

Characteristics and formation mechanisms of Arctic amplification: progress, challenges and ways forward

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Abstract In recent decades, the Arctic has experienced persistent warming, with near-surface warming three to four times higher than the global average, accompanied by the melting of sea ice, snow cover, and ice sheets. This anomalous warming phenomenon is referred to as Arctic amplification (referred to as AA). With the recent advances in AA research, significant understanding has been developed regarding its temporal evolution, spatial distribution, and influencing mechanisms. However, controversies remain concerning the primary drivers of AA, the quantitative contributions of various drivers, and some of the underlying processes. This paper synthesizes recent research findings, revisiting the spatiotemporal characteristics of AA and its driving factors, and analyzes the influencing mechanisms from four perspectives, including albedo feedback, temperature feedback, aerosol–water vapor–cloud feedback, and poleward energy transport via ocean and atmosphere circulation. Existing studies are summarized to several major conclusions, including: AA is characterized by a short emergence time (appearing in the last ~40 years), a strong influence from underlying surface properties, albeit with significant seasonal variations; AA is influenced by a combination of drivers both within and outside the Arctic, and the interactions among these factors are highly complex, preventing a conclusive, overarching understanding of the formation mechanisms from being established. We suggest that future research would benefit from the following three key foci: (1) enhancing studies on the impacts of land surface albedo feedback, aerosols, the Atlantic Meridional Overturning Circulation, and stratospheric processes on AA; (2) optimizing parameterizations of cloud–aerosol and land surface processes in climate and Earth system models, and integrating sea ice drift dynamics into these models; and (3) investigating the interactive mechanisms among various driving factors from a holistic perspective.

Keywords Arctic amplification, sea ice melting, albedo feedback, temperature feedback, poleward energy transport, Atlantic Meridional Overturning Circulation, atmospheric and oceanic circulation

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1 Introduction

Escalated global climate change has led to accelerated melting of sea ice and continental ice sheets which has driven global sea-level rise, intensified heatwaves, and increased floods and extreme precipitation events, not only causing regional ecological shifts but also posing threats to human survival and development (IPCC, 2023). Situated at high latitudes in the Northern Hemisphere, the Arctic encompasses the entirety of the Arctic Ocean and the surrounding high-latitude areas of Asia, Europe, and North America. It is connected to the Atlantic and Pacific Oceans via the Fram and Bering straits respectively. Its unique geographical location makes the Arctic a critical component of the global climate system, ecosystems, and even shipping and resource development (Li et al., 2025). Arctic climate change is governed by both internal and external factors. Key internal processes involve sea ice variability and temperature inversion processes, while external drivers encompass global warming, the atmospheric circulation, and Pacific and Atlantic sea surface temperatures (Bintanja et al., 2011; Di Girolamo et al., 2025; Previdi et al., 2021; Wendisch et al., 2023; Yoshimori et al., 2025). Collectively, these drivers have triggered a series of regional climate responses, including accelerated melting of Arctic glaciers and ice caps as well as the Greenland ice sheet (The GlaMBIE team, 2025), permafrost loss and the consequent tundra expansion, and reduced sea ice coverage (Cheng et al., 2025; Frost et al., 2023; Shu et al., 2022). These changes subsequently affect weather and climate processes in the Arctic and even in mid and low-latitude regions through a cascade of climate feedbacks, making the causes and characteristics of Arctic climate change a focal point of attention for scholars worldwide (Cohen et al., 2020; Dou et al., 2022; England et al., 2021; Hu et al., 2023; Wu et al., 2019; Yang et al., 2025).

Near-surface air temperatures have repeatedly reached record highs, accompanied by sea ice melt and declining multi-year ice cover (You et al., 2021). Since 1979, Arctic temperatures have continued to rise, with warming rates nearly four times the global average (Zhou et al., 2024), and this has been referred to as Arctic amplification (AA) (Jenkins and Dai, 2021; Screen and Simmonds, 2010; Serreze and Francis, 2006). During 1979–2021, the overall warming rate in the Arctic exceeded $0.75\text{ }^{\circ}\text{C}\cdot(10\text{ a})^{-1}$, with the most pronounced warming observed in the Eurasian sector of the Arctic Ocean and around the Svalbard and Novaya Zemlya archipelagos (Rantanen et al., 2022). Projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) indicate that, with the exception of the SSP1-2.6 scenario, AA is expected to peak in the early part of this century before fluctuating and declining to approximately 3.5 times the average level (Chylek et al., 2023; Davy and Griewank, 2023).

