



Seasonal reorganisation of the Asian summer monsoon response to projected Arctic sea-ice loss

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Abstract. The extent to which projected Arctic sea-ice loss affects the seasonal evolution of the Asian summer monsoon, and the physical mechanisms linking Arctic forcing to regional rainfall through remote atmospheric teleconnections, remain unclear. We investigate how projected Arctic sea-ice loss affects the Asian summer monsoon, and in particular how the response evolves within the monsoon season. We use 100-member ensembles from eight CMIP6 models participating in the 10 Polar Amplification Model Intercomparison Project (PAMIP) to examine June–September responses to present-to-future Arctic sea-ice loss. The prescribed sea-ice perturbation and near-surface Arctic warming strengthen through the melt season; precipitation and circulation responses over Asia change markedly between months. Stationary-wave anomalies and wave-activity flux indicate distinct Eurasian–North Pacific propagation pathways that develop within a seasonally varying upper-tropospheric jet. These changes coincide with shifts in upper-level divergence, vertical motion, lower-tropospheric circulation 15 and moisture convergence, with circulation-driven changes dominating the moisture-flux convergence response. Thus, stronger late-summer Arctic forcing does not produce a progressively stronger Asian monsoon response; instead, the atmospheric pathway and regional hydroclimatic response vary substantially through the season. More broadly, the pronounced month-to-month and regional contrasts in the forced response suggest that seasonal averaging may obscure important Arctic-related rainfall signals, while internal atmospheric variability may further complicate their identification in observations.

20 1 Introduction

Arctic sea ice has declined rapidly in recent decades, alongside pronounced Arctic warming and widespread changes in the high-latitude surface energy budget (Stroeve and Notz, 2018; Serreze and Barry, 2011). Enhanced turbulent and radiative heat fluxes from newly exposed ocean surfaces, together with strong temperature feedbacks, contribute to the amplification of Arctic warming (Serreze and Barry, 2011; Dai et al., 2019). Observations indicate that the Arctic has warmed at close to four 25 times the global-average rate since 1979 (Rantanen et al., 2022). Continued warming is expected to drive further reductions in Arctic sea ice, with the Arctic projected to become ice-free in September at least once before mid-century under a wide range of future emission scenarios (Fox-Kemper et al., 2021). These rapid changes have motivated extensive investigations of whether Arctic sea-ice loss can influence atmospheric circulation and climate beyond the Arctic.



30 A growing body of modelling and observational work shows that Arctic sea-ice loss can influence atmospheric circulation
beyond the Arctic. Large-ensemble experiments, particularly within the Polar Amplification Model Intercomparison Project
(PAMIP), provide an important framework for isolating the forced atmospheric response from internal variability and for
assessing its sensitivity to the magnitude and spatial pattern of sea-ice forcing (Smith et al., 2019; Peings et al., 2021; Smith
et al., 2022; Ye et al., 2024). Much of this literature has focused on the cold season, identifying changes in midlatitude
35 circulation, blocking and North Atlantic variability following Arctic sea-ice loss (Screen et al., 2018; Smith et al., 2022).
Previous studies have also demonstrated that remote atmospheric responses depend on both the characteristics of the imposed
sea-ice perturbation and the atmospheric background state through which the response develops (Screen, 2017; Screen et al.,
2018). A pronounced seasonal dependence of the atmospheric response to Arctic sea-ice loss has also been documented (Deser
et al., 2010). This suggests that the atmospheric response to Arctic sea-ice loss depends critically on the background circulation
40 state, which varies substantially across seasons.

This issue is particularly relevant for the Asian summer monsoon (ASM), one of the most prominent components of the global
monsoon system and a major source of annual precipitation across densely populated regions of South, Southeast and East
Asia (Webster et al., 1998; Wang and LinHo, 2002). From June to September, the ASM undergoes substantial changes in
45 precipitation distribution, tropical convection and large-scale circulation, together with pronounced variations in the position
and strength of the upper-tropospheric Asian jet (Wang and LinHo, 2002; Zhang et al., 2006). The atmospheric basic state
through which an externally forced disturbance propagates is therefore far from stationary during the summer season, while
stationary Rossby-wave propagation is sensitive to the configuration of the background flow (Hoskins and Karoly, 1981;
Hoskins and Ambrizzi, 1993). The Asian upper-tropospheric westerly jet also acts as a waveguide for established boreal-
50 summer teleconnection patterns, including the Silk Road pattern and the circumglobal teleconnection (Lu et al., 2002; Enomoto
et al., 2003; Ding and Wang, 2005; Kosaka et al., 2009). Such sensitivity to the background flow provides a basis for expecting
the downstream response to Arctic forcing to vary as both the imposed sea-ice perturbation and the seasonal circulation evolve.

Recent studies have increasingly examined possible links between Arctic sea ice and boreal-summer circulation and rainfall
55 over Asia. Arctic sea-ice variability has been related to Asian summer circulation and precipitation through changes in Eurasian
thermal contrasts, subtropical circulation and Rossby-wave propagation (Wu et al., 2009; Guo et al., 2014; Chatterjee et al.,
2021; Chen et al., 2022; Hu et al., 2023). Chen et al. (2024) showed that May Kara Sea (north of western Siberia) sea-ice loss
can strengthen June–July Meiyu–Baiu rainfall (the East Asian early-summer rainy season) when acting together with Indian
Ocean warming, highlighting the sensitivity of the downstream response to the tropical SST background. The relationship can
60 also operate in the opposite direction, with East and South Asian monsoon variability influencing summer Arctic sea-ice
patterns through atmospheric teleconnections and wind-driven ice transport (Grunseich and Wang, 2016). Using
observationally constrained PAMIP experiments, Zhang et al. (2024) examined the East Asian summer monsoon response to
preindustrial-to-present Arctic sea-ice loss and showed distinct responses in June and July. Their analysis further linked the



contrasting June and July precipitation responses to distinct upper-tropospheric circulation and Rossby-wave propagation pathways diagnosed using wave-activity flux. Duo and Zhang (2025) examined both preindustrial-to-present and present-to-future PAMIP Arctic sea-ice contrasts using observation-constrained sub-ensembles and linked Arctic sea-ice loss to delayed autumn monsoon retreat over the Indochina Peninsula based on the September–November mean response. Together, these studies demonstrate that Arctic sea-ice forcing can influence Asian monsoon climate and, importantly, that the associated atmospheric response can differ substantially between seasons and individual months.

However, an important question remains unresolved: whether and how the month-to-month differences identified in early summer extend across the full June–September monsoon season under projected present-to-future Arctic sea-ice loss, as both the imposed Arctic perturbation and the seasonal circulation background change. The prescribed sea-ice forcing changes in both magnitude and spatial structure through the melt season, while the climatological circulation over Eurasia and Asia simultaneously undergoes marked seasonal evolution. Consequently, the downstream response may reflect both the evolving Arctic forcing pattern and the changing atmospheric propagation environment, rather than simply strengthening with the magnitude of sea-ice loss. Previous work has established that Arctic sea-ice forcing can produce distinct early-summer circulation and Rossby-wave responses. However, whether these month-to-month differences extend into August and September, including changes in stationary-wave propagation, divergent circulation and regional moisture redistribution over the broader Asian monsoon domain, remains less well understood.

Here, we focus on the projected present-to-future Arctic sea-ice contrast to examine the atmospheric consequences of further Arctic sea-ice retreat. Building on previous PAMIP studies of both historical and future sea-ice changes, we resolve the response month by month from June to September across the broader Asian monsoon region. We jointly analyse the evolving Arctic surface perturbation, Asian precipitation and moisture transport, upper-tropospheric divergent and stationary-wave circulation, and the changing Eurasian upper-tropospheric jet within a common multi-model framework. This allows us to assess how the downstream circulation pathway and hydroclimatic response evolve as both the imposed Arctic forcing and the seasonal atmospheric basic state change through the monsoon season.

2 Data and methods

2.1 PAMIP experiments and model data

The experiments analysed in this study are from the Polar Amplification Model Intercomparison Project (PAMIP; Smith et al., 2019). We use PAMIP experiment 1.1 (pdSST–pdSIC), in which present-day sea-surface temperature (SST) and sea-ice concentration (SIC) are prescribed, and experiment 1.6 (pdSST–futArcSIC), in which present-day SST and projected future Arctic SIC are prescribed. Where sea ice is lost in pdSST–futArcSIC, the corresponding future SST is prescribed, while SST



95 outside the perturbed Arctic region remains at present-day values. The difference between the two experiments therefore represents the atmospheric response to projected Arctic sea-ice loss and the associated local SST changes.

