions among the models, all model outputs are bilinearly interpolated onto a common $2.5^{\circ} \times 2.5^{\circ}$ grid consistent with the observational analysis. The analyzed monthly mean variables include surface downward longwave radiative fluxes under all-sky and clear-

sky conditions, 2-m air temperature, sea-level pressure, geopotential height, and zonal and meridional winds. In total, 21 AMIP models are included, with two ensemble members from each model, namely r1i1p1f1 and r2i1p1f1.

To further examine the atmospheric response to autumn BKS sea-ice loss, numerical experiments are conducted using the Community Earth System Model (CESM), with the Community Atmosphere Model version 5 (CAM5) as its atmospheric component. CAM5 is configured at a horizontal resolution of $1^\circ \times 1^\circ$ with 30 vertical levels. Two sets of experiments are performed: a control experiment and a sea-ice perturbation experiment. The control experiment is forced by climatological SIC and sea surface temperature (SST) under standard external forcing conditions and is integrated for 100 years, with the first 10 years discarded as model spin-up. In the sensitivity experiment, observed autumn BKS SIC anomalies are superimposed onto the climatological SIC field. To impose a pronounced sea-ice-loss signal, the composite SIC anomaly is constructed from years when the BKS sea-ice index is below -1σ . All other model configurations are identical between the two experiments. The atmospheric response to autumn BKS sea-ice loss is quantified as the difference between the sensitivity and control experiments.

2.2 Definition of surface LWCRE and climate indices

Surface longwave cloud radiative effect (LWCRE) is defined as the difference between the surface net longwave radiative flux under all-sky and clear-sky conditions, with downward radiative fluxes defined as positive:

Equation 1.

$$\text{LWCRE} = (\text{LW}_{\text{allsky_down}} - \text{LW}_{\text{allsky_up}}) - (\text{LW}_{\text{clrsky_down}} - \text{LW}_{\text{clrsky_up}})$$

Here, the all-sky terms represent surface longwave radiative fluxes under actual sky conditions, whereas the clear-sky terms represent the corresponding fluxes under clear-sky conditions. A positive LWCRE indicates a warming effect on the surface, whereas a negative LWCRE indicates a cooling effect.

Before EOF analysis, the linear trend in winter surface LWCRE is removed. A latitude-weighted empirical orthogonal function (EOF) analysis is then applied to the detrended winter LWCRE anomalies over the BKS–Urals sector (40° – 85°N , 20° – 100°E). The latitude weighting accounts for variations in grid-cell area with latitude. The leading two EOF modes and their

corresponding principal components (PCs) are retained to characterize the dominant modes of winter LWCRE variability. The PCs are standardized before subsequent regression, correlation, and composite analyses.

The Arctic Oscillation (AO) index is defined as the first principal component obtained from a rotated EOF analysis of winter 500-hPa geopotential height anomalies over the Northern Hemisphere north of 20°N. The standardized first principal component is used as the AO index to characterize the phase of the AO and its relationship with the leading mode of winter LWCRE variability.

A Eurasian temperature (ET) index is defined as the area-mean winter surface air temperature anomaly over 45°–70°N and 10°–130°E. The BKS sea-ice index is calculated as the area-mean SIC anomaly over the region bounded by 70°–83°N and 35°–100°E. All regional indices are standardized prior to correlation, regression, and composite analyses.

Winter cold days are defined as days when the daily minimum temperature falls below the local 10th-percentile threshold derived from winter daily temperatures. This index is used to characterize the frequency of extreme cold conditions associated with the leading LWCRE mode.

The horizontal propagation of quasi-stationary Rossby wave activity is diagnosed using the wave activity flux (WAF) formulation of Takaya and Nakamura (1997, 2001). The horizontal WAF is expressed as

Equation 2.

$$W = \frac{p}{2|\bar{U}|} \left(U(\psi_x'^2 - \psi' \psi_{xx}') + V(\psi_x' \psi_y' - \psi' \psi_{xy}') \right. \\ \left. U(\psi_x' \psi_y' - \psi' \psi_{xy}') + V(\psi_y'^2 - \psi' \psi_{yy}') \right)$$

where p denotes pressure normalized by 1000 hPa, $\bar{U} = (U, V)$ represents the background flow, and ψ denotes the stream function. The subscripts denote partial derivatives, and the primes denote perturbations from the monthly climatological state. The direction of the WAF is interpreted as the direction of Rossby wave activity propagation.

2.3 Statistical and composite analyses

Linear regression and correlation analyses are used to examine the statistical relationships between LWCRE variability and atmospheric, radiative, and surface climate variables. Unless

otherwise specified, the statistical significance of regression and correlation coefficients is assessed using a two-tailed Student's t-test.

Composite analysis is used to examine the dependence of LWCRE-related anomalies on the phase of PC1 and autumn BKS sea-ice conditions. Years are classified according to the standardized PC1, with positive and negative phases defined by PC1 values exceeding $+0.5\sigma$ and falling below -0.5σ , respectively. Within each phase, years are further divided into reduced-sea-ice years, defined by BKS sea-ice index values below -0.5σ , and near-normal sea-ice years, defined by values between -0.5σ and $+0.5\sigma$. Statistical significance of composite anomalies is assessed using a one-sample Student's t-test against zero.

A lead-lag correlation analysis is conducted to examine the temporal relationship between daily LWCRE and large-scale atmospheric circulation. Years with positive PC1 values exceeding $+0.5\sigma$ are selected for the analysis. The statistical significance of the lead-lag correlations is assessed using a block-bootstrap resampling procedure with 1,000 resamples and a block length of 20 days to account for temporal autocorrelation. Similar analyses are conducted using alternative PC1 thresholds of 1σ and 1.5σ to evaluate the robustness of the lagged relationship.

The statistical significance of the WAF is also assessed using a permutation-based Monte Carlo test with 1,000 permutations.

3. Results

3.1 Interannual variability of winter surface LWCRE

The climatological distribution of winter surface LWCRE exhibits three pronounced maxima over the North Atlantic, North Pacific, and East European Plain (Fig. 1(a)). In contrast, its standard deviation reveals that the largest interannual variability is concentrated over a coherent Eurasian region extending from the Barents and Kara Seas to the Urals (BKS-Urals) (Fig. 1(b)). This region is characterized by strong interactions among open ocean, seasonal sea-ice margins, and complex topography, which enhance lower-tropospheric baroclinicity and increase the sensitivity of atmospheric circulation to surface thermal perturbations (Petoukhov and Semenov 2010; Shi et al. 2022). Moreover, the BKS-Urals sector is located along a key pathway of Arctic-Eurasian atmospheric teleconnections, where local thermodynamic anomalies can interact with large-scale circulation through anticyclonic circulation anomalies and Rossby wave dynamics.

Although turbulent sensible and latent heat fluxes are traditionally considered dominant components of wintertime surface energy exchange (Vihma 2014), surface LWCRE represents an important radiative contribution over mid- and high-latitude Northern Hemisphere continents during winter (Gupta et al. 1993; Hu et al. 2018). This radiative contribution is particularly evident over the Urals, where the interannual variance of LWCRE substantially exceeds that of turbulent heat fluxes. Specifically, the LWCRE variance is approximately 2–16 times larger than that of sensible heat flux and 10–100 times larger than that of latent heat flux (Figs. 1(c), 1(d)), indicating that LWCRE represents a substantial component of interannual surface energy variability over the BKS–Urals region. Such pronounced radiative variability may influence regional thermal conditions and provide a potential thermodynamic pathway through which Arctic surface processes modulate Eurasian atmospheric circulation variability.