With increasing research on AA in recent years, the academic community has developed a systematic understanding

of its driving mechanisms and linkages to mid-latitude climate variability. Recent research has identified various feedbacks (albedo, outgoing longwave radiation increases due to warmer surfaces (the “Planck feedback”), lapse-rate, water vapor and cloud), aerosols, atmospheric and oceanic energy transport as significant factors contributing to AA (Block et al., 2020; Dai and Jenkins, 2023; Dai et al., 2019; Lee et al., 2024; Wendisch et al., 2019). However, there is no consensus regarding the relative contributions of these factors and their coupled processes. For instance, most scholars agree that sea ice loss, and the resulting surface albedo changes, is a primary driver of AA, but some studies have suggested that lapse-rate feedback may dominate AA during certain periods (Boeke et al., 2021; Jenkins and Dai, 2021; Previdi et al., 2020; Ye et al., 2025). Several studies have suggested that recent extreme weather events, circulation anomalies and climate change in the Northern Hemisphere mid-latitudes are closely linked to AA or Arctic sea ice variability (Blackport et al., 2024; Hu et al., 2023; Liu et al., 2021; Liu Z et al., 2025; Zhang C et al., 2025). Because of the coupling of different processes and feedbacks, there is yet no consensus on the driving mechanisms of AA within the academic community. Comprehensive reviewing of these mechanisms is essential, not only for clarifying the dynamics of Arctic climate change, but also for understanding its implications for mid-latitude climate and extreme events.

Previous review studies mainly focused on the impacts of surface albedo or oceanic and atmospheric circulations on AA (Li J et al., 2024; Wu et al., 2019). In this review, we synthesize recent studies to systematically analyze the spatiotemporal dynamics of AA. Given the complexity of its driving mechanisms, we adopt a comprehensive framework that evaluates major drivers, including the roles of permafrost thaw and vegetation change, and then compares their associated feedback loops. This integrated approach highlights the interplay between local and remote drivers, demonstrating that a holistic consideration of major influences is critical for a complete understanding of AA. Building on this synthesis of drivers and recent advances, we then identify key challenges that persist in contemporary research and outline several promising directions for future work.

2 Evidence for Arctic amplification

Arctic warming influences regional and global climate changes, making the temporal evolution of Arctic climate a subject of widespread interest (Walsh, 2014). The Arctic has been warming significantly faster than lower latitudes, with substantial variations across different periods (Cohen et al., 2014). In the early 20th century, the Arctic temperatures remained relatively stable, then cooled slightly in the mid-century, and rose sharply from the 1980s onward, far exceeding the global average (England et al., 2021; Figure 1). Arctic sea ice decline exhibits similar temporal characteristics, with a reduction rate of $6.22\%\cdot(10\text{ a})^{-1}$ since 1979, which is

