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Key Points:

- The short-term fluctuations of Arctic sea ice in marginal ice zone have increased over recent decades, especially in summer and autumn
- Greater ice fluctuations enhance ocean heat absorption in summer and heat release in winter, accelerating Arctic warming
- Bidirectional causal feedback exists between sea-ice variability and anomalous heat fluxes and is strongest in Arctic marginal ice zone

Supporting Information:

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

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Increased Arctic Sea-Ice Variability Is Associated With Amplified Air-Sea Heat Fluxes

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Abstract While the role of long-term sea ice decline in shaping Arctic climate change is well-established, the contribution of short-term sea-ice variability remains insufficiently explored. Here we present observational evidence that since 2007, sea ice fluctuations in Arctic marginal ice zone have remained at a high level. The annual-mean daily variability of sea ice concentration rose by 11.4%, with high-variability days becoming more frequent, especially in summer and autumn. Composite analyses reveal enhanced net heat uptake in summer (+11.9%) and greater ocean-to-atmosphere heat release in winter (+45.3%), both of which intensify after 2007. Causal analyses reveal a feedback, with higher sea ice variability being closely linked to and reinforced by anomalous net heat fluxes. These findings highlight the increasing short-term variability of the Arctic sea-ice and its key role in regulating local air-sea heat exchange.

Plain Language Summary The Arctic is warming much faster than the global mean, and its sea ice is shrinking. The sea ice is melting over time, but our study shows that short-term changes of sea-ice in marginal ice zone have remained relatively high since 2007, with high-variability days occurring more often, particularly in summer and autumn. These ice fluctuations allow the ocean to absorb more heat in summer and release more heat in winter. This extra heat exchange may contribute to Arctic warming and quicken the sea ice loss. As a result, short-term sea-ice variability can strongly influence local air-sea heat exchange in a rapidly changing Arctic.

1. Introduction

Over the past 40 years, the Arctic has warmed nearly four times faster than the global average—a phenomenon called Arctic Amplification (Rantanen et al., 2022). Key drivers include ice-albedo feedback, changes in heat transport, cloud/water vapor effects (Previdi et al., 2021; Serreze & Barry, 2011). Among these, sea ice loss plays a central role: as ice retreats, darker ocean absorbs more solar radiation, releasing more heat into the atmosphere, amplifying regional warming (Previdi et al., 2021; Serreze & Barry, 2011). This enhanced ocean-atmosphere heat exchange—especially in areas of marginal ice zone (MIZ)—further accelerates Arctic warming through reducing the insulating effect and delayed energy feedbacks (Previdi et al., 2021; Screen & Simmonds, 2010; Serreze & Francis, 2006).

Recent Arctic changes show a critical shift around 2007 from thick, deformed multi-year ice to thinner, more homogeneous first-year ice (Overland et al., 2019; Sumata et al., 2023), alongside more extreme events like abrupt ice loss and marine heatwaves (Graham et al., 2017; Huang et al., 2021). Concurrently, solar heat uptake in the upper ocean has risen over 5% in some areas due to persistent ice retreat (Perovich & Richter-Menge, 2009).

While long-term Arctic sea ice trends (extent, thickness, and seasonality) are well-studied (Meier et al., 2014; Stroeve & Notz, 2018), the climate impacts of short-term sea-ice variability remain unclear. Two key questions persist: (a) Has high-frequency ice variability changed with warming? (b) How do short-term sea-ice fluctuations influence air-sea energy exchange?

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This study focuses on daily-to-seasonal Arctic sea-ice fluctuations and their impacts on surface energy budgets especially in MIZ. We find these short-term variations are closely associated with changes in ice-albedo interactions and air-sea heat exchange. Since 2007, increased sea ice variability has been accompanied by stronger local surface fluxes anomalies. These results highlight the critical role of short-term cryosphere dynamics in modulating local atmosphere–ocean energy exchange.

2. Data and Methods

2.1. Sea Ice Concentration

We used sea ice concentration (SIC) data from NOAA/NSIDC Climate Data Record of Passive Microwave SIC, Version 4, which provides a consistent SIC time series from multiple satellite sensors (Meier et al., 2014).

The data set covers 1979–2024 with daily 25 km resolution. Version 4 combines NASA Team and Bootstrap algorithms, incorporating corrections for sensor calibration, land spillover, and atmospheric effects, making it one of the most reliable satellite-based SIC records (Parkinson & DiGirolamo, 2021).

2.2. Surface Heat Flux

Surface heat flux data come from ECMWF's ERA5 reanalysis (1940–present, $0.25^\circ \times 0.25^\circ$, hourly) (Copernicus Climate Change Service, 2023; Hersbach et al., 2018). Hourly surface heat fluxes were integrated over 24 hr, and the resulting daily values were used in the analyses. While uncertainties exist in ice-covered areas due to surface heterogeneity and boundary layer parameterizations, ERA5 is widely used for its high resolution and consistency (Graham et al., 2017).