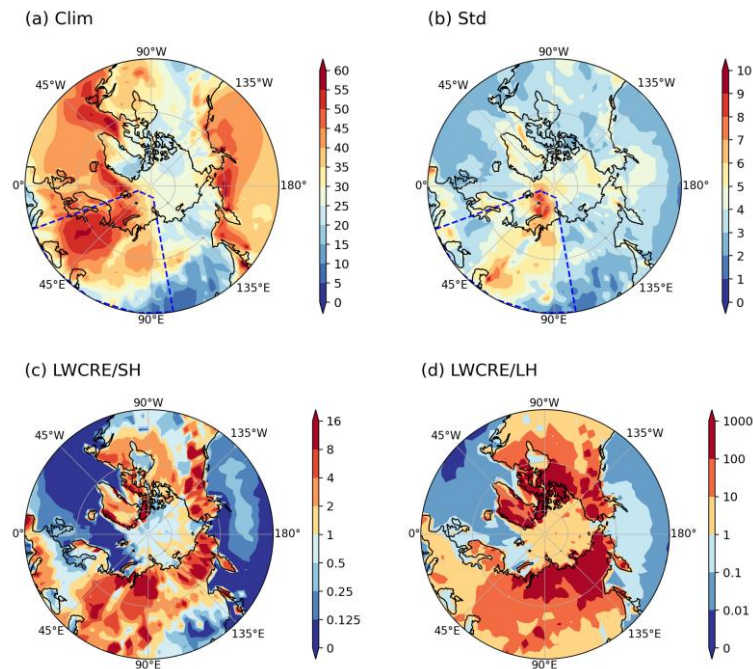


Figure 1. (a) Climatological means (units: $W m^{-2}$) and (b) standard deviations of winter surface LWCRE. The variance ratio between winter surface LWCRE and (c) sensible heat (SH) flux, and (d) latent heat (LH) flux.

EOF decomposition of detrended winter surface LWCRE anomalies in the BKS–Urals sector (40° – 85° N, 20° – 100° E) yields two leading modes that collectively explain 47.89% of the total variance (Figs. 2(a), 2(b), 2(c), 2(d)). The first EOF mode (EOF1) explains 31.90% of the variance, and its corresponding principal component (PC1) is dominated by interannual variability on timescales of approximately 3–8 years (not shown). Spatially, EOF1 exhibits pronounced LWCRE anomalies on both flanks of the Urals, representing a dominant interannual mode of Arctic–Eurasian radiative coupling. The second EOF mode (EOF2)

explains 15.99% of the variance, and its corresponding principal component (PC2) exhibits variability on a 3–5-year timescale (not shown). EOF2 is characterized by a meridional dipole structure, with opposite LWCRE variations between the high-latitude region north of 60°N (particularly east of Novaya Zemlya) and the lower-latitude region to the south. This mode also reflects an Arctic–midlatitude coupling pattern, but differs from EOF1 in its spatial structure and dominant timescale. Similar leading modes are obtained when the analysis is repeated using the non-detrended dataset. PC1 remains dominated by interannual variability, whereas PC2 exhibits a pronounced long-term trend, transitioning from a negative to a positive phase around 2004, suggesting that this mode contains a substantial low-frequency component associated with changes in the Arctic background state.

While both EOF modes are associated with a warm-Arctic–cold-Eurasia temperature configuration, their associated temperature patterns exhibit distinct spatial characteristics. During the positive phase of EOF1, warming (enhanced atmospheric thickness) is centered over Greenland, whereas cooling (reduced atmospheric thickness) dominates northern Eurasia (Fig. 2(e)). In contrast, the positive phase of EOF2 features an eastward displacement of Arctic warming toward the BKS and the northern Russian coast, accompanied by cooling extending southeastward into East Asian midlatitudes. This produces a “warm BKS–cold East Asia” pattern, consistent with the findings of Mori et al. (2014) (Fig. 2(f)).

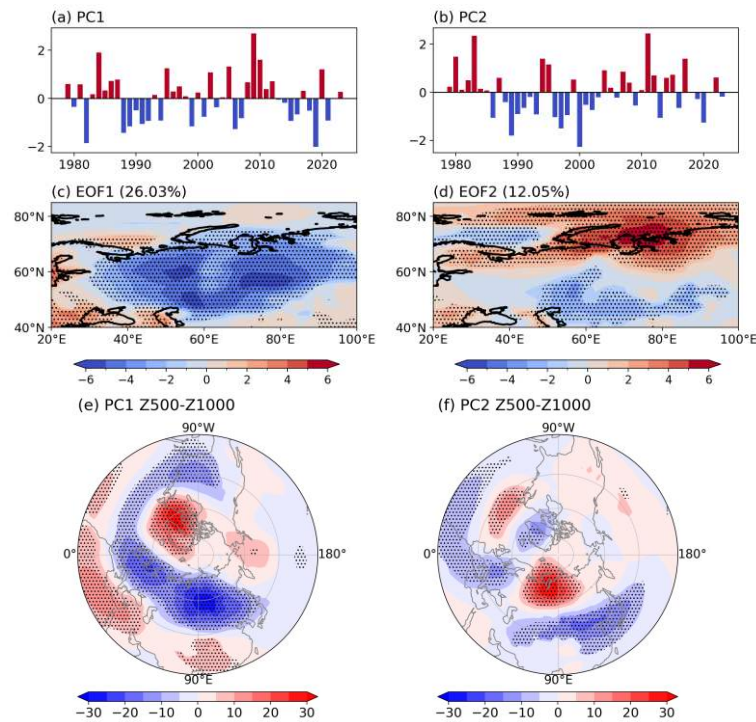
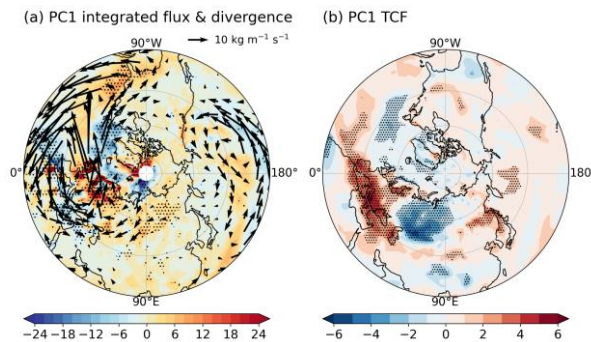


Figure 2. The two leading modes of detrended winter surface LWCRE (units: $W m^{-2}$) derived from EOF analysis. (a) Normalized PC1 time series. (b) Normalized PC2 time series. (c) Winter surface LWCRE

anomalies regressed onto the standardized PC1 (EOF1). (d) As in (c), but for PC2 (EOF2). (e), (f) As in (c), (d), but for 1000–500-hPa geopotential thickness anomalies (units: gpm). Stippled areas in (c), (d), (e), (f) indicate anomalies exceeding the 90% confidence level.