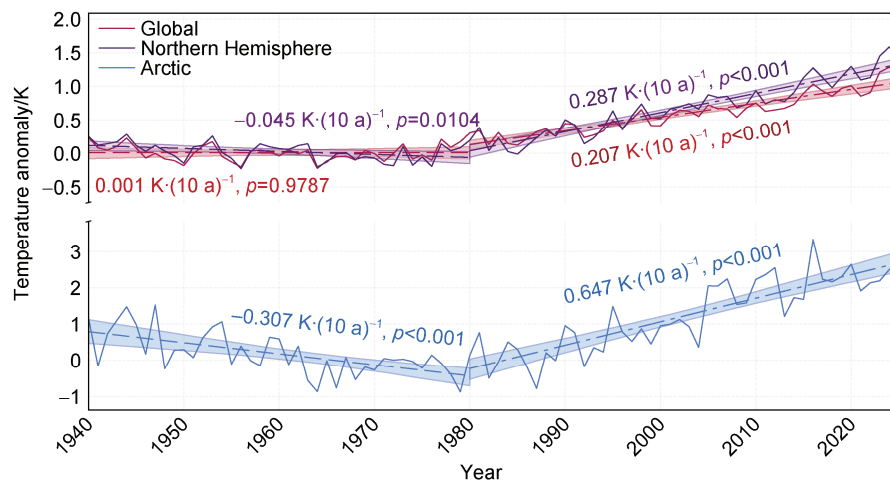


Figure 1 Annual mean near-surface air temperature across the Arctic (north of 70°N), the Northern Hemisphere and the globe from 1940 to 2025, derived from the Berkeley Earth temperature dataset (Rohde and Hausfather, 2020). The dashed and dot-dash line represent the near-surface air temperature change trends from 1940 to 1980 and from 1980 to 2025, respectively. The shaded areas indicate the 95% confidence interval of the linear regression.

more than double the rate observed since 1949 (Cai et al., 2021). Consequently, AA and rapid warming have become a prominent feature mainly since the late 20th century. This trend is projected to continue, although its future pace is expected to vary inversely with the severity of carbon emission scenarios, with the pace being more rapid under lower emissions. CMIP6 simulations indicate that under medium- and high-emission scenarios, the AA ratio (the ratio of Arctic warming to global warming) will gradually decline to around 2.4 (± 0.2) before stabilizing, but under low-emission scenarios, AA is expected to increase again in the mid-to-late 21st century, potentially surpassing the peak observed at beginning of the century (Davy and Griewank, 2023). This result is consistent with prior research, having suggested that the rate of future Arctic warming is strongly mediated by projected Arctic sea ice loss under varying emission scenarios, because low-emission pathways preserve summer ice and its amplifying feedback while high-emission pathways do not (Ono et al., 2022). AA demonstrates marked seasonal characteristics, with a pattern of autumn and winter dominance. Between 1979 and 2021, summer warming was approximately twice the global average rate, significantly lower than the roughly five-fold amplification observed in autumn and winter, which was also evident during the sub-period 1987–2000 (Chylek et al., 2023; Rantanen et al., 2022). Previously it was noted that AA peaks in autumn (Lainé et al., 2016), but recent studies have suggested that under the combined effects of greenhouse gas forcing, changes in sea ice thermal inertia, and the saturation of sea ice melt rates, the seasonal peak of Arctic warming has gradually shifted from autumn to winter (Liang et al., 2022; Wu et al., 2023). The prolonged Arctic summer delays the oceanic heat release window to the atmosphere, thereby shifting the peak heat release from autumn to winter, a shift projected to persist until sea ice

completely disappears (Yang et al., 2022).

The surface is a crucial component of the climate system. Variations in its properties influence near-surface atmospheric heating, leading to regional climate differentiation. While the Arctic has warmed at a rate significantly exceeding the global average in recent decades, the diversity of its surface types has resulted in pronounced spatial heterogeneity in temperature changes (Goodwin and Williams, 2023). As shown in Figure 2, pronounced near-surface warming anomalies are primarily located over the Beaufort, Chukchi, Kara, and Barents seas, with localized warming peaks in the Barents–Kara seas. These are areas which have concurrently experienced extensive sea ice loss since 2004 (Alexeev et al., 2013; Clark et al., 2021; Dai et al., 2022). Short-term coupled and transient Atmospheric General Circulation Model (AGCM) experiments have identified anomalous cooling in high-latitude Siberia, contradicting the general Arctic warming trend and forming a “warm Arctic, cold Siberia” pattern (Labe et al., 2020). On daily timescales, Arctic warming events, through nonlinear eddy-mean flow feedback, generate a geopotential height dipole characterized by an Arctic high and a mid-latitude Eurasian low, leading to significant cooling in the lower troposphere over mid-latitude Eurasia (Yin et al., 2025). On long-term scales, Arctic sea ice loss excites an anomalous anticyclone over the Barents–Kara seas and Ural region, which transports warm, moist air to the Arctic and cold air to central Eurasia, thereby suppressing long-term warming (Gong et al., 2025). While altitude and latitude are key factors shaping regional climate, a previous study suggested a positive correlation between altitude and warming rate, indicating that high-altitude areas warm on average 1.26 times faster (Wang Q et al., 2014). However, this relationship has been challenged by recent findings, which indicate that future warming rates in the East