Using ERA5 data (1979–2024), we analyze four surface variables: net short-wave radiation, net long-wave radiation, sensible heat flux, and latent heat flux. To investigate air-sea exchange, we analyze (a) net surface heat flux, (b) short-wave radiation, and (c) non-shortwave flux (net longwave + sensible + latent fluxes).

We adopt the NSIDC passive-microwave SIC for variability analysis because it provides a direct observation-based record optimized for capturing ice-edge variability, whereas ERA5 SIC is prescribed as a boundary condition within the reanalysis system and is typically smoother at fine spatial scales. In ERA5, SIC is prescribed from the EUMETSAT OSI-SAF passive-microwave products (Hersbach et al., 2018). Although ERA5 SIC is not identical to the NSIDC passive-microwave SIC used here, both are largely constrained by passive-microwave observations during the satellite era (Hersbach et al., 2018; Meier et al., 2024). To minimize potential biases, our analysis emphasizes spatiotemporal anomalies and composite differences rather than absolute flux values, also reducing focus on grid cells with persistently high ice concentrations. Therefore, our heat-flux anomalies and composite results are unlikely to be sensitive to minor SIC differences.

2.3. Sea Ice Variability

To characterize short-term variability along the Arctic sea-ice, we constructed daily SIC anomalies (SIC') in 1979–2024. The daily climatology for each calendar day was calculated using an 11-year $\times$ 11-day moving window, centered on the target day and year (i.e., ± 5 years and ± 5 days), with intra-annual endpoints treated circularly and boundary years (1979 and 2024) using available days only. The SIC' represent deviations from this slowly evolving smoothed climatological baseline, retaining short-term variability on daily to interannual time scales while removing the mean seasonal cycle and suppressing low-frequency (decadal-scale) background variability.

We calculated several indicators of sea-ice variability. Annual-mean daily SIC variability was quantified by standard deviation of daily SIC' at each grid to obtain the short-term fluctuation intensity. In addition, we calculated the annual cumulative variability by summing the absolute daily SIC' at each grid.

High-variability days were defined as days when a daily SIC anomaly exceeds +0.1 or falls below −0.1 ($|SIC'| > 0.1$). This threshold was selected following extreme-event definition conventions (e.g., Hobday et al., 2016). The empirical distribution of Arctic daily $|SIC'|$ values over 1979–2024 shows that 91.1% of values are ≤ 0.10 (i.e., only 8.9% exceed 0.10), yielding an exceedance probability close to the $\sim 10\%$ associated with a 90th-percentile threshold and thus effectively distinguishing normal background fluctuations from anomalously high sea-ice variability (Figure S1 in Supporting Information S1).

We counted annual high-variability days per grid, analyzing their changes pre- and post-2007. To ensure robustness, sensitivity tests with alternative thresholds ($|\text{SIC}'| > 0.05$ and $|\text{SIC}'| > 0.15$) were also conducted, and the drawn conclusions are unaffected by the thresholds (Figures S2–S4 in Supporting Information S1). To further address ice-edge variability, we additionally applied a distance-based metric derived from the daily position of the 15% SIC contour. This analysis, presented in Text S1 and Figure S5 in Supporting Information S1, yields results consistent with our primary SIC-based variability metrics.

2.4. Composite Analysis

To assess the impact of short-term sea ice variability on surface heat flux, we performed a composite analysis of daily surface heat flux anomalies on sea ice high-variability days ($|\text{SIC}'| > 0.1$). It can be expressed as (Hayashida et al., 2020):

$$\overline{\Delta Q}_{\text{season}}(x, y) = \frac{1}{N_{\text{year}}} \sum_{\text{year}} \left(\sum_{t \in T_{\text{season}}} [Q(x, y, t) - \overline{Q}_{\text{clim}}(x, y, t)] \right)$$

where, $\overline{\Delta Q}_{\text{season}}(x, y)$ is the annual-mean cumulative flux anomaly at grid point (x, y) for a given season; $Q(x, y, t)$ is the surface heat flux on day t ; $\overline{Q}_{\text{clim}}(x, y, t)$ is the climatology flux for the day t , using a 11 years $\times$ 11 days moving window; T_{season} represents all high-variability days in that season; and N_{year} is the number of years. Our seasonal analysis focuses on two seasons: June–July–August (JJA), corresponding to the summer season, and December–January–February (DJF), corresponding to the winter season. A two-sided bootstrap resampling with 1,000 replacement was used to assess the statistical significance of the composite analysis and the differences between 1979–2006 and 2007–2024. The null hypothesis of no difference was tested, and results were deemed significant at the 95% confidence level ($p < 0.05$) (P. Zhang et al., 2023).