The spatial structures of LWCRE modes are closely associated with regional variations in atmospheric moisture transport and cloud radiative processes (Liu et al. 2025). During the positive phase of EOF1, anomalous moisture divergence over the Urals (Fig. 3(a)) is accompanied by reduced cloud cover (Fig. 3(b)) and decreased downward longwave radiation, consistent with the formation of negative LWCRE anomalies and surface cooling over northern Eurasia. These coupled moisture, cloud, and circulation anomalies indicate that EOF1 reflects a circulation-related radiative mode connecting Arctic conditions with Eurasian thermal anomalies. In contrast, during the positive phase of EOF2, enhanced moisture convergence occurs north of 60°N and east of Novaya Zemlya (Fig. 3(c)). The associated moisture transport favors increased cloudiness (Fig. 3(d)) and enhanced downward longwave radiation, contributing to positive LWCRE anomalies and surface warming over the high-latitude BKS region. Meanwhile, anomalous moisture divergence between 40° and 60°N suppresses cloud development and reduces LWCRE, resulting in surface cooling. The contrasting moisture–cloud–radiation anomalies between high and lower latitudes characterize EOF2 as another distinct Arctic–midlatitude coupling mode, with a spatial structure different from EOF1.

Given that EOF1 explains the largest proportion of the total variance, the subsequent analysis focuses on the atmospheric circulation and climate anomalies associated with the interannual variability of winter surface LWCRE over the Urals, aiming to clarify the role of this dominant LWCRE mode in modulating the Arctic–Eurasian climate linkage.



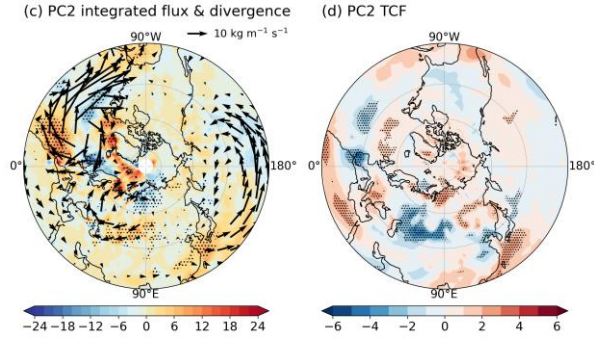


Fig. 3. Winter fields regressed onto PC1 (a–b) and PC2 (c–d): (a, c) vertically integrated moisture flux (arrows; units: $\text{kg m}^{-1} \text{s}^{-1}$) and its divergence (shading; units: $10^{-6} \text{kg m}^{-2} \text{s}^{-1}$); (b, d) total cloud cover (units: %). Stippling denotes anomalies significant at the 90% confidence level.

3.2 Dynamical pathway linking winter surface LWCRE variability to Eurasian climate anomalies

Figure 4 illustrates the atmospheric circulation and climate responses associated with EOF1. The positive phase of EOF1 is associated with negative LWCRE anomalies over the Urals, accompanied by anomalous anticyclonic circulation over the Arctic lower troposphere and anomalous cyclonic circulation over the midlatitude North Atlantic (Fig. 4(a)). This circulation response suggests a close association between regional radiative anomalies over the Urals and large-scale Arctic–midlatitude atmospheric variability. In the midtroposphere, the anticyclonic anomaly extends from the Barents Sea to the northern Urals and is associated with two downstream-propagating Rossby wave trains. One branch propagates southwestward toward the midlatitude North Atlantic, forming cyclonic anomalies that exhibit a quasi-barotropic structure and correspond well with the negative NAO-like circulation pattern. The other branch propagates southeastward toward Northeast Asia, producing cyclonic anomalies and deepening the East Asian trough, thereby providing a favorable circulation background for southward cold-air intrusion (Fig. 4(b)). This circulation pattern exhibits a pronounced AO-like structure, as further supported by the strong negative correlation between PC1 and the AO index ($r = -0.79, p < 0.01$).

Associated with the Arctic anticyclonic circulation, enhanced northerly flow over Eurasia strengthens the southward advection of Arctic cold air, leading to widespread surface cooling over northern Eurasia (Fig. 4(c)) and a significant increase in the frequency of extreme cold days (Fig. 4(d)). The strongest cooling exceeds 2.4 K over Siberia, a region previously identified as a key pathway for cold-air accumulation and subsequent cold surge development toward East Asia (Bueh et al. 2022; Zhang et al. 2025). Accordingly, the increase in extreme cold days extends southeastward toward the Yangtze River basin. Meanwhile, anomalous

anticyclonic circulation over Greenland is accompanied by southerly flow along its southwestern flank, resulting in pronounced Greenland warming (Fig. 4(a)). Together, these temperature anomalies form a characteristic Greenland warming–northern Eurasian cooling dipole associated with the leading LWCRE mode, highlighting the role of LWCRE variability as a potential radiative pathway through which Arctic processes modulate Arctic–Eurasian winter climate interactions.

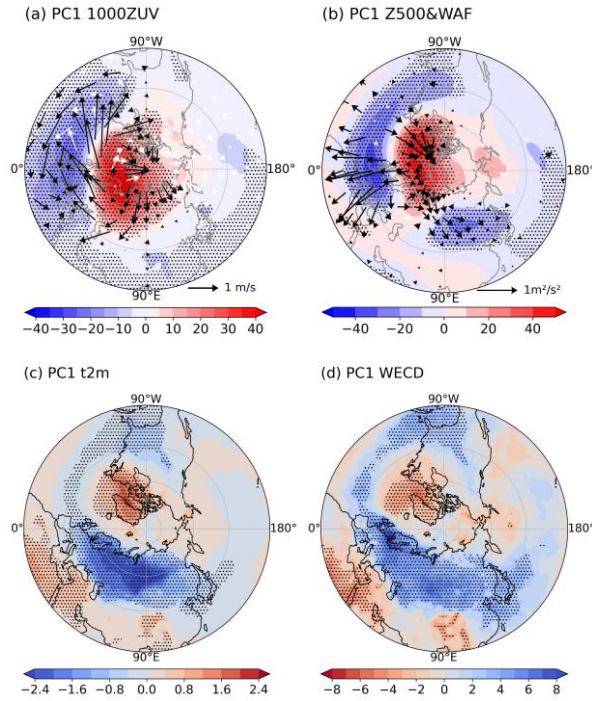


Fig. 4. Winter fields regressed onto PC1. (a) 1000 hPa geopotential height (shading; units: gpm) and horizontal wind (arrows; units: m s^{-1}). (b) 500 hPa geopotential height (shading; units: gpm) and TN wave activity flux (arrows; units: $\text{m}^2 \text{s}^{-2}$). (c) 2 m air temperature (units: K). (d) Cold-spell frequency. Stippling denotes anomalies significant at the 90% confidence level. In (a) and (b), black arrows indicate significance at the 90% confidence level, while white arrows indicate non-significance.