Present-day SST and SIC forcing fields are based on the 1979–2008 HadISST climatology (Rayner et al., 2003), while future Arctic boundary conditions represent approximately 2 °C of global warming above pre-industrial conditions following the PAMIP protocol (Smith et al., 2019). Both experiments are 14-month atmosphere-only simulations beginning on 1 April 2000, as specified by the PAMIP protocol. The first two months are discarded as spin-up, and June–September of the first simulation year is analysed.

Eight PAMIP models were included based on the availability of both the pdSST–pdSIC and pdSST–futArcSIC experiments with at least 100 ensemble members and the atmospheric variables required for the diagnostics used in this study (Table 1). For each model and experiment, 100 ensemble members were analysed. Ensemble means were first calculated separately for each model and then combined as an unweighted multi-model mean. SIC output was available for five of the eight models (AWI-CM-1-1-MR, CanESM5, CESM2, CNRM-CM6-1 and HadGEM3-GC31-MM), whereas all eight models were used for the atmospheric analyses.

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Table 1. PAMIP models used in this study and availability of sea-ice concentration output.

Model	Modelling centre	Atmospheric horizontal resolution	Ensemble members used per experiment	SIC available
AWI-CM-1-1-MR	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), Germany	$\sim 0.94^\circ \times 0.94^\circ$	100	Yes
CanESM5	Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada (CCCma), Canada	$\sim 2.8^\circ \times 2.8^\circ$	100	Yes
CESM2	National Center for Atmospheric Research (NCAR), USA	$0.9^\circ \times 1.25^\circ$	100	Yes
CNRM-CM6-1	Centre National de Recherches Météorologiques and CERFACS (CNRM–CERFACS), France	$\sim 1.4^\circ \times 1.4^\circ$	100	Yes
FGOALS-f3-L	Chinese Academy of Sciences (CAS), China	$\sim 1^\circ \times 1^\circ$	100	No
HadGEM3-GC31-MM	Met Office Hadley Centre (MOHC), UK	$0.56^\circ \times 0.83^\circ$	100	Yes
IPSL-CM6A-LR	Institut Pierre-Simon Laplace (IPSL), France	$1.27^\circ \times 2.5^\circ$	100	No
NorESM2-LM	NorESM Climate Modelling Consortium / Norwegian Climate Centre (NCC), Norway	$1.9^\circ \times 2.5^\circ$	100	No



The prescribed present-day SIC is additionally compared with the 1979–2008 climatology from the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 6 (Meier et al., 2026; Fig. S1).

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Model output is regridded to a common $2.5^\circ \times 2.5^\circ$ grid using bilinear interpolation. Unless otherwise stated, atmospheric responses are defined as $\text{pdSST} - \text{futArcSIC}$ minus $\text{pdSST} - \text{pdSIC}$. Inter-model robustness is assessed, where indicated, from agreement in the sign of the model responses. Stippling denotes regions where at least seven of the eight models agree with the sign of the multi-model-mean response.

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The 250-hPa velocity potential (χ) and divergent wind are used to characterise the upper-tropospheric divergent circulation. Wave-activity flux (WAF) is calculated following Takaya and Nakamura (2001), using the monthly $\text{pdSST} - \text{pdSIC}$ climatology as the background flow and the stationary-wave streamfunction response as the perturbation field. Vertically integrated moisture transport and moisture-flux convergence (MFC) are calculated from specific humidity and horizontal wind (Trenberth et al., 2011).

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3 Results

3.1 Seasonal evolution of the prescribed Arctic sea-ice perturbation and thermal response

The prescribed Arctic sea-ice perturbation evolves markedly from June to September (Fig. 1). In June, the largest SIC reductions occur over Hudson Bay, with additional losses over Baffin Bay and the Barents–Eurasian Arctic margin. By July, the Hudson Bay anomaly weakens, while sea-ice loss strengthens across the Kara and Laptev Seas and adjacent Siberian coast. In August, strong negative SIC anomalies form a broad and relatively continuous band from the Kara and Laptev Seas eastward across the East Siberian and Chukchi Seas into the Beaufort sector. By September, the perturbation reaches its largest amplitude and most spatially coherent structure, with strong sea-ice loss extending farther into the central Arctic.

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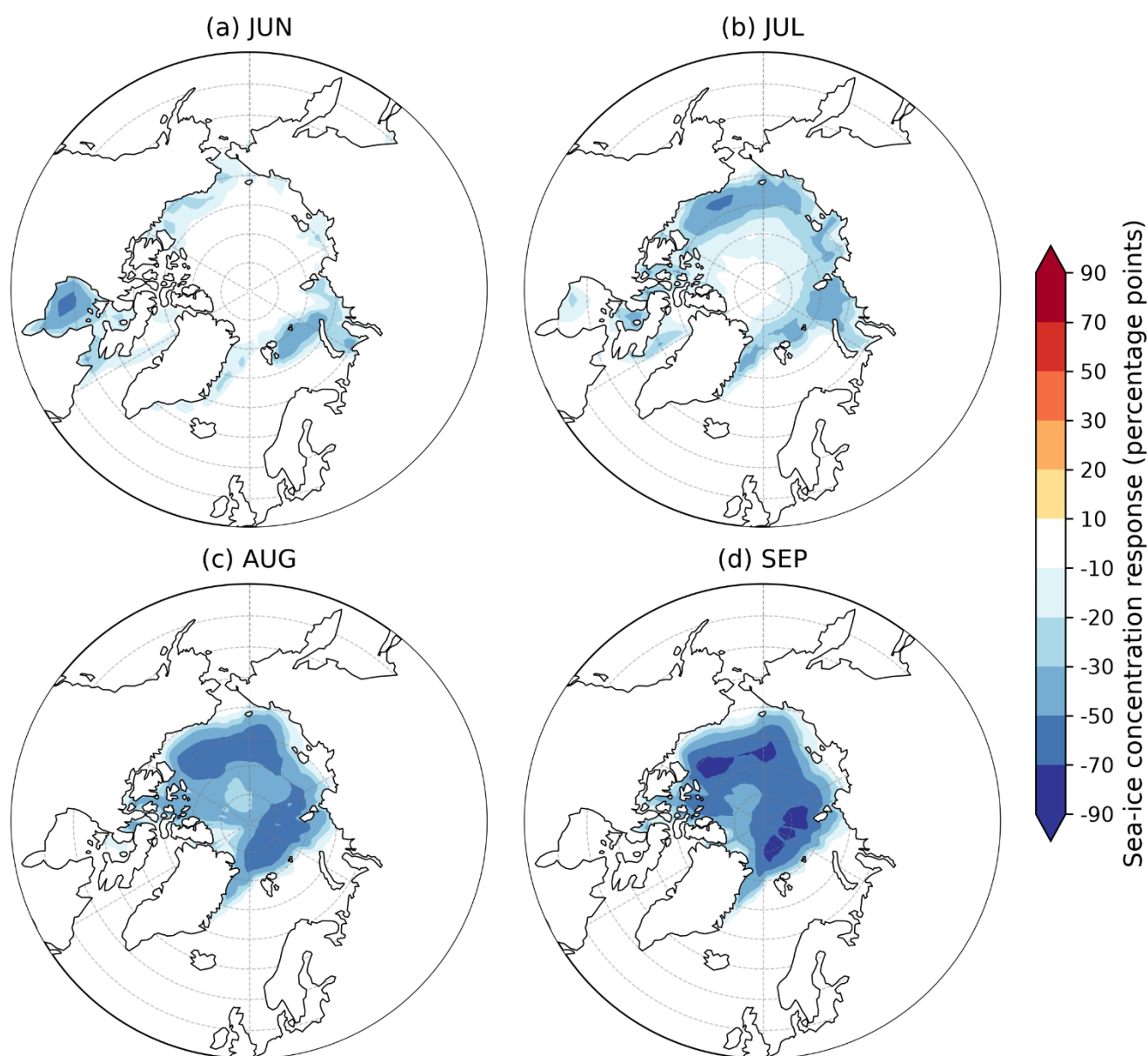