2.5. Liang–Kleeman Information Flow

We employ the Liang–Kleeman Information Flow method to quantify the directional causality between $|\text{SIC}'|$ and net surface heat flux anomalies (Liang, 2014, 2021). Rooted in information theory and dynamical systems, it provides a rigorous basis for evaluating causality and the strength of interactions between variables. This approach has been applied in Arctic climate research to investigate the factors influencing sea ice decline and variability (Docquier et al., 2022, 2024; Dörr et al., 2024). For each grid point, given two time series X_1 and X_2 , the information flow rate from X_2 to X_1 is denoted as $\hat{T}_{2 \rightarrow 1}$, where the “hat” indicates that it is an estimator derived from sample statistics rather than the true information flow (Liang, 2014). It is computed as

$$\hat{T}_{2 \rightarrow 1} = \frac{C_{11} C_{12} C_{2,dl} - C_{12}^2 C_{1,dl}}{C_{11}^2 C_{22} - C_{11} C_{12}^2}$$

where C_{ij} is the sample covariance between X_i and X_j , and $C_{i,dl}$ is the sample covariance between X_i and $\frac{dX_j}{dt}$ (Euler forward differencing approximation of X_j at time t). The sign of $\hat{T}_{2 \rightarrow 1}$ indicates whether X_2 exerts a destabilizing (positive) or stabilizing (negative) influence on X_1 . In the figures, we show only grid points where the information flow passes the 95% significance test (Wald z -test), and we plot the absolute values $|\hat{T}_{2 \rightarrow 1}|$ to emphasize the spatial pattern and magnitude of the causal influence, as larger absolute values indicate stronger causal relationships (Lv et al., 2025). This study employs the Liang–Kleeman Information Flow method to analyze the causality between the de-seasonalized daily time series of $|\text{SIC}'|$ and net heat flux anomaly over the full annual cycle, which provides a more stable sample for covariance estimation. Seasonal (JJA and DJF) information-flow fields are also calculated as a robustness check and reported in Supporting Information S1.

3. Results

Since 1979, the minimum Arctic sea ice extent (SIE) has decreased from over $7.5 \times 10^6 \text{ km}^2$ to below $4.5 \times 10^6 \text{ km}^2$ (Figure 1). The rate of decline has slowed after 2007, consistent with recent assessments (Polyakov et al., 2023; Stern, 2025). Evidence for a shift toward a thinner and more uniform sea-ice regime in 2007 (Sumata et al., 2023) motivates our use of 2007 as a reference year for period-based comparisons of short-term variability.

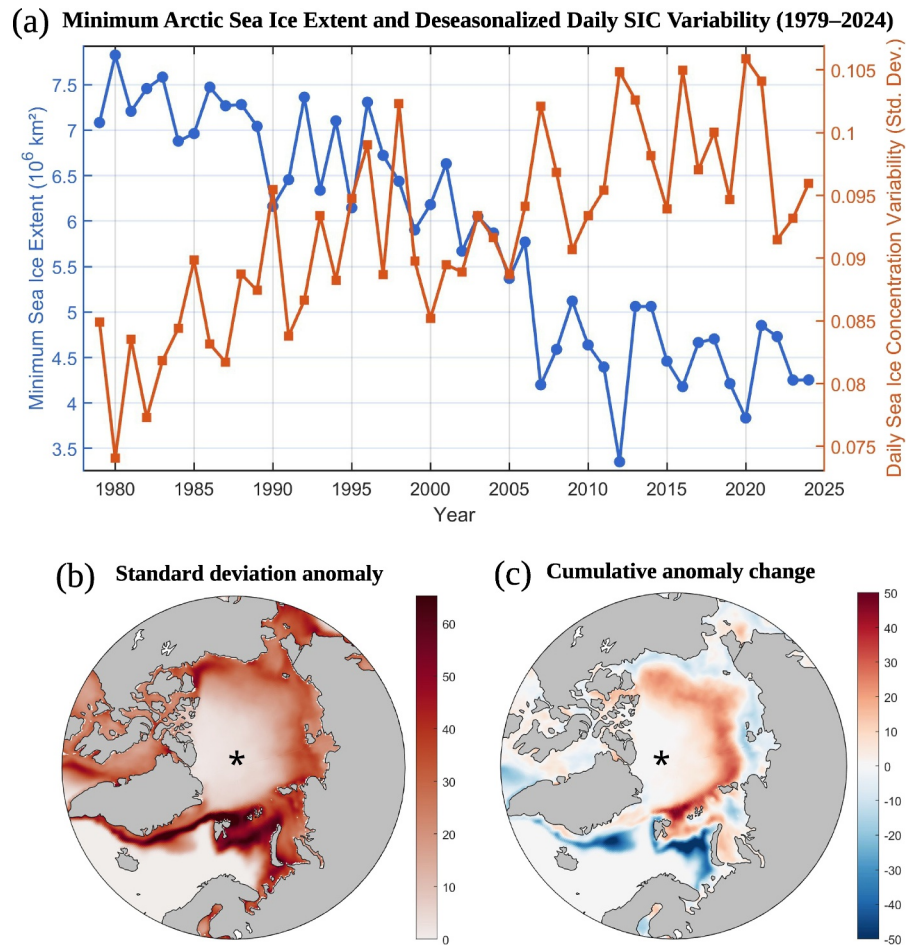


Figure 1. Variability of Arctic sea ice and its post-2007 change. (a) Annual minimum sea ice extent (blue) and the spatially averaged (Arctic-mean) annual-mean deseasonalized daily sea ice concentration (SIC) variability (orange) during 1979–2024. (b) Spatial distribution of the annual cumulative absolute SIC variability from 1979 to 2024. (c) Change in cumulative SIC variability between the post-2007 (2007–2024) and pre-2007 (1979–2006) periods. The star marks the North Pole.