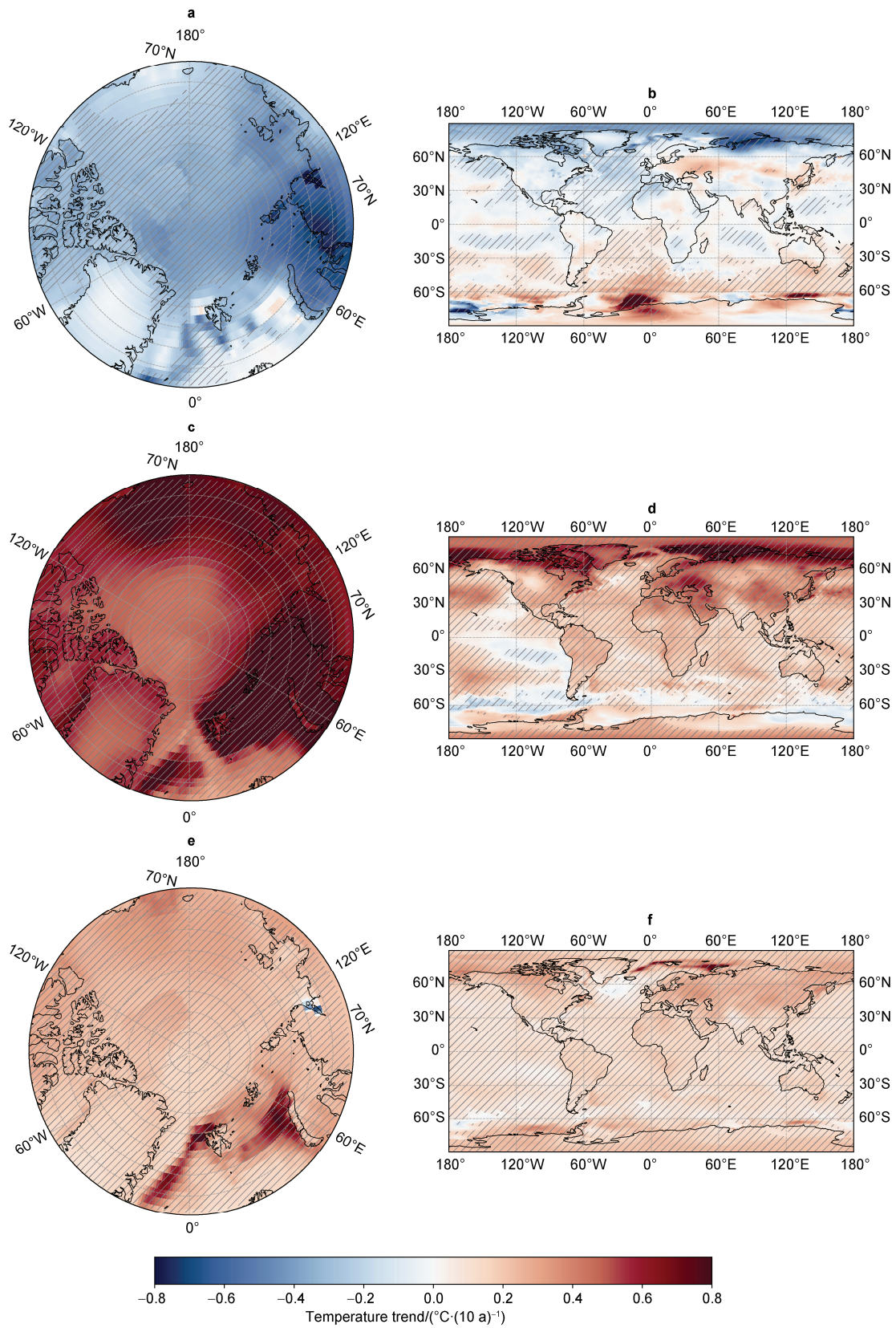


Figure 2 Spatial distribution of annual mean near-surface air temperature trends in the Arctic and global over 1940–1980 (a, b), 1980–2025 (c, d), and 1940–2025 (e, f) periods derived from the Berkeley Earth temperature dataset (Rohde and Hausfather, 2020). Gray hatching indicates the trend is statistically significant at the 99% confidence level.