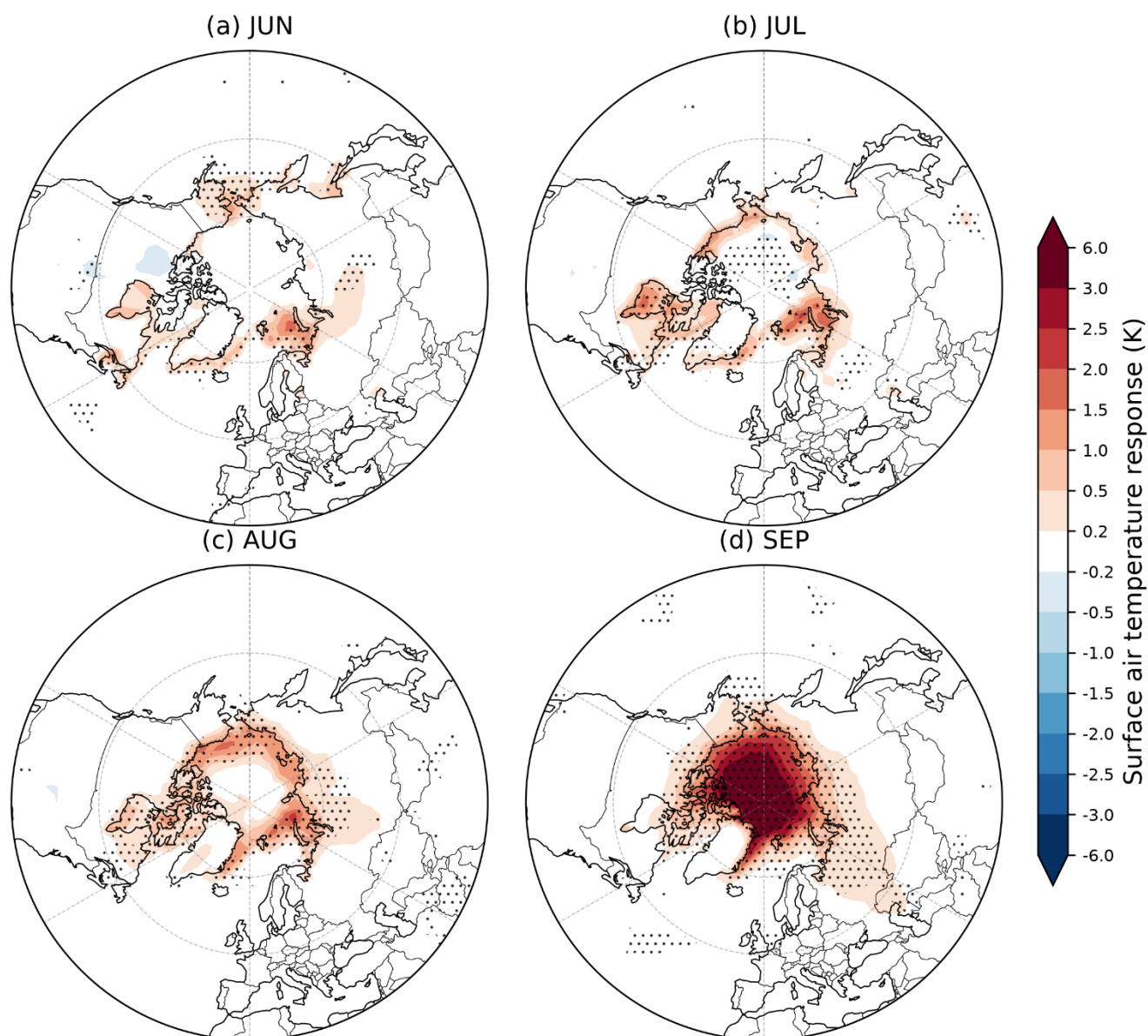
Fig. 1. Monthly evolution of the prescribed Arctic sea-ice concentration perturbation from June to September. SIC represents the fraction of each grid cell covered by sea ice. Shading shows the five-model mean difference in prescribed SIC between pdSST-futArcSIC and pdSST-pdSIC (%) for (a) June, (b) July, (c) August and (d) September.

The prescribed present-day SIC broadly reproduces the observed seasonal distribution and retreat of Arctic sea ice in the NOAA/NSIDC climatology (Fig. S1). The relative changes in SIC show the same seasonal progression, with the strongest and most widespread fractional reductions developing in August and September (Fig. S2). A comparison with observed relative



SIC changes over 1979–2008 shows a broadly similar seasonal progression, although the prescribed future perturbation is stronger and more spatially extensive (Fig. S3).

145 This seasonal evolution of the imposed surface perturbation is broadly reflected in the near-surface air temperature (TAS) response (Fig. 2). In June, when the SIC perturbation is relatively regional, warming is also comparatively localised around the Arctic margins and remains weak over much of the central Arctic. As sea-ice loss expands across the Eurasian and Pacific Arctic in July and August, positive TAS anomalies become progressively more widespread. By September, the broad and coherent loss of Arctic sea ice is accompanied by the strongest near-surface thermal response, with warming exceeding 3 K
150 over large parts of the Arctic Ocean and extending onto the adjacent continental margins.



Stippling indicates where at least 7 of 8 models agree on the sign of the multi-model-mean response.

Fig. 2. Seasonal evolution of the near-surface air temperature response to Arctic sea-ice loss. Shading shows the eight-model multi-model-mean near-surface air temperature response (ATAS; pdSST–futArcSIC minus pdSST–pdSIC; K) for (a) June, (b) July, (c) August, and (d) September. Stippling indicates regions where at least seven of the eight models agree on the sign of the multi-model-mean response.



The spatial correspondence is not exact, however. Atmospheric heat transport can redistribute the locally induced warming away from regions of strongest surface forcing, contributing to spatial differences between the SIC and TAS responses. The seasonal evolution of the TAS response broadly follows the changing magnitude and spatial extent of the prescribed SIC reduction. Incremental SIC changes show that the sea-ice-loss response strengthens substantially from June to August and continues to intensify over the central Arctic from August to September (Fig. S4). Consequently, by September, much of the central Arctic experiences substantially greater SIC loss than in August, coinciding with the pronounced increase in near-surface warming. In PAMIP, sea-ice retreat is accompanied by changes in the locally prescribed SST, so the thermal response reflects the combined local surface boundary-condition perturbation rather than SIC alone.

The connection with the evolving surface forcing becomes progressively weaker with height. At 850 hPa, the temperature response is substantially weaker and more spatially heterogeneous than the near-surface response (Fig. S5). The 850-hPa response does not show a simple monotonic progression from June to August, but becomes stronger and more spatially extensive in September. At 500 hPa, the thermal response weakens further and becomes more spatially heterogeneous, with localised warm and cool anomalies showing a weaker spatial correspondence with the regions of strongest SIC loss and near-surface warming (Fig. S6).

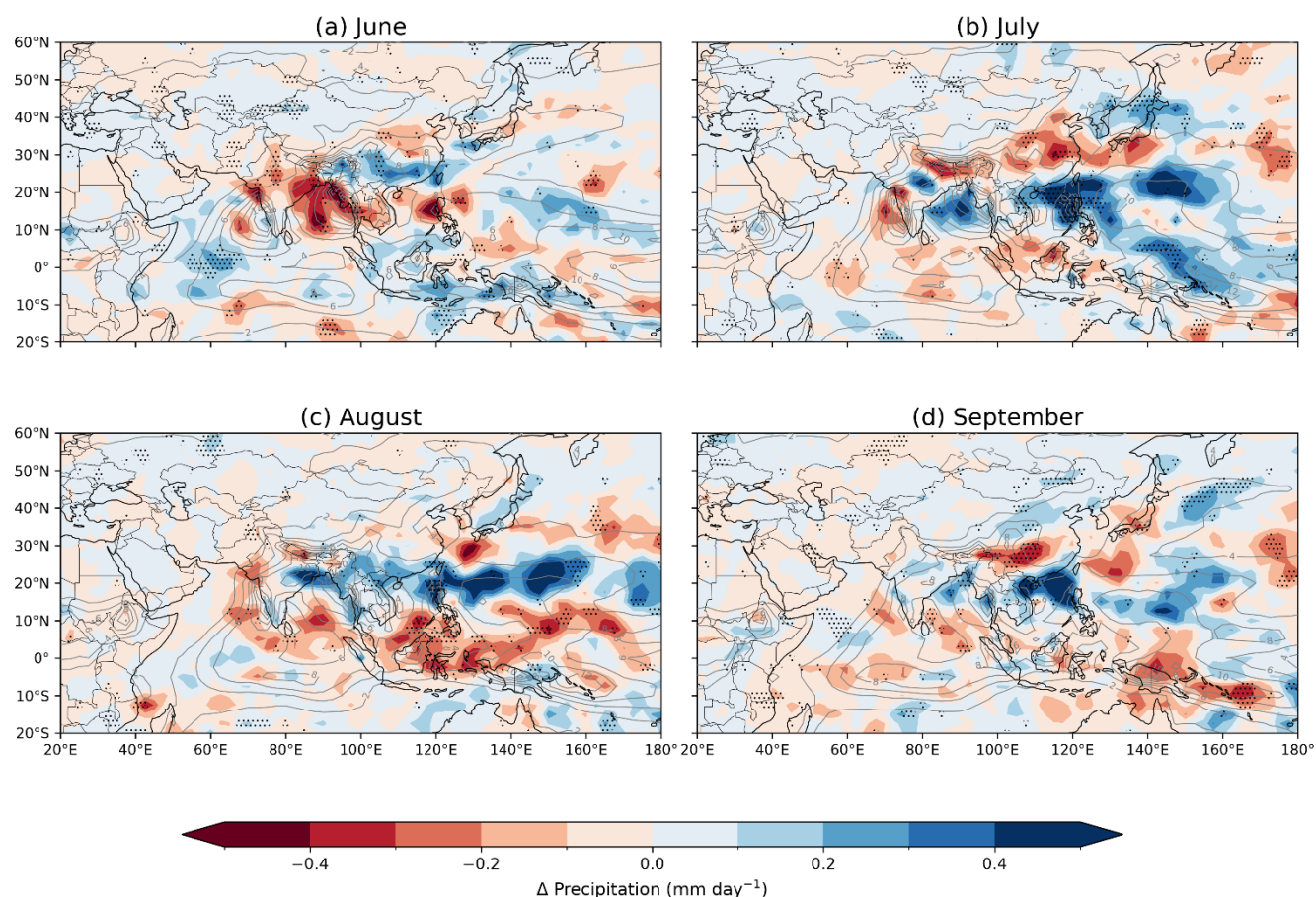
Thus, the strengthening Arctic surface perturbation from June to September is accompanied by a clear expansion and intensification of the near-surface warming response, whereas the lower-tropospheric response shows a less monotonic month-to-month evolution before becoming markedly broader in September. The direct thermodynamic signature also attenuates rapidly with height. The response is therefore strongly surface intensified, while the middle- and upper-tropospheric circulation anomalies cannot be interpreted as a simple vertical or horizontal extension of the near-surface warming pattern. This predominantly lower-tropospheric thermal structure is consistent with previous sea-ice-loss experiments showing that the strongest direct atmospheric warming occurs close to the surface and weakens substantially above the Arctic boundary layer (Deser et al., 2010; Screen et al., 2013).