Using detrended and deseasonalized daily SIC, the annual standard deviation increases from 0.088 in 1979–2006 to 0.098 in 2007–2024, an 11.4% rise, indicating higher day-to-day variability in the later period. Notably, 2007 reached a record-low minimum SIE and an intensification of daily SIC variability. Together, these changes not only underscore the ongoing retreat of Arctic ice cover, but also highlight the growing fluctuations of the sea ice. In addition, based on the previous studies identifying a change point in Arctic sea ice around 2007 (Sumata et al., 2023), we performed change-point and trend diagnostics (Texts S2, S3, and Figures S6–S9 in Supporting Information S1). While a clear shift is confirmed for SIE in 2007, no robust or consistent change point is detected for short-term SIC or sea-ice edge variability. Accordingly, 2007 is retained as a reference year to separate the analyses into pre- and post-2007 periods, without implying a transition.

The spatial distribution of the annual cumulative absolute SIC variability from 1979 to 2024 (Figure 1b) reveals that regions of high variability are primarily located in the marginal seas of the Arctic, particularly in the Barents and Kara Seas. In contrast, the central Arctic, dominated by thick multi-year ice, exhibits much lower sea ice variability. The difference in cumulative SIC variability between 2007–2024 and 1979–2006 (Figure 1c) indicates a pronounced northward expansion of increasing sea ice variability after 2007. A large, continuous band of enhanced variability extends from the Kara Sea eastward across the Laptev, East Siberian, and Chukchi Seas to the Canadian Arctic Archipelago, especially along the boundary adjacent to the central Arctic Ocean. In contrast, variability near the continental margins has decreased. This pattern reflects the post-2007 expansion of open water in lower-latitude regions, where former MIZ have become persistently ice-free. The MIZ has migrated northward and exhibits stronger short-term fluctuations in the later period.

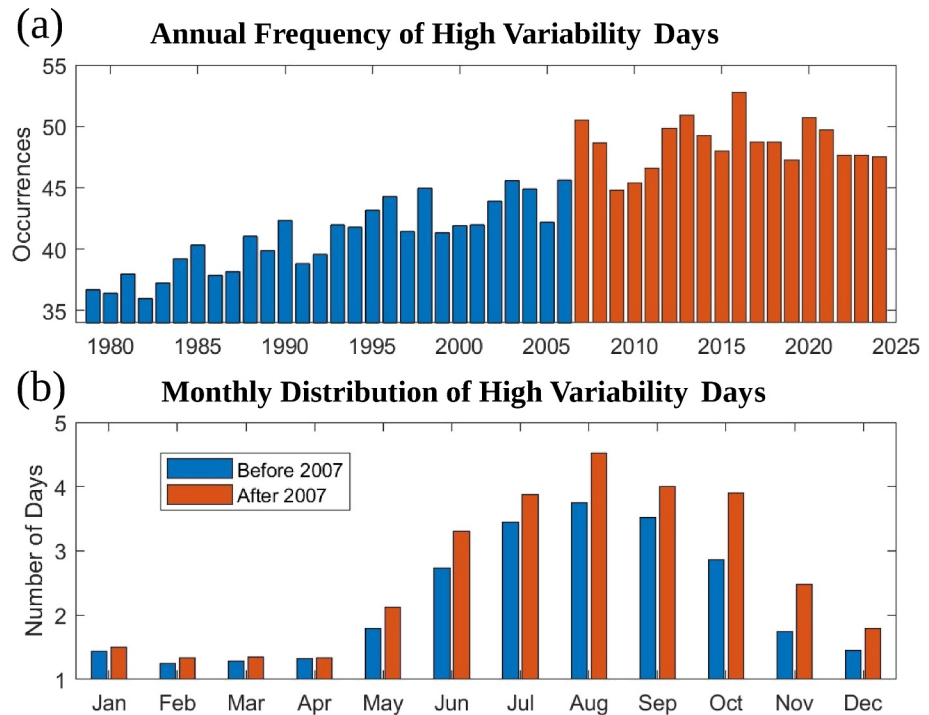


Figure 2. Occurrences of high-variability days (1979–2024). (a) Annual-mean number of high sea ice concentration variability days per grid from 1979 to 2024. (b) Monthly distribution of high-variability days per grid for the periods from 1979 to 2006 (blue) and from 2007 to 2024 (red).