To further examine the temporal relationship between cloud radiative anomalies and large-scale circulation variability, we conducted a lead–lag analysis between the winter LWCRE index, defined as the standardized LWCRE anomalies averaged over the BKS–Urals region, and the geopotential height index, defined as the standardized geopotential height anomalies over the same region. Years with extreme positive PC1 values, corresponding to anomalously negative LWCRE over the Urals, were selected (Fig. 2(a)), and the correlations were calculated using a 0.5σ threshold. As shown in Fig. 5, negative correlations are evident when LWCRE anomalies lead geopotential height anomalies, with the strongest relationship occurring at lags of 8–10 days (red highlights). This result indicates that negative LWCRE anomalies tend to precede positive geopotential height anomalies over the BKS–Urals region on subseasonal timescales.

From a physical perspective, reduced cloud cover decreases downward longwave radiation and enhances surface radiative cooling, a process that is consistent with conditions favorable for the development or maintenance of anticyclonic circulation over the region. However, the lead–lag relationship does not by itself establish that LWCRE anomalies drive the subsequent circulation response, as both variables may be influenced by a common underlying atmospheric process. Similar results are obtained when alternative thresholds of 1σ and 1.5σ are used (not shown). Therefore, the lead–lag analysis provides evidence for a temporal precedence of LWCRE anomalies relative to the circulation response, while suggesting, rather than demonstrating, a potential role for LWCRE variability in modulating the evolution of regional anticyclonic circulation anomalies.

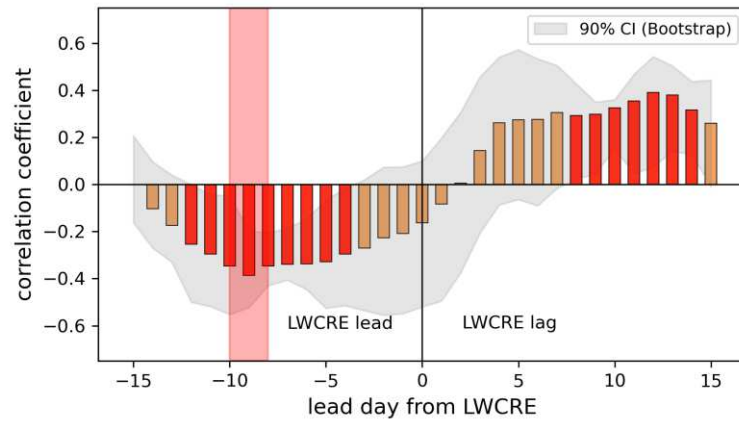


Fig. 5. Lagged correlation coefficients between the daily LWCRE index and the geopotential height index for winter. The bars denote Pearson correlations at each lag. The grey shaded envelope represents the 90% confidence interval obtained via block bootstrap. Lags where the envelope does not cross the zero line are statistically significant at the 90% level, and are highlighted with red bars.

To assess the statistical association of LWCRE-related variability with the atmospheric circulation and temperature anomalies over northern Eurasia, we first use the standardized ET index defined over 45° – 70° N and 10° – 130° E. Regression of atmospheric circulation and surface temperature anomalies onto the normalized ET index produces spatial patterns that closely resemble those associated with PC1 (Figs. 6(a), 6(b)), indicating that the ET index effectively captures the dominant circulation and temperature variability linked to the leading LWCRE mode. To further examine the role of LWCRE in the Arctic–Eurasian atmospheric linkage, the linear component of the ET index associated with PC1 is removed, and the resulting residual ET index is regressed onto atmospheric circulation and surface temperature fields. After removing the PC1-related signal, the Arctic anticyclonic anomaly becomes substantially weaker, the negative NAO-like circulation over the North Atlantic nearly disappears, and only a weak trough remains over the Ural region, indicating a pronounced weakening of the

downstream Eurasian wave train (Fig. 6(c)). Correspondingly, the cold anomalies over northern Eurasia are markedly reduced and remain statistically significant only over Siberia and northeastern China (Fig. 6(d)). These results suggest a potential modulating role of LWCRE-related variability in the eastward-propagating Rossby wave train and associated winter temperature anomalies over northern Eurasia and downstream East Asia.

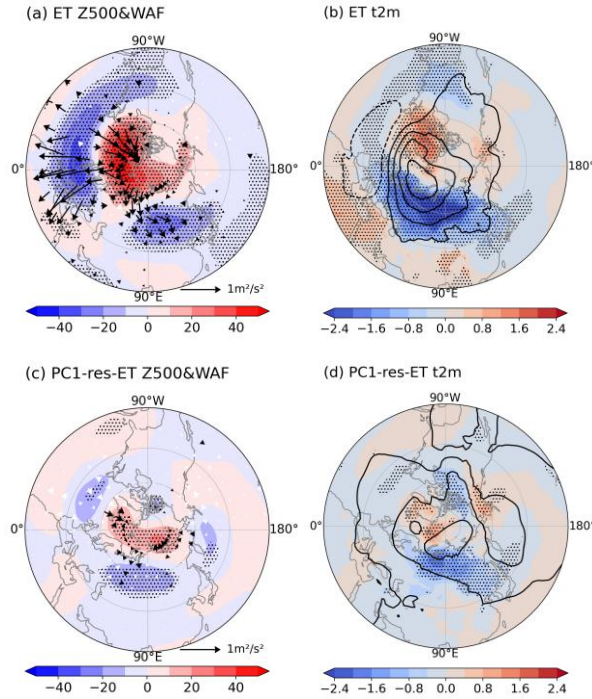


Fig. 6. Winter fields regressed onto the ET index. (a) 500 hPa geopotential height (shading; units: gpm) and TN wave activity flux (arrows; units: $\text{m}^2 \text{s}^{-2}$). (b) 2 m air temperature (units: K). (c–d) As in (a–b), but with the PC1-related signal linearly removed from the ET index. Stippling denotes anomalies significant at the 90% confidence level. In (a) and (c), black arrows indicate significance at the 90% confidence level, while white arrows indicate non-significance.

3.3 Modulation of LWCRE-related temperature anomalies by autumn BKS sea ice

The above analysis demonstrates that atmospheric circulation anomalies associated with winter surface LWCRE variability over the Urals are closely linked to AO/NAO-like circulation patterns and substantially influence Eurasian wave activity and temperature anomalies. Given that Arctic sea ice variability has been widely suggested as an important external forcing of Northern Hemisphere extratropical climate (Honda et al. 2009; Tang et al. 2013; Peings and Magnusdottir 2015; Nakamura et al. 2019), an important question is whether Arctic sea ice variability is associated with the LWCRE-related climate anomalies or represents a distinct source of variability. Here, we examine the seasonal relationship between Arctic sea ice variability and the leading LWCRE mode and assess their relative statistical associations with northern Eurasian winter cooling.

Figure 7 shows the regression of autumn and winter sea ice concentration anomalies onto the normalized PC1 index. Positive PC1 values are associated with reduced sea ice concentration over the autumn Barents–Kara Sea (BKS) region (Fig. 7(a)), whereas the winter response is much weaker, with localized sea ice reduction mainly confined to Baffin Bay and slight sea ice increases over the BKS–Greenland Sea sector (Fig. 7(b)). This strong seasonal dependence indicates that LWCRE variability over the Urals is more closely associated with autumn BKS sea ice anomalies than with concurrent winter sea ice changes. The correlation coefficient between autumn BKS sea ice and PC1 is -0.38 ($p < 0.01$), indicating that autumn BKS sea ice variability shares approximately 14% of its variance with the leading LWCRE mode (the BKS sea ice index is defined over the region enclosed by the black contour in Fig. 7(a)).