3.2 Seasonal evolution of precipitation and moisture redistribution over the Asian monsoon region

The precipitation response over the Asian monsoon region varies markedly from June to September (Fig. 3), accompanied by substantial changes in vertically integrated moisture transport and moisture-flux convergence (MFC; Fig. 4). Positive precipitation anomalies are generally associated with enhanced moisture convergence, whereas negative precipitation anomalies tend to occur with anomalous moisture divergence, although the correspondence is not spatially exact. Fig. 4 shows the MFC response and vertically integrated moisture-transport anomalies, while the accompanying sea-level pressure and 850-hPa wind responses are shown in Fig. S7.



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Fig. 3. Month-to-month evolution of the Asian monsoon precipitation response to imposed future Arctic sea-ice conditions. Shading shows the eight-model mean precipitation response (pdSST-futArcSIC minus pdSST-pdSIC; mm day⁻¹) in (a) June, (b) July, (c) August, and (d) September. Dark-grey contours show the eight-model mean precipitation climatology in the pdSST-pdSIC experiment at 2, 4, 6, 8, and 10 mm day⁻¹. Stippling indicates regions where at least seven of the eight models agree on the sign of the precipitation response.

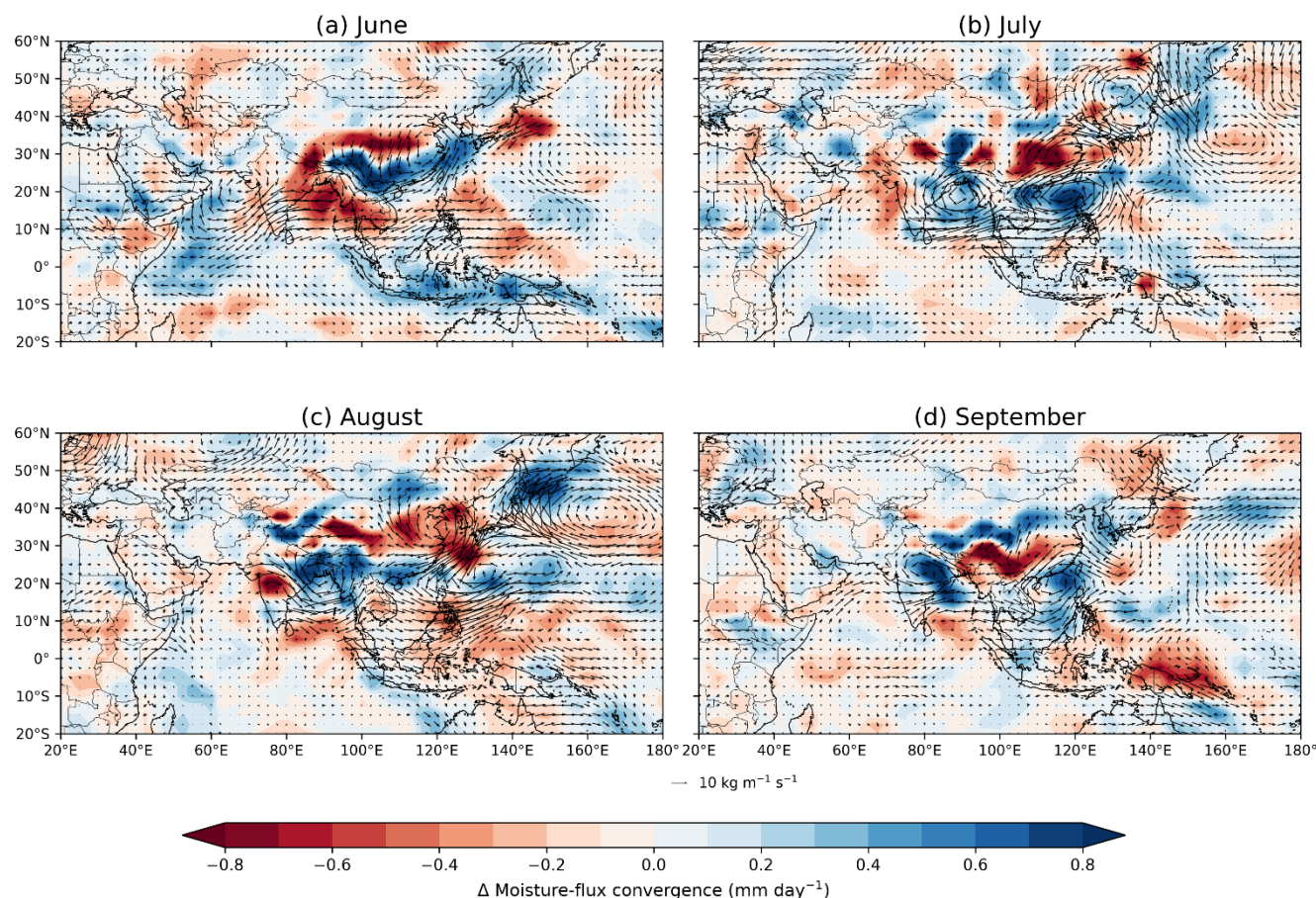


Fig. 4. Seasonal evolution of the vertically integrated moisture transport and moisture-flux convergence response to Arctic sea-ice loss. Shading shows the eight-model multi-model-mean moisture-flux convergence response (ΔMFC ; pdSST-futArcSIC minus pdSST-pdSIC ; mm day^{-1}) for (a) June, (b) July, (c) August, and (d) September. Black vectors show the corresponding response in vertically integrated moisture transport ($\text{kg m}^{-1} \text{s}^{-1}$). Positive ΔMFC values indicate enhanced moisture convergence, while negative values indicate enhanced moisture divergence. The reference moisture-transport vector denotes $10 \text{ kg m}^{-1} \text{s}^{-1}$.

In June, reduced precipitation is concentrated over western India and the northeastern India–northern Bay of Bengal sector, with additional negative anomalies over parts of Indochina and the northern South China Sea–Philippines region. Enhanced precipitation occurs over the tropical Indian Ocean and parts of the Maritime Continent, while a separate positive anomaly extends from the Yangtze River region towards southern Japan and the western North Pacific. The MFC response shows anomalous moisture divergence over parts of the India–Bay of Bengal–Indochina sector, broadly corresponding to the main rainfall reductions. The associated moisture-transport and 850-hPa circulation anomalies (Fig. S7a) indicate accompanying changes in the low-level flow and regional moisture distribution.