High-variability days were defined as days when the daily $|\text{SIC}'| > 0.1$. We calculate the annual mean and seasonal cycle of high-variability days per grid. The results show an overall increasing tendency in the occurrence of such events, with an exceptional peak in 2007, followed by fluctuations at similarly elevated levels rather than a sustained surge (Figure 2). The majority of high-variability days occur between July and October (Figure 2b), coinciding with the key phases of Arctic sea-ice melt and early refreezing. Compared to the pre-2007 period, the post-2007 exhibits a substantial increase in the frequency of high-variability days during summer and autumn, indicating intensified short-term (daily to sub-seasonal) sea-ice fluctuations. Sensitivity tests with alternative thresholds of $|\text{SIC}'|$ (0.05 and 0.15) yield consistent results (Figure S2 in Supporting Information S1). To further investigate the impacts of the increased fluctuations, we next perform a composite analysis of surface heat fluxes and SIC patterns on high-variability days.

The composite analysis indicates that in JJA, the net heat flux anomalies in high-variability days show positive values in almost all the Arctic Ocean (Figure 3a). This suggests that, during periods of rapid fluctuations of sea ice, a greater amount of heat flux enters the ocean. The area-weighted mean of the net heat flux anomaly in JJA relative to the long-term seasonal average is 11.9%, and the increasing rate can reach more than 30% in many areas (Figure 3b). Conversely, in DJF, the composite of net heat flux shows pronounced negative anomalies, indicating a significant heat loss from the ocean to the atmosphere (Figure 3d). The area-weighted mean of the percentage changes in DJF is 45.3%, and the increase exceeds 150% in regions such as the Kara and Chukchi Seas (Figure 3e). In general, the impact of short-term variability of sea ice on net heat flux in DJF is greater than in JJA (Figure 3 and Figure S10 in Supporting Information S1).

Composite analysis is further conducted respectively for the two periods 1979–2006 and 2007–2024. The results indicate a significant increase in net heat flux entering the ocean during JJA months after 2007 compared to the earlier period, with most areas increasing by $0.2\text{--}0.4 \times 10^8 \text{ J/m}^2/\text{day}$, reaching more than 20% increase of the total (Figure 3c, Figures S10a, S10b, and S11a in Supporting Information S1). In DJF, the changes in net heat flux anomaly after 2007 show an opposite spatial pattern, indicating that more heat is released from the ocean to the atmosphere after 2007 (Figure 3f, Figures S10c, S10d, and S12b in Supporting Information S1). In most areas, the heat release caused by short-term fluctuations in DJF increased by $1\text{--}2 \times 10^8 \text{ J/m}^2/\text{day}$ after 2007, reaching more