To assess the relative associations of LWCRE-associated variability and sea ice anomalies with northern Eurasian cooling, partial regression analysis was performed. The regional-mean surface air temperature anomaly over northern Eurasia (45° – 70° N, 10° – 130° E) reaches -1.66 K. After removing the LWCRE-related component from the temperature variability, the magnitude of the cold anomaly decreases by 62.7%, whereas removing the sea-ice-related component produces only a 10.8% reduction. When both components are removed simultaneously, the cooling anomaly is reduced by 64.5%. These results indicate that both winter surface LWCRE variability and autumn BKS sea ice anomalies are associated with northern Eurasian winter cooling, with the LWCRE-related component showing a substantially stronger statistical association with the temperature response. The combined reduction associated with removing the two factors is smaller than the sum of their individual reductions, indicating substantial overlap in the temperature variability associated with the two factors. This overlap may reflect shared variability between Arctic sea ice conditions and LWCRE, potentially mediated by cloud–sea ice interactions, as suggested by previous studies highlighting the role of such interactions in Arctic climate variability (Overland et al. 2011; Wendisch et al. 2019). Overall, these observational results suggest that autumn BKS sea ice variability is closely coupled with, but does not dominate, the LWCRE-related Eurasian temperature variability.

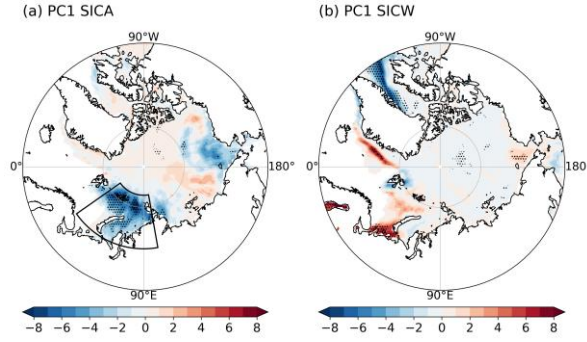


Fig. 7. Autumn (a) and winter (b) SIC (units: %) regressed onto PC1. Stippling denotes anomalies significant at the 90% confidence level.

To examine the modulating influence of autumn BKS sea ice on winter surface LWCRE-associated variability, a composite analysis was performed based on the standardized PC1 and BKS sea ice indices. Years were first classified according to the phase of PC1, with positive (negative) phases defined by PC1 values exceeding $+0.5\sigma$ (falling below -0.5σ). Within each phase, years were further divided into reduced sea ice (BKS sea ice index $< -0.5\sigma$) and normal sea ice ($-0.5\sigma \leq \text{BKS sea ice index} \leq 0.5\sigma$) categories.

During the positive phase of EOF1, winters with near-normal BKS sea ice exhibit relatively weak negative LWCRE anomalies over the Urals, with amplitudes of approximately -8 to -10 W m^{-2} (Fig. 8(a)). Correspondingly, the Arctic anticyclonic circulation anomalies remain weak, and only one Rossby wave train extends southwestward toward the Azores–Mediterranean region, while the downstream wave train over Asia is poorly developed (Fig. 8(c)). As a result, the associated cooling is largely confined to Europe and central Siberia (Fig. 8(e)). In contrast, during years of reduced autumn BKS sea ice, the negative LWCRE anomalies over the Urals are substantially enhanced, with peak amplitudes exceeding -12 W m^{-2} (Fig. 8(b)). The Arctic anticyclonic circulation is simultaneously strengthened, and the anticyclonic anomaly extending from the BKS to the Urals is accompanied by a pronounced southeastward-propagating Rossby wave train that deepens the East Asian trough (Fig. 8(d)). Consistent with these circulation changes, the AO index decreases from -0.40 to -1.58 , and the associated cold anomalies expand southward from northern Eurasia into central Asia. Consequently, the regional-mean surface air temperature anomaly strengthens from -1.19 K to -2.74 K (Fig. 8(f)). These composite differences suggest that reduced autumn BKS sea ice is associated with an intensified Arctic–midlatitude circulation linkage and stronger LWCRE-related atmospheric and temperature anomalies, resulting in more pronounced and spatially extensive cooling over northern Eurasia. Inspection of individual years and leave-one-

out composites further indicates that the major LWCRE, circulation, and temperature anomaly patterns are not dominated by any single event.

During the negative phase of EOF1, reduced BKS sea ice is associated with weaker positive LWCRE anomalies over the Urals and a poleward displacement of the anomalous centers of 500-hPa geopotential height and surface temperature (Fig. S1). Consequently, the warm anomalies over Eurasia are weakened, while weak cold anomalies emerge over the southern part of the analysis domain. These results suggest that autumn BKS sea ice loss may tend to offset the climatic influence of positive LWCRE anomalies over the Urals, in contrast to its apparent amplifying influence during the positive phase of EOF1. However, because only a limited number of observed winters satisfy both the negative EOF1 phase and reduced sea ice conditions, the statistical robustness of these results is limited. Therefore, the asymmetric influence of BKS sea ice between the positive and negative phases of EOF1 should be interpreted with caution, and its robustness and the underlying mechanisms are further examined using numerical model experiments.

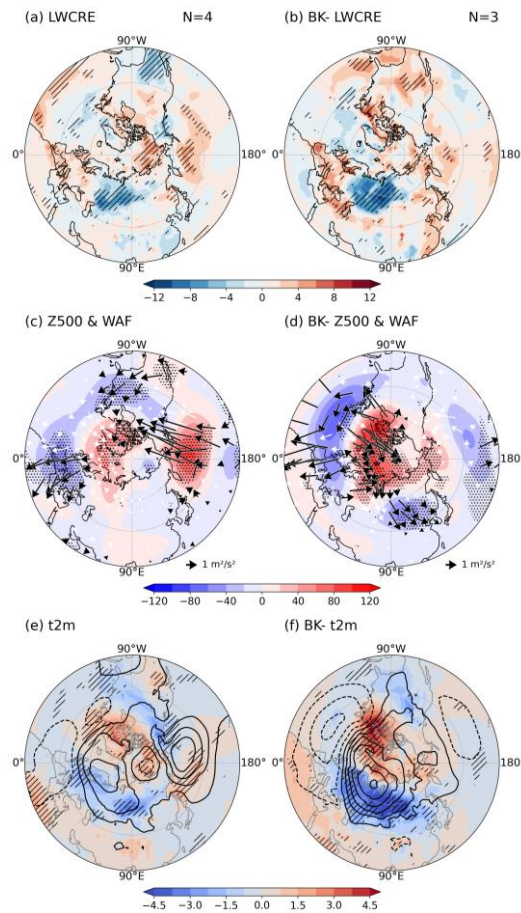


Fig. 8. Winter composites based on ERA5 data under PCI+ for normal sea ice years (a, c, e) (N=4) and reduced BKS sea ice years (b, d, f) (N=3). The number of years (N) is indicated in the top-right corner of each panel. (a, b) LWCRE (units: $W m^{-2}$); (c, d) 500-hPa geopotential height (shading; units: gpm) and TN

wave activity flux (arrows; units: $m^2 s^{-2}$); (e, f) 2-m air temperature (units: K). Stippling denotes anomalies significant at the 90% confidence level. In (c) and (d), black arrows indicate significance at the 90% confidence level, while white arrows indicate non-significance.