By July, the precipitation response changes sign across much of the Bay of Bengal–Indochina–western North Pacific sector. A broad region of enhanced rainfall extends from the Bay of Bengal across Indochina, the South China Sea and the Philippines into the western North Pacific, whereas reduced precipitation remains over the Arabian Sea–northwestern India sector and appears farther north over parts of East Asia. The MFC response shows enhanced convergence across much of the tropical and subtropical wet region, particularly over the South China Sea–Philippines sector, with anomalous divergence farther north over eastern China. The 850-hPa circulation response is characterised by an anomalous cyclonic circulation over the South China Sea–Philippines sector, associated with negative sea-level pressure anomalies (Fig. S7b). Anomalous westerly flow along its southern flank favours eastward moisture transport from the Bay of Bengal–Indochina region towards the South China Sea and Philippines, contributing to the enhanced moisture convergence and precipitation over this sector. This is consistent with the enhanced moisture convergence and broad positive precipitation anomalies across the same region.

In August, the precipitation response becomes more zonally organised. A pronounced positive band extends from northern and northeastern India through the Bay of Bengal and Indochina eastward towards the western North Pacific, while negative anomalies occur mainly to the south over the tropical Indian Ocean–Maritime Continent sector and locally farther north over East Asia. The MFC field shows enhanced moisture convergence over northern India–Bay of Bengal and farther east over the Philippine Sea–western North Pacific, broadly corresponding to the main wet anomalies, with moisture divergence on adjacent flanks. At lower levels, a pronounced positive sea-level pressure anomaly and associated anticyclonic circulation develop over the western North Pacific (Fig. S7c), embedded within a broader reorganisation of the lower-tropospheric circulation across East Asia and the North Pacific. Together with the moisture-transport anomalies in Fig. 4c, this circulation pattern is accompanied by enhanced moisture convergence along the zonally elongated wet corridor extending from northern India through Indochina towards the western North Pacific. This circulation–moisture configuration is consistent with the positive precipitation band centred approximately along 15–30°N. Among the four months, August therefore exhibits one of the clearest spatial correspondences between the precipitation and moisture-convergence responses.

By September, the precipitation response becomes more regionally structured than in July and August. Enhanced precipitation is concentrated over southern China, the Gulf of Tonkin and the northern South China Sea, with an additional positive anomaly over northeastern India and the northern Bay of Bengal. In contrast, reduced precipitation extends across parts of central and eastern China, including the Yangtze River sector, towards the East China Sea and parts of Japan. The MFC response is similarly regional, with enhanced moisture convergence over northern India–Bay of Bengal and the South China Sea sector, while anomalous moisture divergence occurs over adjacent parts of East Asia. The September response therefore differs markedly from the more continuous precipitation and moisture-convergence patterns in July and August, indicating a further reorganisation of the regional hydroclimatic response. The PSL and 850-hPa wind anomalies in Fig. S7d show a more regionally heterogeneous lower-tropospheric circulation response than in July and August. This circulation pattern is accompanied by contrasting moisture-convergence and divergence anomalies across Asia, consistent with enhanced



precipitation over southern China–the northern South China Sea and the northern Bay of Bengal, but reduced precipitation farther north over central and eastern China.

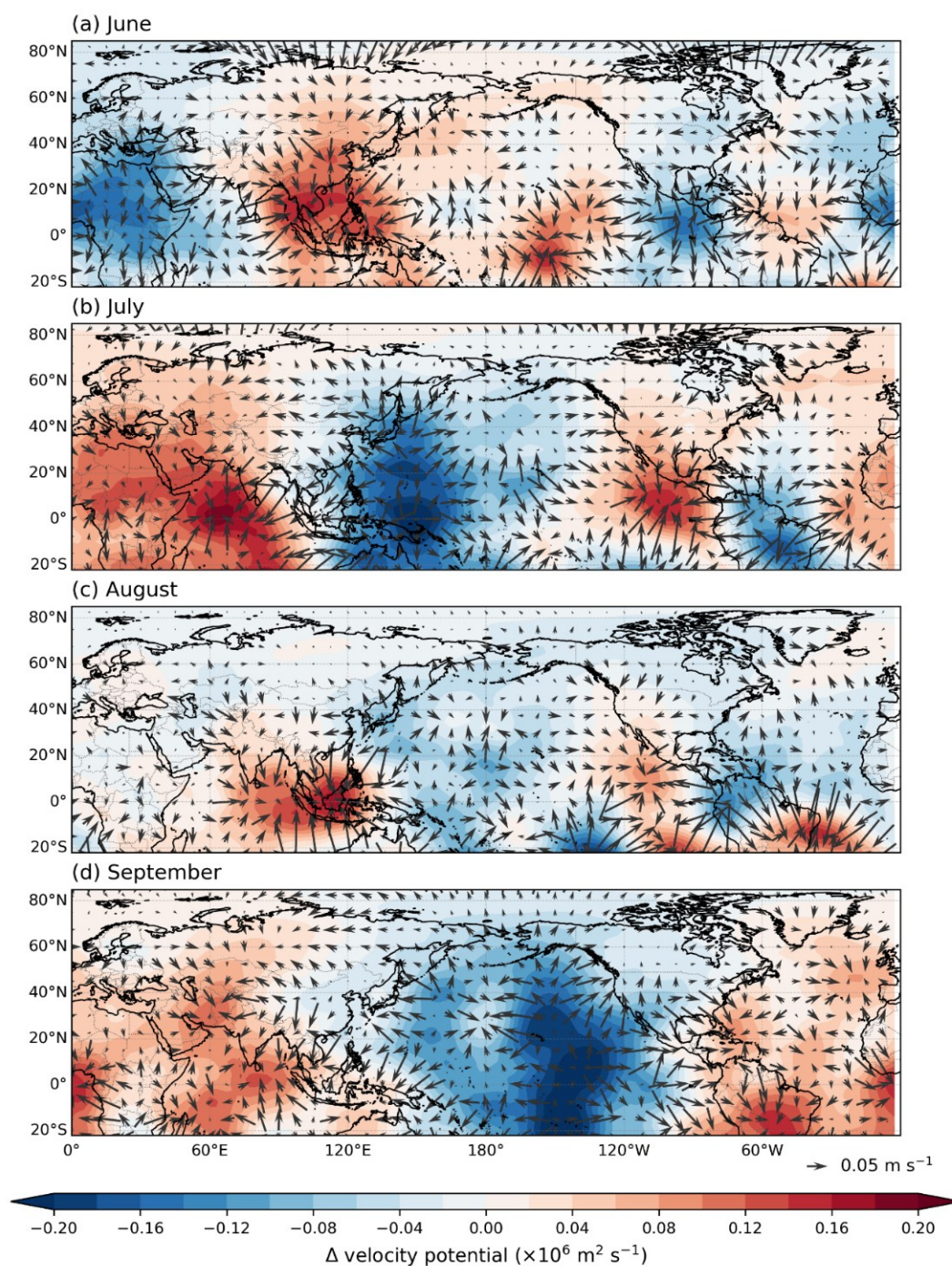
To further diagnose the MFC response, it is separated into dynamic, thermodynamic and nonlinear contributions following Seager et al. (2010) and Endo and Kitoh (2014) (Figs. S8–S9). The dynamic contribution is substantially larger than the thermodynamic contribution across the four months and reproduces much of the spatial structure of the total MFC response (Fig. S8). The thermodynamic contribution is weaker and more spatially diffuse, while the nonlinear contribution is small in comparison (Fig. S9). This indicates that the MFC response is dominated by circulation anomalies acting on the climatological moisture distribution.

The relative precipitation response provides complementary information on the fractional magnitude of these changes (Fig. S10). The largest percentage changes occur partly over climatologically drier regions in the western part of the domain, where small baseline precipitation enhances the relative response; the spatial evolution of the monsoon rainfall response is therefore more clearly represented by the absolute changes in Fig. 3.

A notable feature of the hydroclimatic response is the pronounced month-to-month reversal in both precipitation and moisture convergence. The Bay of Bengal–Indochina–western North Pacific sector changes from predominantly reduced precipitation and anomalous moisture divergence in June to widespread enhanced precipitation and moisture convergence in July and August, before reorganising again in September. Together with the dominance of the dynamic MFC contribution, these changes show that the regional precipitation response is closely tied to month-dependent circulation-driven moisture redistribution.