Siberian Arctic could range from $-0.70\text{ }^{\circ}\text{C}\cdot\text{km}^{-1}$ to $-2.46\text{ }^{\circ}\text{C}\cdot\text{km}^{-1}$ with altitude, suggesting an anti-altitude dependence characteristics on AA (Miller et al., 2021; Wang et al., 2016). The warming across Arctic surface types follows distinct seasonal patterns, with ice-covered zones, ice-retreat zones, and land experiencing the strongest winter warming and pronounced seasonal variation, while ice-free ocean areas show both weaker warming and more uniform seasonal changes (Liu et al., 2023).

In summary, Arctic temperatures remained relatively stable in the early 20th century and cooled slightly in the mid-century. Pronounced AA has primarily emerged in the last four decades, peaking in the early 21st century. Its future trajectory depends critically on Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP) scenarios. Spatially, while warming is widespread across the Arctic, its rate exhibits clear heterogeneity, generally characterized by the most pronounced warming in ice-retreat zones, weaker warming over ice-free ocean, and anomalous cooling in high-latitude Siberia.

3 Drivers of Arctic amplification

3.1 Surface albedo

Surface albedo is a physical quantity representing the fraction of incident solar radiation reflected by a surface. By influencing the absorption and reflection of solar energy at Earth's surface, it modifies surface temperature and climate. The absorption of solar radiation by ocean and land surfaces raises their temperatures, leading to upward longwave radiation emissions and sensible heat exchange that warm the near-surface atmosphere. This process, known as the surface albedo feedback, further accelerates surface warming and the melting of sea ice and snow cover (Colman, 2013). In recent decades, sustained global warming has driven continuous near-surface warming in the Arctic, triggering extensive reductions in sea ice, snow cover, and permafrost, which in turn lowers surface albedo and alters the Arctic climate (Bintanja, et al., 2011; Crichton et al., 2025; Frost, et al., 2023).

Sea ice is a crucial component of the Arctic climate system as it is closely linked to the albedo feedback. The reduction in Arctic sea ice extent, which has been most pronounced in the Barents Sea, is associated with declining surface albedo through the ice-albedo feedback (Duncan et al., 2020; Heukamp et al., 2025). It has been demonstrated that the seasonal characteristics of AA are linked to sea ice melt, as well as the surface albedo feedback (Screen and Simmonds, 2010). This phenomenon arises from the different heat capacities of land and ocean, whereby the ocean's higher heat capacity enables it to act as an atmospheric heat source from mainly in autumn and winter (Wu and Dai, 2025), releasing stored excess energy that warms the lower troposphere, slows near-surface atmospheric cooling, and thus enhances Arctic warming

during these seasons (Dai et al., 2019). The pattern of summer oceanic heat storage and winter heat release in the Arctic Ocean has been identified as a key mechanism for AA and a major factor explaining why oceanic warming in the Arctic exceeds land warming (Lainé et al., 2016). Furthermore, oceanic thermal differences and seasonal heat storage affect the duration of the Arctic melt season, which in turn affects surface albedo. Microwave remote sensing data from 1979–2013 showed that the upper Arctic Ocean stored an additional $752\text{ MJ}\cdot\text{m}^{-2}$ of heat, extending the melt season by $5\text{ d}\cdot(10\text{ a})^{-1}$, while the autumn sea ice freeze-up in the Kara, Laptev, East Siberian, Chukchi, and Beaufort seas was delayed by $6\text{--}11\text{ d}\cdot(10\text{ a})^{-1}$ (Stroeve et al., 2014). Consequently, sea ice loss and oceanic seasonal heat storage and release alter both surface albedo feedback and ocean heat transport (OHT), processes which play significant roles in AA and the anomalous autumn-winter warming (Boeke et al., 2021; Goosse et al., 2018; Ye et al., 2025).