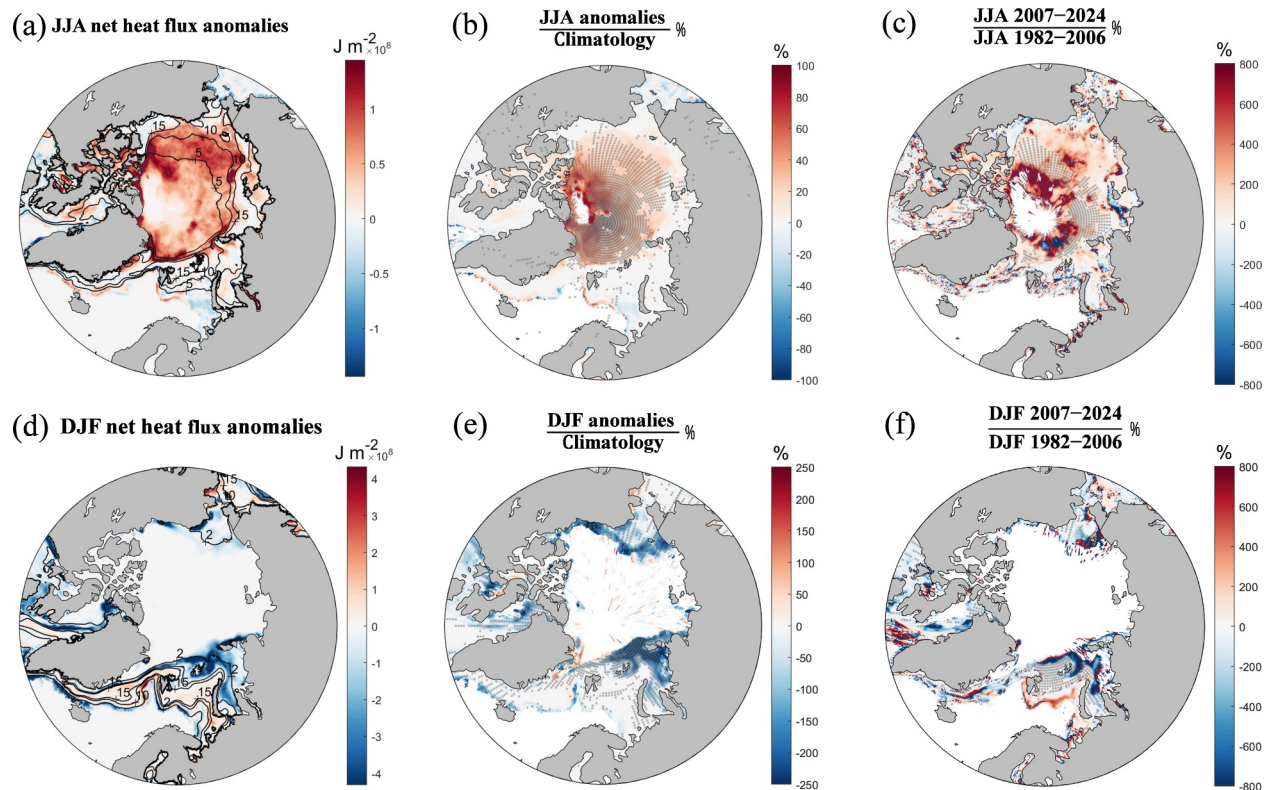


Figure 3. Composites and their changes of net heat flux anomalies during high-variability days. (a) Composite result in JJA, overlaid with contours of annual cumulative absolute sea ice concentration anomalies in JJA; (b) percentage changes in net heat flux anomalies relative to the long-term seasonal mean climatology in JJA; (c) percentage changes in net heat flux anomalies between 1979–2006 and 2007–2024 in JJA; (d–f) are the same as (a–c), but in DJF. Areas that have never been part of the marginal ice zone in DJF are masked as areas of zero magnitude. Positive values indicate downward heat flux into the ocean, while negative values represent upward heat loss. Gray stippling denotes statistically significant grid cells ($p < 0.05$). Please note that results for JJA and DJF use different colorbar ranges.

than 80% increase of the total (Figure 3f and Figure S11b in Supporting Information S1). The ratio of composite anomalies relative to the long-term seasonal average has also shown an increase in spatial extent and magnitude (Figure S12 in Supporting Information S1), especially in DJF, from 31.7% in 1979–2006 to 50.3% in 2007–2024. Only composite-analysis results that pass the significance test are highlighted with stippling in Figures 3b, 3c, 3e, and 3f. Sensitivity tests with thresholds of 0.05 and 0.15 further confirm their robustness (Figures S3 and S4 in Supporting Information S1).

The net heat flux anomalies during high-variability days exhibit clear seasonal characteristics. In summer (JJA), enhanced shortwave absorption regulated by surface albedo contributes to increased ocean heat uptake and ice melt, whereas in winter (DJF), longwave, sensible, and latent fluxes warm the atmosphere (Figures S11c and S11d in Supporting Information S1). As both SIC and heat flux fields were deseasonalized and detrended using an 11-year, 11-day sliding climatology, the anomalies represent short-term deviations rather than long-term retreat. This seasonal asymmetry aligns with established mechanisms of Arctic amplification, where reduced sea ice leads to greater solar absorption in summer (Perovich et al., 2020) and increased upward heat fluxes in winter (Gong et al., 2017; Screen & Simmonds, 2010; Serreze et al., 2009). Unlike prior studies that focus on long-term trends or theoretical mechanisms (e.g., Cohen et al., 2020), our analysis quantifies these energy flux changes specifically during days of extreme sea-ice variability. This highlights the role of short-term SIC fluctuations in shaping seasonal air–sea energy exchange in the Arctic. However, the regions of strongest net heat-flux anomalies do not fully coincide with the areas of highest cumulative SIC variability (Figures 3a and 3d). The composite fields represent mean anomalies during high-variability days and are defined relative to the seasonal climatology (Figure S13 in Supporting Information S1). As a result, regions with a large climatological heat flux—such as along the climatological ice edge—do not necessarily exhibit the largest anomalies after a higher background state is removed (Figure S13 in Supporting Information S1). In contrast, areas with weaker climatological fluxes may display comparatively larger deviations during extreme variability events.