3.3 Seasonal evolution of the upper-tropospheric circulation and stationary-wave propagation

The mid-tropospheric response provides an additional link between the regional vertical-motion anomalies and the upper-level circulation. Although the direct temperature response is weak at 500 hPa (Fig. S6), coherent geopotential-height anomalies remain evident and vary substantially from month to month (Fig. S11). This contrast shows that vertically extended circulation anomalies coexist with a strongly surface-intensified thermal response, without implying a simple vertical continuation of the near-surface warming pattern. The upper-tropospheric circulation response also varies substantially from June to September (Figs. 5 and 6). The velocity-potential and divergent-wind response in Fig. 5 is used to characterise the large-scale divergent circulation associated with regional precipitation and vertical-motion anomalies. In Fig. 6, the stationary-wave streamfunction is obtained by removing the zonal-mean streamfunction from each experiment, and the corresponding WAF is used to diagnose the direction and spatial structure of the extratropical stationary-wave response. Considered together, these fields allow the upstream stationary-wave anomalies, downstream wave-activity pathways and associated Asian circulation responses to be examined within a common dynamical framework.



280 **Fig. 5.** Seasonal evolution of the upper-tropospheric divergent circulation response to Arctic sea-ice loss. Shading shows the eight-model multi-model-mean 250-hPa velocity-potential response ($\Delta\chi$; pdSST–futArcSIC minus pdSST–pdSIC; $\times 10^6$ m² s⁻¹), and vectors show the corresponding 250-hPa divergent-wind response (m s⁻¹) for (a) June, (b) July, (c) August, and (d) September. The reference vector denotes 0.05 m s⁻¹.

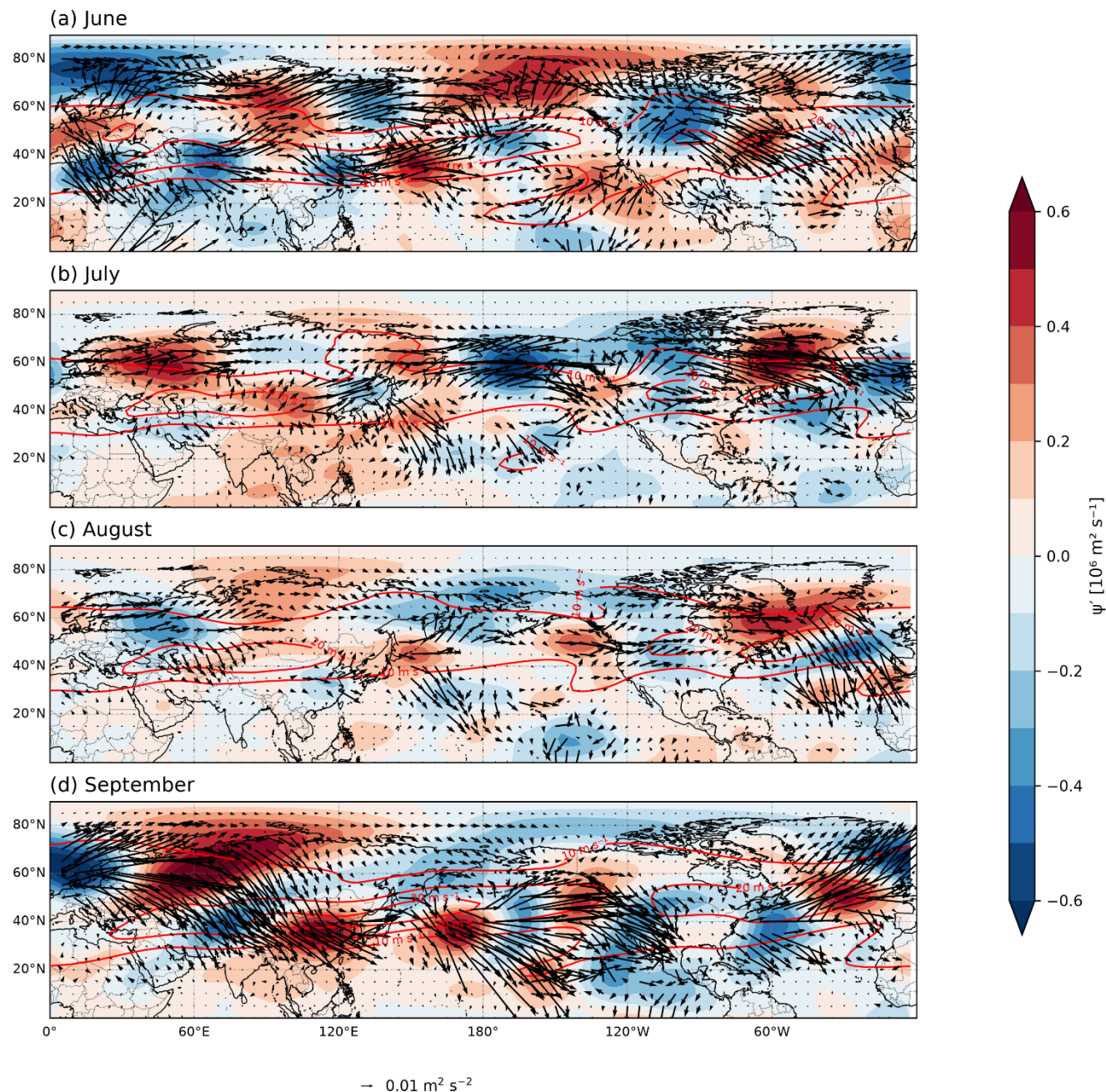


Fig. 6. Seasonal evolution of the upper-tropospheric stationary-wave response to Arctic sea-ice loss. Shading shows the eight-model multi-model-mean 250-hPa stationary-wave streamfunction response (pdSST-futArcSIC minus pdSST-pdSIC; $\times 10^6 \text{ m}^2 \text{ s}^{-1}$) for (a) June, (b) July, (c) August, and (d) September. Black vectors show the corresponding 250-hPa wave-activity flux (WAF), while red contours show the 250-hPa climatological zonal wind in the pdSST-pdSIC experiment at 10 and 20 m s⁻¹. The reference WAF vector denotes 0.01 m² s⁻². WAF vectors are shown only where the climatological 250-hPa horizontal wind speed is at least 5 m s⁻¹.



In June, coherent stationary-wave anomalies extend from northern Eurasia towards East Asia and the North Pacific, with WAF directed predominantly eastward and southeastward across Eurasia (Fig. 6a). This configuration identifies an upstream-to-downstream wave-activity pathway linking the high-latitude Eurasian circulation response with the Asian sector. Downstream, positive velocity-potential anomalies and anomalous upper-level convergence are centred over Indochina and the South China Sea (Fig. 5a), where anomalous subsidence is also evident at 500 hPa (Fig. S12a). These circulation anomalies are accompanied by anomalous moisture divergence across much of the India–Bay of Bengal–Indochina sector (Fig. 4a) and reduced precipitation over the same broad region (Fig. 3a). Taken together, the June fields show a dynamically consistent association between the upstream extratropical stationary-wave response, downstream circulation anomalies, and regional moisture and precipitation changes over the Asian monsoon region.

By July, the upper-tropospheric circulation and stationary-wave pathway reorganise substantially. The stationary-wave response becomes more zonally elongated across the Eurasian–North Pacific sector, with WAF extending eastward from Eurasia into the North Pacific (Fig. 6b). Over East Asia and the western North Pacific, the downstream positive streamfunction anomaly represents an upper-level anticyclonic circulation anomaly. Anomalous descent occurs on its eastern flank over parts of the subtropical western North Pacific, where positive sea-level pressure anomalies also develop (Figs. S12b and S7b). Farther south, anomalous ascent extends across the South China Sea–Philippines and adjacent western North Pacific sector, coinciding with negative sea-level pressure anomalies and an anomalous cyclonic low-level circulation (Figs. S12b and S7b). These ascending regions also correspond to enhanced moisture convergence and positive precipitation anomalies (Figs. 4b and 3b), providing a more direct vertical link between the upper-level stationary-wave structure and the regional rainfall response. Consistent with the anomalous ascent and enhanced convection, a broad negative velocity-potential anomaly is centred over the equatorial western Pacific, with associated upper-level divergent flow extending across the tropical western North Pacific (Fig. 5b). Together, these anomalies define a July wave–circulation–moisture configuration distinct from that in June, with enhanced ascent, moisture convergence and rainfall extending across much of the tropical and subtropical Asian monsoon region. The meridional circulation and precipitation structure over the western North Pacific and East Asia also resembles a Pacific–Japan (PJ)-like configuration, in which tropical western North Pacific convective anomalies are accompanied by an extratropical circulation response over East Asia (Nitta, 1987; Huang and Sun, 1992; Kosaka and Nakamura, 2006).