To assess the robustness of the observational results, we first examine the CMIP6 AMIP simulations. The multi-model ensemble (MME) successfully reproduces the leading mode of winter surface LWCRE variability, with a spatial correlation coefficient of 0.88 between the simulated and observed EOF1 patterns, although the simulated anomaly amplitudes are somewhat weaker (Fig. S2, Fig. S3, Fig. S4). The same composite criteria used for the observations are applied to the model simulations.

During the positive phase of EOF1, reduced autumn BKS sea ice is associated with enhanced negative LWCRE anomalies over the Urals relative to years with near-normal sea ice conditions (Fig. 9(b)). Correspondingly, the East Asian trough deepens, and the downstream Rossby wave train extending from the Arctic to Northeast Asia becomes more pronounced (Fig. 9(d)). These circulation changes are accompanied by stronger cooling over northern Eurasia, with the regional-mean surface air temperature anomaly decreasing from -1.63 K (Fig. 9(e)) to -2.02 K (Fig. 9(f)), representing an enhancement of approximately 23.9%. Overall, the simulated circulation and temperature responses closely resemble those obtained from the reanalysis composites. During the negative phase of EOF1, however, reduced autumn BKS sea ice is associated with only a modest weakening of the positive LWCRE anomalies (Figs. 9(g), 9(h)), while the associated atmospheric circulation anomalies remain largely unchanged (Figs. 9(i), 9(j)). Although the peak warming over northern Eurasia is slightly weaker under reduced sea ice conditions, the regional-mean temperature anomaly changes little, decreasing only from 1.63 K to 1.57 K (Figs. 9(k), 9(l)). These results provide multi-model support for an asymmetric association between autumn BKS sea ice conditions and LWCRE-related climate variability. Reduced sea ice is associated with amplified atmospheric circulation anomalies and enhanced northern Eurasian cooling during the positive phase of EOF1, whereas its influence on the regional-mean temperature response is weak during the negative phase.

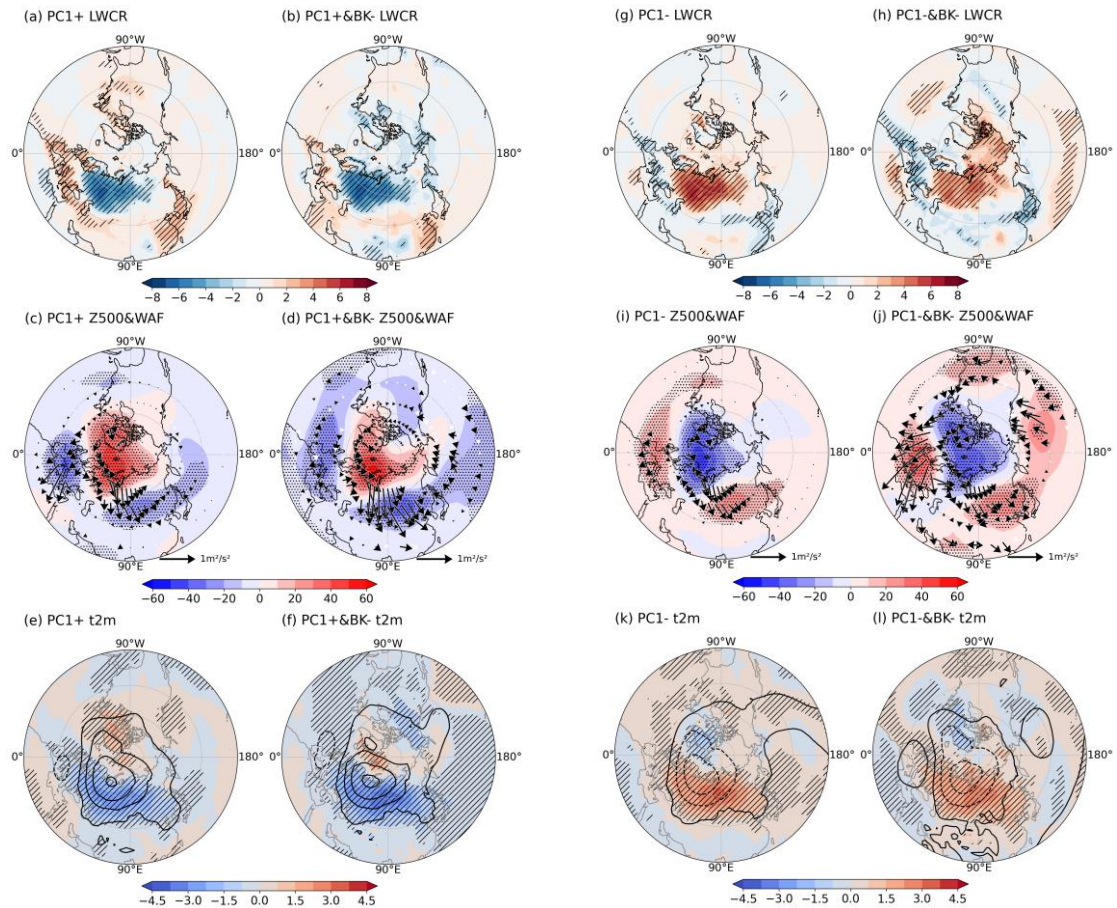


Fig. 9. Winter composites based on AMIP data. Panels (a–f) display the PC1+ composites, with the layout identical to Fig. 8; panels (g–l) are as in (a–f) but for PC1–.

Given the considerable intermodel spread in the simulation of winter surface LWCRE among the CMIP6 AMIP models, together with the difficulty of separating the influence of autumn BKS sea ice variability from other sources of climate variability, such as ENSO, additional experiments were conducted using CAM5. These experiments were designed to further assess the robustness of the observational and AMIP results and to examine the atmospheric response to prescribed autumn BKS sea ice loss.

Figure 10 compares the LWCRE, atmospheric circulation, and surface air temperature anomalies between the control experiment with climatological sea ice conditions and the sensitivity experiment with reduced autumn BKS sea ice. CAM5 reproduces the broad spatial characteristics of the observed LWCRE anomaly patterns, although the simulated anomalies extend farther northwest than those in the reanalysis (Figs. 10(a), 10(b), 10(g), 10(h)). During the positive phase of EOF1, reduced autumn BKS sea ice strengthens the LWCRE anomalies over Eurasia and produces a more pronounced meridional dipole structure. At 500 hPa, the Arctic anticyclonic anomaly expands southward toward the Urals, while the southeastward-propagating Rossby wave train becomes more pronounced, leading to a deeper

East Asian trough (Figs. 10(c), 10(d)). These circulation changes enhance the cold anomalies over northern Eurasia, with the regional-mean surface air temperature anomaly decreasing from -2.62 K in the control experiment to -3.07 K in the sensitivity experiment (Figs. 10(e), 10(f)). This difference corresponds to an additional cooling of 0.45 K, or an enhancement of approximately 17.2%, attributable to the imposed autumn BKS sea ice loss. During the negative phase of EOF1, the sensitivity experiment exhibits somewhat weaker LWCRE and 500-hPa geopotential height anomalies than the control experiment (Figs. 10(g)–10(j)). Although the downstream wave train toward Northeast Asia becomes slightly stronger, the associated surface temperature response changes little. The regional-mean warm anomaly over northern Eurasia changes only marginally, from 2.02 K in the control experiment to 2.06 K in the sensitivity experiment (Figs. 10(k), 10(l)). Thus, no clear amplification or attenuation of the Eurasian warming response is evident under reduced autumn BKS sea ice conditions.