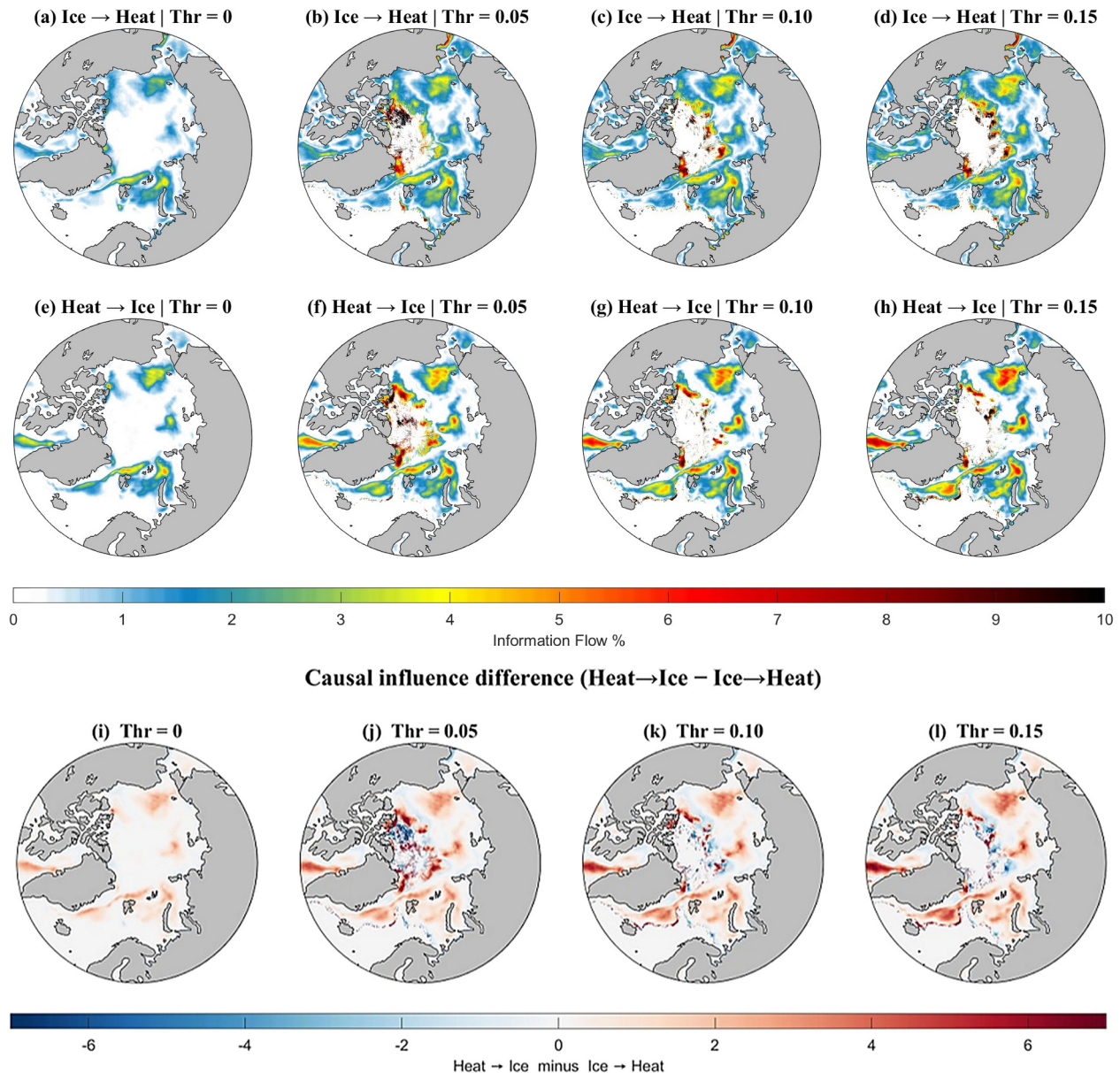


Figure 4. Causal relationships between ISIC'I (abbreviated as Ice) and net heat flux anomaly (abbreviated as Heat) in the Arctic, with different ISIC'I thresholds (0, 0.05, 0.10, and 0.15). (a–d), the causal influence of ISIC'I on net heat flux anomaly (Ice → Heat). (e–h) The reverse influence (Heat → Ice). Only regions where the causal relationships exceed the 95% significance level are shown. (i–l) Show the causal influence difference (Heat → Ice minus Ice → Heat), where positive values indicate regions dominated by heat-to-ice influence and negative values indicate the opposite. Grid points that do not pass the 95% significance test are set to zero when computing spatial differences.

Although this study focuses on air–sea heat exchange, we also computed the sea-ice phase-change term (Q_{phase}) which represents the latent heat flux associated with sea-ice melt and formation in the Arctic, with all details provided in Texts S4 and S5, Figures S14 and S15 in Supporting Information S1.

To complement the composite analysis, we further applied the Liang–Kleeman information flow framework (Liang, 2014), which allows us to quantify the causal direction and strength between ISIC'I and net heat flux anomalies. The results (Figure 4) show that the causal influence of ISIC'I on heat flux anomalies (Ice → Heat) is statistically significant and becomes stronger with increasing ISIC'I thresholds (Thr = 0–0.15). The causal linkage is bidirectional, with both Ice → Heat and Heat → Ice pathways significant, particularly along the MIZ. The effect strengthens under more extreme sea ice variability, indicating that high-variability conditions actively enhance

anomalous heat uptake or release. The reverse pathway (Heat $\rightarrow$ Ice) also intensifies with higher thresholds, reflecting feedbacks of anomalous surface heat fluxes on sea ice. A seasonal analysis (JJA and DJF, Figures S16 and S17 in Supporting Information S1) shows patterns highly consistent with the full-year results, confirming that the identified causal links do not depend on seasonality.