The surface albedo feedback, closely linked to sea ice retreat, is considered as a key driver of AA (Dai et al., 2019; Screen and Simmonds, 2010). Figure 3 illustrates the estimated contributions of various drivers to AA under five different contexts, including albedo feedback, lapse rate feedback, water vapor and cloud feedback, CO_2 and Planck feedback. The albedo feedback emerges as the major driver of AA, with surface albedo feedback alone contributing 1.82 K , accounting for 85% of the warming and representing the largest single contributor (Taylor et al., 2013). The albedo feedback intensifies warming at high latitudes, reversing the pattern of “stronger warming at low latitudes” to one of “stronger warming at high latitudes”, thereby further promoting AA (Cai and Lu, 2007). Simulation results by Jenkins and Dai (2021) indicated that the formation and magnitude of AA depend on sea ice loss, such that without its melting, the impact of surface albedo feedback would be significantly reduced.

Continued thinning of Arctic sea ice, driven by persistent near-surface warming, allows more oceanic heat to penetrate the ice layer and in turn warm the atmosphere in winter, thereby triggering a series of climate system responses that further influence AA (Bocquet et al., 2023; Serreze and Barry, 2011). From 1958 to 2018, the average Arctic sea ice thickness decreased by 2 m, representing a 66% reduction, primarily due to the loss of thick ice and the conversion of multi-year ice to seasonal ice (Kwok, 2018). Simulation results have shown that Arctic sea ice thinning since 1982 has increased the AA index by 37% and contributed to a winter near-surface air temperature increase of $1\text{ }^{\circ}\text{C}\cdot(10\text{ a})^{-1}$ through internal Arctic climate processes (Lang et al., 2017). Additionally, links have been identified between Arctic sea ice thickness changes, sea ice drift, local atmospheric circulation, and near-surface Arctic warming (Li M et al., 2024; Tandon et al., 2018). Reduced thickness significantly enhances the sea ice response to wind stress, inducing sea ice drift, with regions of increased drift corresponding to areas of temperature rise in parts of the