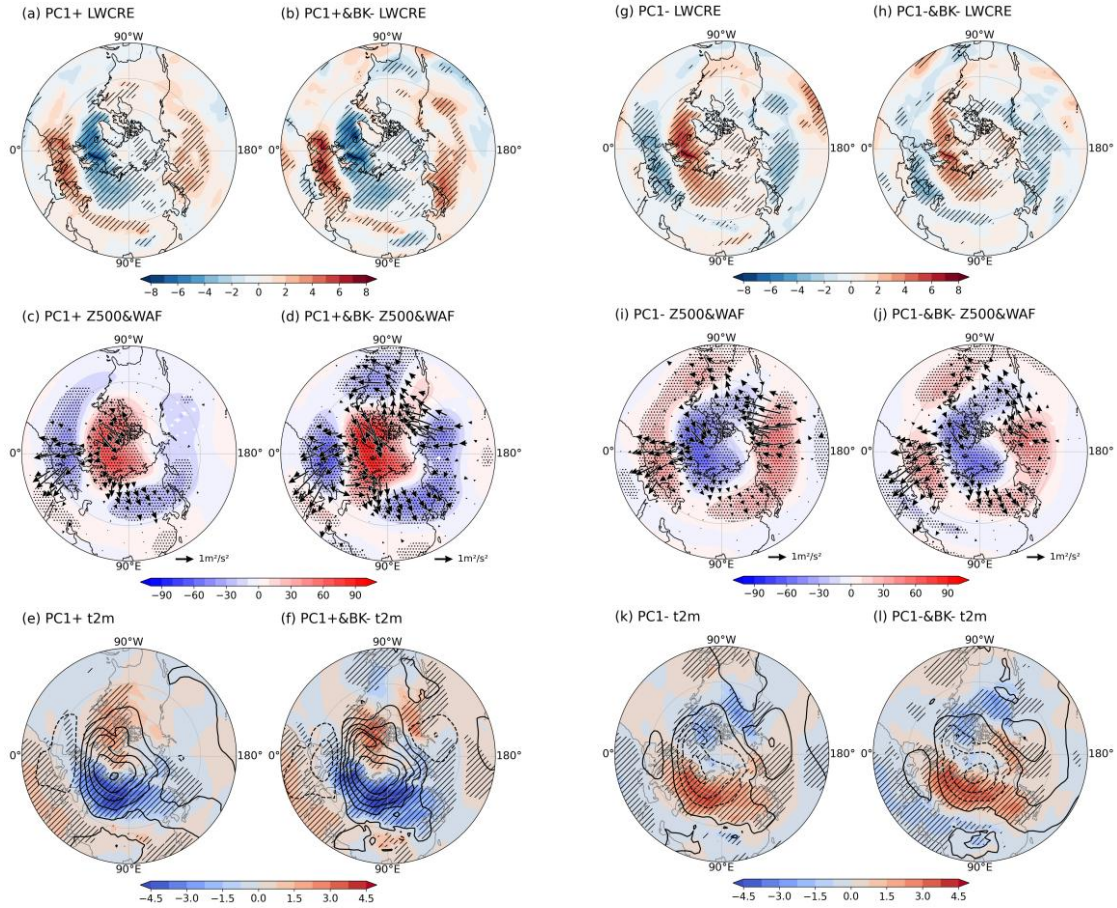


Fig. 10. As in Fig. 9, but for winter CAM5 composites. The control experiment corresponds to normal sea ice, and the sensitivity experiment corresponds to reduced BKS sea ice.

The CAM5 experiments further support the observational and AMIP results, indicating that autumn BKS sea ice loss primarily modulates, rather than fundamentally alters, the atmospheric

circulation anomalies associated with the leading mode of winter surface LWCRE variability. This modulating effect is most evident during the positive phase of EOF1, when sea ice loss strengthens the downstream Rossby wave response and enhances northern Eurasian cooling by approximately 17.2%. The relatively modest magnitude of this additional cooling, however, suggests that the LWCRE-related atmospheric variability remains the primary component associated with the circulation and temperature anomalies, with autumn BKS sea ice loss providing a secondary modulation. During the negative phase of EOF1, the influence of reduced sea ice is weak, with no substantial change in the regional-mean temperature response.

4. Conclusions

Compared with sensible and latent heat fluxes, surface LWCRE exhibits substantially greater interannual variability over northern Eurasia during winter. EOF analysis of ERA5 data identifies a leading mode of winter surface LWCRE variability characterized by pronounced anomalies over the Urals. The corresponding PC exhibits pronounced interannual variability, and its associated circulation anomalies are closely linked to the AO and an eastward-propagating Rossby wave train across Eurasia. These circulation anomalies are accompanied by the canonical warm Greenland–cold northern Eurasia temperature dipole and pronounced winter climate anomalies extending into East Asia.

Further analysis reveals a significant association between Ural LWCRE variability and autumn BKS sea ice conditions. During the positive phase of EOF1, characterized by negative LWCRE anomalies over the Urals, reduced autumn BKS sea ice is associated with stronger Arctic–midlatitude circulation anomalies and enhanced LWCRE-related temperature responses, thereby intensifying northern Eurasian cooling and favoring its southward extension toward lower latitudes. Nevertheless, LWCRE-related atmospheric variability shows a substantially stronger statistical association with northern Eurasian winter temperature anomalies than autumn BKS sea ice variability, indicating that autumn BKS sea ice primarily acts as a secondary modulator of the LWCRE-related climate response. The AMIP simulations and CAM5 sensitivity experiments further support this interpretation, with reduced autumn BKS sea ice associated with enhanced northern Eurasian cooling in AMIP and prescribed sea ice loss producing an approximately 17% enhancement in CAM5. The influence of autumn BKS sea ice is also asymmetric between the two phases of EOF1, with reduced sea ice strengthening the cooling response during the positive phase but exerting only a weak influence on the regional-mean temperature response during the negative phase.