In August, the dynamical configuration changes again. Although the imposed Arctic surface perturbation has strengthened relative to early summer, the Eurasian branch of the stationary-wave response becomes less spatially continuous, with a more fragmented WAF structure across Eurasia and Asia (Fig. 6c). The large-scale velocity-potential response is also weaker than in July (Fig. 5c). Nevertheless, the regional vertical-motion response over the Asian monsoon sector remains highly organised, with anomalous ascent extending from northern India and the Bay of Bengal eastward across Indochina and the South China Sea towards the western North Pacific, accompanied by anomalous descent farther south over the tropical Indian Ocean–



325 Maritime Continent sector (Fig. S12c). This meridional contrast closely corresponds to the precipitation response, with a broad
 positive rainfall band extending across approximately 15–30°N and negative anomalies occurring mainly to the south (Fig.
 3c). Pronounced moisture convergence along the northern India–Bay of Bengal–Indochina–western North Pacific corridor
 further supports this pattern (Fig. 4c). August therefore shows that the regional hydroclimatic response remains spatially
 coherent despite a less continuous large-scale stationary-wave and velocity-potential signal, with the lower-tropospheric
 330 circulation and associated moisture convergence providing a more direct regional link to the precipitation pattern (Figs. S7c
 and 4c).

In September, a strong and spatially coherent stationary-wave pattern extends across the North Atlantic–Eurasian–North
 Pacific sector, with widespread WAF indicating a well-defined downstream propagation pathway (Fig. 6d). Over the Pacific,
 335 the main negative velocity-potential anomaly is centred over the tropical central Pacific, with associated divergent outflow
 extending across the surrounding tropical Pacific (Fig. 5d). The corresponding 500-hPa vertical-motion response remains
 regionally structured over Asia (Fig. S12d), with contrasting ascent and descent anomalies rather than the broad coherent
 ascent seen in July. This circulation pattern is accompanied by enhanced moisture convergence and precipitation over southern
 China–the northern South China Sea and the northern Bay of Bengal, together with moisture divergence and reduced
 340 precipitation over parts of central and eastern China (Figs. 3d and 4d). September therefore shows that a strong and coherent
 large-scale stationary-wave response can project onto a highly regional hydroclimatic pattern over Asia when the downstream
 circulation configuration differs from that in earlier months.

Overall, the upper-tropospheric response exhibits pronounced month-to-month reorganisation from June to September. The
 stationary-wave structure and WAF identify distinct propagation pathways across Eurasia and the North Pacific in different
 345 months, while the associated divergent-circulation response over Asia changes in both position and strength. These changes
 are accompanied by corresponding shifts in vertical motion, lower-tropospheric circulation, moisture transport and
 precipitation over the Asian monsoon region. The strengthening Arctic surface perturbation through late summer therefore
 does not produce a progressively stronger or geographically fixed downstream response. Instead, the atmospheric pathway
 linking the Arctic perturbation to the Asian monsoon region undergoes marked month-to-month reorganisation as both the
 350 imposed forcing pattern and the background atmospheric circulation evolve through the season.

3.4 Seasonal evolution of the Eurasian upper-tropospheric jet

To characterise the seasonally evolving atmospheric basic state, we examine the position and strength of the Eurasia upper-
 tropospheric jet using a longitude-dependent maximum-wind approach, consistent with previous characterisations of the
 seasonal East Asian upper-tropospheric jet (Zhang et al., 2006) and with an analogous jet-core approach used for wintertime
 355 East Asian jet variability by Chan et al. (2020).

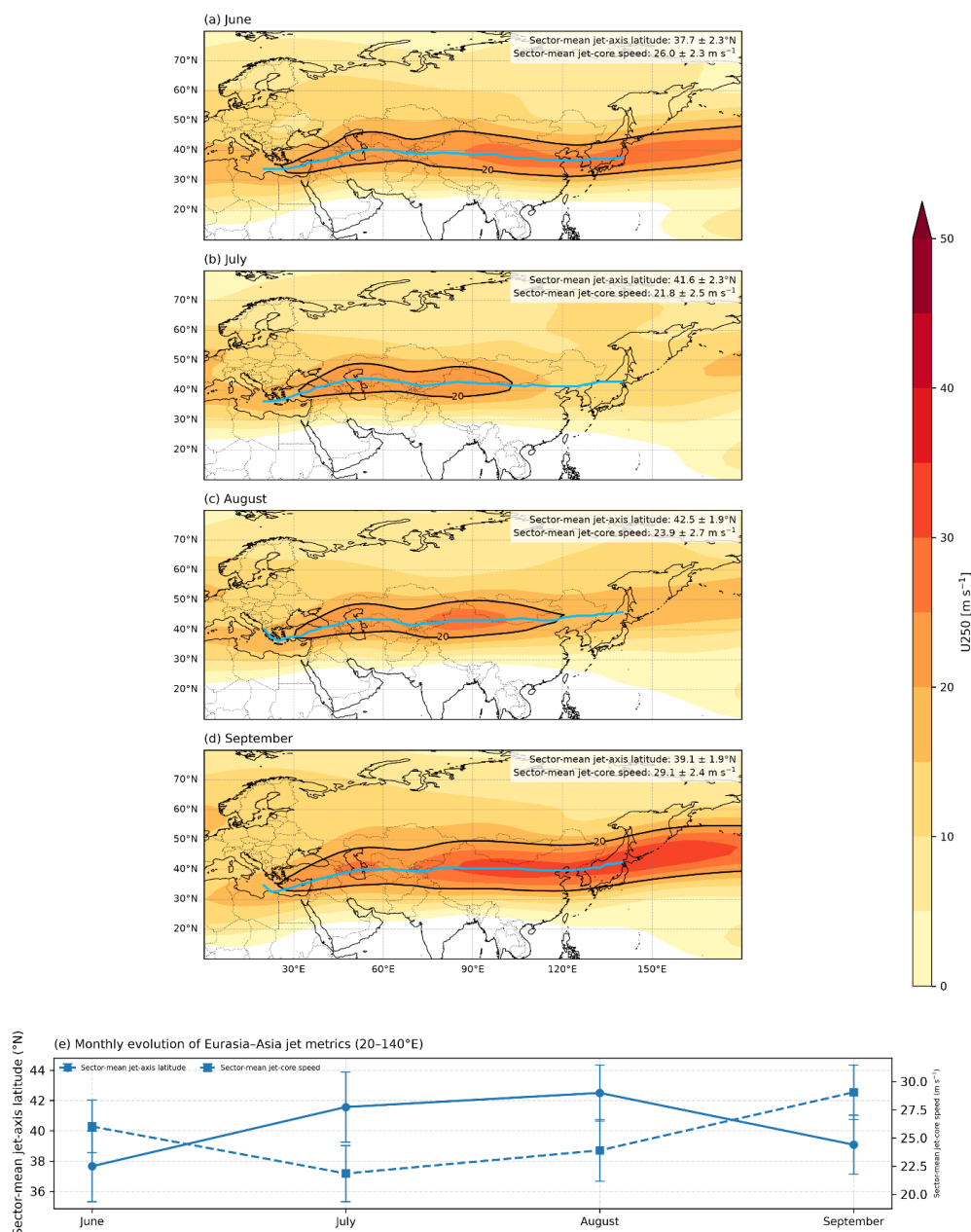


Fig. 7. Monthly evolution of the climatological upper-tropospheric jet over Eurasia and Asia. Shading in (a–d) shows the eight-model multi-model-mean 250-hPa zonal-wind climatology (U250; m s⁻¹) in the pdSST–pdSIC experiment for (a) June, (b) July, (c) August, and (d) September. Cyan lines indicate the eight-model mean jet-axis latitude at each longitude over 20°E–140°E. For each model, the jet axis is defined at each longitude as the latitude of maximum U250 within 20°–60°N. Black contours denote U250 = 20 m s⁻¹ and are included only to visualise the climatological jet structure; this threshold is not used in calculating the jet metrics. Values in (a–d) give the eight-model mean ±1 inter-model standard deviation of the sector-mean jet-axis latitude and sector-mean jet-core speed over 20°E–140°E. (e) Monthly evolution of the sector-mean jet-axis latitude (solid line; left axis) and sector-mean jet-core speed (dashed line; right axis) from June to September. Error bars in (e) denote ±1 inter-model standard deviation across the eight models.



The Eurasian upper-tropospheric jet exhibits pronounced seasonal changes in both position and strength (Fig. 7e). The sector-mean jet axis shifts poleward from $37.7 \pm 2.3^\circ\text{N}$ in June to $41.6 \pm 2.3^\circ\text{N}$ in July and $42.5 \pm 1.9^\circ\text{N}$ in August, before shifting equatorward to $39.1 \pm 1.9^\circ\text{N}$ in September. The paired August-minus-July jet-axis change is $+0.93 \pm 1.28^\circ$, which is relatively small compared with the inter-model spread, although six of the eight models exhibit a poleward shift. The sector-mean jet-core speed decreases from $26.0 \pm 2.3 \text{ m s}^{-1}$ in June to $21.8 \pm 2.5 \text{ m s}^{-1}$ in July, increases to $23.9 \pm 2.7 \text{ m s}^{-1}$ in August, and reaches $29.1 \pm 2.4 \text{ m s}^{-1}$ in September. In contrast to the relatively uncertain jet-axis change, the paired August-minus-July jet-core-speed increase is more consistent across models ($+2.05 \pm 1.26 \text{ m s}^{-1}$), with seven of the eight models showing an increase.