To directly compare the two pathways, we also examine their spatial difference (Heat $\rightarrow$ Ice minus Ice $\rightarrow$ Heat, Figures 4i–4l). Positive values highlight regions where surface net heat flux anomalies exhibit stronger causal strength toward sea-ice variability, whereas negative values indicate a locally even stronger causal signal. The difference maps confirm that the MIZ is the dominant region where Heat $\rightarrow$ Ice exceeds Ice $\rightarrow$ Heat, while also revealing pockets where the Ice $\rightarrow$ Heat causal signal is locally comparable under higher variability thresholds. This pattern highlights the MIZ as a hotspot where extreme sea-ice variability most effectively modulates air–sea energy exchange. Because information-flow magnitudes represent causal strength rather than physical impact, the difference field should be interpreted as indicating the relative dominance of the two causal pathways.

4. Discussion and Conclusions

Our findings highlight that the short-term variability of the Arctic sea-ice has increased over the past 40 years, particularly in summer and autumn in MIZ and ice edge. This increase in variability is associated with a stronger seasonal cycle of air–sea heat exchange, with enhanced heat absorption by the ocean in summer and increased heat release to the atmosphere in winter. These results suggest that short-term sea-ice fluctuations especially in the MIZ are an important but previously under-recognized contributor to local air–sea energy exchange, in addition to long-term ice-loss trends. The intensified heat-exchange response during high-variability days indicates that short-term ice variability has become an increasingly influential component of recent Arctic surface-flux behavior. The strengthened surface heat flux exchange seasonality associated with increased short-term sea ice variability may help reinforce Arctic Amplification.

A common external driver could also be at play behind the increased SIC variability in the marginal ice zone and the associated heat-flux anomalies. As thick multiyear ice is replaced by thinner, more fragile ice, the ice cover becomes more sensitive to short-term atmospheric forcing and less predictable on short timescales, thereby amplifying event-scale ice-edge fluctuations and their co-variability with surface heat-flux anomalies (Holland et al., 2019; Meng et al., 2023; Mioduszewski et al., 2019). Around 2007, the Arctic sea-ice cover underwent a major structural shift, transitioning from thicker, more deformed multi-year ice to thinner, more homogeneous first-year ice (Sumata et al., 2023). This structural change substantially reduced the stability of the ice pack. Weakened first-year ice is more easily fractured, advected, and deformed under synoptic disturbances such as storms or rapid pressure changes (Rheinländer et al., 2022). This suggests that the weakened sea ice became increasingly sensitive to short-term synoptic disturbances, making external atmospheric forcing a plausible common driver of both the intensified sea-ice variability and the accompanying anomalies in surface heat flux, particularly after 2007. In this view, the observed co-variability likely reflects not only the intrinsic feedbacks between sea-ice anomalies and surface heat-flux anomalies, but also their joint response to stronger and more effective atmospheric forcing acting on a mechanically weakened ice cover.

Our analysis shows that the most pronounced sea ice variability increases occur in the marginal seas, particularly in the Kara, Laptev, East Siberian, and Chukchi Seas. These regions have already experienced substantial sea ice retreat, which, in combination with heat-flux changes associated with sea-ice variability, may accelerate ice loss even further. Our causal analyses reveal a reinforcing feedback, in which higher sea-ice variability leads to anomalous net heat fluxes and is in turn amplified by them, further intensifying energy exchange and Arctic Amplification.

The growing variability of the ice adds new complexities to predictions of future Arctic climate change. While some climate models may accurately capture the long-term decline of Arctic sea ice, they often fail to fully account for the impact of short-term variability on ocean–atmosphere heat exchange. In light of the observed intensification of SIC variability, future modeling efforts must consider its potential feedback effects on Arctic warming.

4.1. As Applicable—Inclusion in Global Research Statement

This study was conducted through collaborative efforts involving researchers from multiple institutions across different regions. All co-authors have contributed to the research in accordance with AGU Publications authorship criteria. Data collection adhered to all necessary legal and ethical guidelines. We only used publicly available data sets. No permits were required for the use of publicly available data sets. The results are expected to benefit climate researchers, policymakers, and environmental monitoring agencies focusing on Arctic climate variability and its global implications.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The data used in this study are publicly available for download. The NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 4 is available at Meier et al. (2014). Since 31 July 2025, Version 4 has been retired and replaced by Version 5 (CDR V5). ERA5 hourly reanalysis data on single levels from 1940 to the present is available at Copernicus Climate Change Service (2023). The PIOMAS v2.1 (Pan-Arctic Ice Ocean Modeling and Assimilation System) data set, which provides daily Arctic sea ice thickness, is available at J. Zhang and Rothrock (2003). The code used for data processing and plotting is available at Zenodo at Wang (2026). All data sets are openly accessible, and there are no restrictions on their use.

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