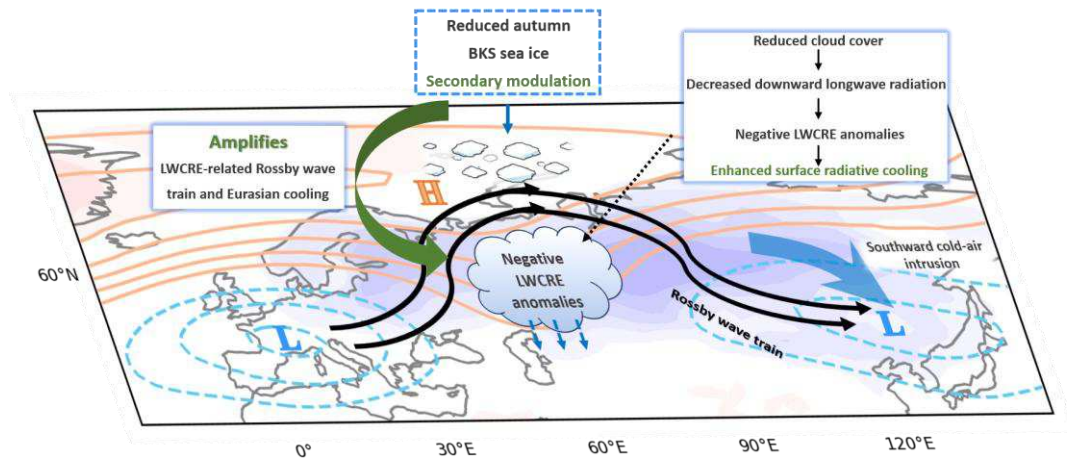


Fig. 11. Schematic illustration of the radiative–dynamical linkage associated with negative winter LWCRE anomalies over the Urals and the secondary modulation by reduced autumn BKS sea ice. Decreased cloud cover and downward longwave radiation are associated with negative LWCRE anomalies and enhanced surface radiative cooling over the Urals. The associated anticyclonic circulation and eastward-propagating Rossby wave train favor southward cold-air intrusion and northern Eurasian cooling. Reduced autumn BKS sea ice further amplifies the LWCRE-related Rossby wave response and Eurasian cooling, with an approximately 17% enhancement of regional-mean cooling in the CAM5 sensitivity experiment. Shaded areas indicate cold anomalies; red (blue) contours represent positive (negative) 500 hPa geopotential height anomalies, with H (L) denoting their respective centers.

5. Discussion

As shown in Fig. 7, winter sea ice anomalies over Baffin Bay are also significantly associated with PC1, in addition to autumn BKS sea ice anomalies. Further analysis, however, indicates that Baffin Bay sea ice variability primarily affects surface temperature over Greenland and the surrounding regions, with a much weaker influence on Eurasian climate than that associated with autumn BKS sea ice. Autumn BKS sea ice anomalies may also provide a more physically plausible precursor signal because they can influence the subsequent winter circulation through persistent sea ice–atmosphere interactions, as suggested by previous observational and modeling studies (Honda et al. 2009; Screen and Simmonds 2010; Nakamura et al. 2019). By contrast, winter Baffin Bay sea ice anomalies occur concurrently with the atmospheric circulation response, making it more difficult to distinguish whether they represent an independent forcing or are themselves a response to the circulation anomalies. For this reason, the present study focuses primarily on the role of autumn BKS sea ice variability.

Both the AMIP simulations and the CAM5 experiments indicate that reduced autumn BKS sea ice is associated with enhanced northern Eurasian cooling linked to negative winter LWCRE

anomalies over the Urals (Table 1). The additional cooling under reduced sea ice conditions is -0.39 K in AMIP, while the CAM5 sensitivity experiment yields an additional cooling of -0.45 K attributable to the prescribed sea ice reduction, suggesting a broadly consistent simulated response across the two modeling frameworks. These values are nevertheless substantially smaller than the -1.55 K difference estimated from ERA5. This discrepancy does not arise from a weaker total cold response in the models. Rather, under near-normal sea ice conditions, both AMIP and CAM5 already produce stronger LWCRE-associated cooling over Eurasia than is found in ERA5, leaving a smaller incremental difference under reduced sea ice conditions. One possible explanation is that the models generate stronger atmospheric internal variability under circulation conditions favorable for Eurasian cooling. In addition, both the observational and AMIP composites may include the combined effects of other sources of climate variability, such as snow-cover variability and ENSO, which are not explicitly isolated in these analyses. By contrast, the CAM5 sensitivity experiments provide a more controlled estimate of the response to prescribed autumn BKS sea ice loss.

The models also consistently indicate that northern Eurasian warming during the negative phase of EOF1 is relatively insensitive to reduced autumn BKS sea ice. This differs from the ERA5 composites, in which sea ice loss appears to weaken the warm anomaly. The discrepancy likely reflects the limited number of observed winters that simultaneously satisfy the negative-PC1 and reduced-sea-ice criteria. With such a small sample, the composite may be disproportionately influenced by a few extreme winters, thereby reducing the stability and statistical robustness of the inferred response. The model results therefore provide stronger support for the asymmetric influence of BKS sea ice loss, with reduced sea ice amplifying the cold response during the positive phase of EOF1 but exerting little systematic influence during the negative phase.

Differences also emerge between the AMIP multi-model ensemble and CAM5 in their representation of the background LWCRE-related variability. Under near-normal sea ice conditions, AMIP produces approximately symmetric northern Eurasian temperature anomalies between the positive and negative phases of EOF1, whereas CAM5 simulates a substantially stronger cold response during the positive phase than the warm response during the negative phase. Under reduced autumn BKS sea ice conditions, AMIP tends to underestimate both the regional-mean temperature anomaly and the amplitude of the principal cooling center, while CAM5 more closely reproduces the ERA5 response. These differences likely reflect the distinct experimental designs. The AMIP multi-model ensemble averages across models and

initial-condition members, thereby suppressing model-specific internal variability and emphasizing the robust component shared across models. CAM5, in contrast, retains the characteristics and biases of a single model but provides a more controlled estimate of the atmospheric response to prescribed sea ice perturbations. The two approaches are therefore complementary: AMIP is useful for evaluating the cross-model robustness of the LWCRE-associated circulation response, whereas CAM5 more directly isolates the incremental influence of autumn BKS sea ice loss.

Table 1. Temperature anomalies from observations and model data (units: K; region: 10°–130°E, 45°–70°N).

	Regional mean		Central intensity	
	EOF1+	EOF1–	EOF1+	EOF1–
(a) Normal sea ice				
ERA5	–1.19	2.12	–3.77	4.33
AMIP	–1.63	1.63	–2.95	3.26
CAM5	–2.62	2.02	–4.89	3.85
(b) Reduced sea ice				
ERA5	–2.74	0.64	–5.94	3.88
AMIP	–2.02	1.57	–3.79	2.85
CAM5	–3.07	2.06	–5.88	3.73

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Statements & Declarations

Funding

This study was supported by the Natural Science Foundation of China (Grant 42375026).

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Huiru Yang: Methodology, Investigation, Data Curation, Formal Analysis, Visualization, Writing—Original Draft. Shuoyi Ding: Conceptualization, Supervision, Validation, Writing—Review and Editing. All authors discussed the results, commented on previous versions of the manuscript, and read and approved the final manuscript.

Data Availability

Data Availability Statement: The ERA5 reanalysis data used in this study are available from the Copernicus Climate Change Service (C3S) Climate Data Store (<https://cds.climate.copernicus.eu/>). The monthly sea ice concentration from the UK Met Office Hadley Centre are available from (<https://www.metoffice.gov.uk/hadobs/hadisst/data/>). The CMIP6/AMIP6 simulation data are accessible via the Earth System Grid Federation (ESGF, <https://esgf-node.llnl.gov/>). The CAM5 sensitivity experiment data are available from the corresponding author upon reasonable request.

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