These pronounced seasonal changes in the latitude and strength of the Eurasian upper-tropospheric jet provide a dynamically varying background for the month-to-month reorganisation of the stationary-wave response. The poleward migration of the jet from June to August, followed by its equatorward shift and marked strengthening in September, alters the background westerly flow through which stationary-wave activity propagates. The changing jet configuration is therefore consistent with the substantial differences in WAF structure and downstream circulation seen in Fig. 6. Although the present diagnostics do not isolate the jet as an independent causal forcing, they support the interpretation that the seasonal basic state helps condition the pathway and regional expression of the Arctic-forced circulation response.

4 Discussion and conclusions

This study examines how the Asian monsoon response to projected Arctic sea-ice loss evolves from June to September within the PAMIP framework. The results show that the downstream atmospheric response undergoes substantial seasonal reorganisation rather than simply scaling with the increasing magnitude of Arctic sea-ice loss. Three main findings emerge from this study. First, although the prescribed Arctic sea-ice perturbation strengthens and expands through the melt season, the Asian monsoon response does not intensify monotonically from June to September. Instead, precipitation and circulation anomalies undergo pronounced month-to-month reorganisation. Second, these changes are accompanied by distinct stationary-wave propagation pathways, upper-level divergent circulation, vertical motion and regional moisture redistribution, with the dynamic MFC contribution dominating over the thermodynamic and nonlinear terms. Third, the circulation response develops within a strongly evolving climatological upper-tropospheric jet, indicating that the seasonal atmospheric basic state helps condition the propagation and regional expression of the Arctic-forced response.

Within the PAMIP framework, the ensemble-mean atmospheric differences can be attributed to the prescribed Arctic boundary-condition perturbation because the two experiments share the same remote SST and external-forcing background and differ only in Arctic SIC and the associated local SST adjustments in regions of sea-ice retreat. The MFC decomposition further shows that circulation anomalies acting on the climatological moisture distribution provide the leading contribution to



400 the regional moisture response. At the same time, the climatological upper-tropospheric jet changes substantially in latitude and strength from June to September, whereas the direct sea-ice-loss-induced jet response remains comparatively small (Fig. S13). The associated changes in the background westerly flow provide different propagation environments for the stationary-wave response in each month, consistent with the substantial month-to-month differences in WAF structure and downstream circulation geometry. Although the present diagnostics do not isolate the jet as an independent causal factor, they support the interpretation that the seasonal basic state helps modulate the pathway through which the Arctic-forced circulation response reaches Asia.

The pronounced seasonal dependence found here is consistent with previous PAMIP studies of Arctic–Asian summer teleconnections, but the present analysis extends this framework in several important respects. Zhang et al. (2024) identified distinct East Asian summer monsoon responses to Arctic sea-ice loss in June and July using observationally constrained PAMIP sub-ensembles. In contrast, we focus on the projected present-to-future Arctic sea-ice contrast and extend the analysis across the full June–September monsoon season and the broader Asian monsoon domain. More importantly, the precipitation changes are examined together with the corresponding stationary-wave pathways, evolving upper-tropospheric basic state, vertical circulation and circulation-driven moisture redistribution. This shows that the seasonal reorganisation is not confined to rainfall alone, but extends across the dynamical pathway linking the Arctic perturbation to the Asian monsoon region. The enhanced September precipitation over southern China, the Gulf of Tonkin and the northern South China Sea is also qualitatively consistent with the delayed autumn monsoon retreat over the Indochina Peninsula reported by Duo and Zhang (2025), although the present analysis does not explicitly diagnose monsoon withdrawal timing.

420 The sensitivity of the downstream response to the surrounding climate background is also evident when the present results are compared with Chen et al. (2024). They found enhanced June–July Meiyu–Baiu rainfall when May Kara Sea sea-ice loss acted together with Indian Ocean warming, whereas the present PAMIP experiments show reduced July precipitation along approximately 25–35°N from eastern China towards the East China Sea and south of Japan (Fig. 3b). The contrasting responses arise under different boundary-condition settings: Chen et al. (2024) included concurrent Indian Ocean warming, while the present experiments isolate projected Arctic sea-ice loss with the remote SST background held fixed. This comparison further illustrates that the Asian monsoon response to Arctic sea-ice loss depends on the broader boundary-condition and circulation background in which the forcing acts, rather than being associated with a single fixed regional rainfall pattern.

The prescribed Arctic sea-ice perturbation can also be placed in the context of observed changes over the satellite era. Observed relative SIC changes derived from the 1979–2008 linear trend show a broadly similar seasonal progression, with stronger and more spatially extensive reductions developing in August and September (Fig. S3). However, the prescribed future perturbation is generally stronger and extends farther into the central Arctic than the recent observed changes. The incremental SIC response further shows substantial strengthening of sea-ice loss from June to August and continued intensification over the central Arctic



from August to September (Fig. S4), helping to place the pronounced late-summer thermal response in the context of the
435 evolving surface forcing.

Several limitations should be acknowledged. First, the atmosphere-only PAMIP design excludes coupled ocean–atmosphere
feedbacks and remote SST responses, which can modify the magnitude and spatial structure of the atmospheric response to
Arctic sea-ice loss (Deser et al., 2016). Second, because both the magnitude and spatial structure of the prescribed Arctic
440 perturbation and the climatological atmospheric circulation evolve from June to September, their individual contributions to
the month-to-month response cannot be formally separated within the present experimental design. The stationary-wave, WAF
and jet diagnostics therefore identify a dynamically consistent pathway and its seasonal modulation, but do not quantify the
independent contribution of each component. Third, although the 100-member ensembles substantially reduce sampling
uncertainty associated with internal atmospheric variability, only eight PAMIP models are included and SIC output is available
445 for five, so model structural uncertainty is not fully sampled. Finally, the present diagnostics do not explicitly isolate the
dynamical transition between the extratropical stationary-wave response and the tropical–subtropical monsoon circulation.
Feedbacks involving Asian monsoon convection may therefore contribute to the detailed divergent-circulation and
precipitation responses and cannot be separated from the broader atmospheric adjustment in these experiments. These
limitations affect the degree to which individual dynamical contributions can be separated, but not the attribution of the
450 ensemble-mean response to the imposed Arctic surface boundary perturbation within the PAMIP framework.

Overall, projected Arctic sea-ice loss produces a strongly month-dependent atmospheric and hydroclimatic response across
the Asian monsoon region from June to September. Although the Arctic surface perturbation strengthens through the melt
season, the downstream Asian response does not strengthen monotonically. Instead, stationary-wave propagation, divergent
455 circulation, vertical motion and circulation-driven moisture redistribution reorganise from month to month as both the Arctic
forcing pattern and the atmospheric basic state evolve. These results indicate that the regional Asian monsoon response depends
not only on the magnitude of Arctic sea-ice loss, but also on the seasonally varying atmospheric pathway through which the
response is transmitted.



Code and data availability

460 The PAMIP model simulations analysed in this study are part of CMIP6 and are available through the Earth System Grid Federation (ESGF). We use PAMIP experiment 1.1 (pdSST–pdSIC) and experiment 1.6 (pdSST–futArcSIC). The NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 6, used for comparison with the prescribed present-day sea-ice conditions, is available from the National Snow and Ice Data Center and is described by Meier et al. (2026). Analysis scripts used to produce the diagnostics and figures are available from the corresponding author upon
465 reasonable request.

Author contributions

TZ and MM conceived the study. TZ performed the analysis, prepared the figures, and wrote the initial draft of the manuscript. MM supervised the study, contributed to the interpretation of the results, and reviewed and edited the manuscript. DS contributed to the scientific interpretation and reviewed the manuscript.

470 Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

The authors acknowledge the modelling groups participating in PAMIP and CMIP6 for producing and making available their model output, and the Earth System Grid Federation (ESGF) for providing access to the data. The authors also acknowledge
475 the National Snow and Ice Data Center for providing the NOAA/NSIDC sea-ice concentration data.

Financial support

We acknowledge support from the UK Natural Environment Research Council (NERC) grant NE/N006038/1.

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Preprint. Discussion started: 23 October 2026

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