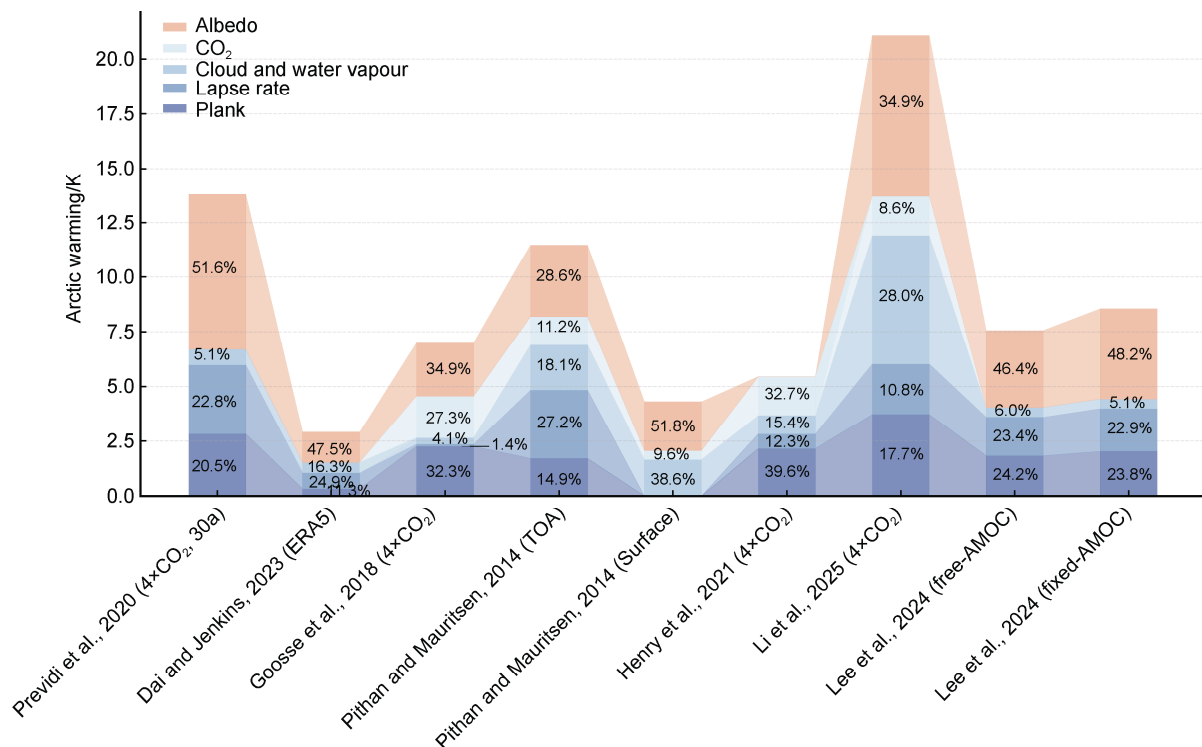


Figure 3 Contribution of five main drivers (albedo feedback, CO₂, water vapor and cloud feedback, lapse-rate feedback, and Planck feedback) to Arctic warming compared in different research results. These values are not directly comparable across studies but serve to illustrate the range and uncertainty of reported feedback estimates. The y-axis indicates the total temperature attribute to all drivers in each study. Different colors represent distinct drivers of Arctic warming, and the percentages indicate each driver's proportional contribution among these five factors. These percentages were recalculated from the numerical values reported in the cited studies.

Atlantic and Arctic Oceans (Zhang F et al., 2025). However, the specific contributions of Arctic sea ice drift and thickness changes to Arctic warming remain unclear due to the complexity of the polar environment and the scarcity of effective observational data (Fu et al., 2021; Xu et al., 2025).

Satellite remote sensing data reveals that sustained global warming and AA are driving the extensive loss of sea ice and snow cover across the Arctic (Frost et al., 2023). This process has triggered a cascading chain of environmental responses, including permafrost degradation, tundra expansion, increased vegetation indices, and ecological recovery, which together are termed “Arctic greening” (Myers-Smith et al., 2020; Wu et al., 2020). Arctic vegetation expansion coincides with declining summer sea ice extent and glacier retreat and, through sea ice–atmosphere–cryosphere interactions, may exacerbate AA (Ingrosso et al., 2025; Jeong et al., 2012). Under 2×CO₂ forcing, increased Arctic vegetation activity enhances surface warming and turbulent heat fluxes into the atmosphere, intensifying summer sea ice melt and surface ocean warming, which in turn amplifies winter and spring warming and promotes subsequent vegetation growth, establishing a vegetation–atmosphere–sea ice positive feedback (Jeong et al., 2014). Still, Arctic vegetation

expansion may weaken the surface albedo feedback and generate both positive and negative feedbacks across different surfaces and seasons, which regulates near-surface air temperature (Alessandri et al., 2021). Simulation results showed that vegetation recovery and “Arctic greening” promoted biogeophysical feedbacks, amplifying Arctic warming and increasing regional average precipitation and temperature (Zhang et al., 2018). Future expansion of tundra and forest area in the Arctic, along with rising net primary productivity, may alter surface morphology and near-surface water vapor content, leading to decreases in upward shortwave radiation and cloud cover decreases, as well as an increase in downward shortwave radiation, which promote vegetation growth and establish a vegetation–cloud feedback that would significantly amplify Arctic warming (Cho et al., 2018).

Vegetation expansion not only directly influences Arctic climate change through feedback mechanisms but also induces AA by triggering permafrost thaw. Land-atmosphere coupled modeling studies indicate that increased Arctic vegetation perturb near-surface air temperature, amplifying surface snow melt and exposing more permafrost to the atmosphere, which absorbs increased solar radiation during summer, raising soil temperature and accelerating permafrost thaw (Wang X et

al., 2022; Wang Z et al., 2019). Permafrost degradation leads to thermokarst processes, forming waterlogged depressions, thermokarst lakes, that increase surface water and lower surface albedo, thereby driving air temperature rise in Arctic permafrost regions and establishing a temperature–vegetation–permafrost positive feedback (Webb et al., 2021).

In summary, Arctic sea ice loss and surface albedo feedback are of great significance to the amplification of warming in the Arctic. Sea ice thinning and retreat enhance oceanic surface radiative fluxes and seasonal heat storage, warming the near-surface atmosphere and creating the characteristic pattern of stronger AA in cold seasons compared to summer. The albedo feedback is an important driver of Arctic climate change and plays a significant role in promoting the formation and development of AA, although whether it is the dominant factor under certain conditions remains debated. For example, the temperature inversion process, which limits surface radiation escape to space and emits downward longwave radiation during warming, has been argued to be a major contributor driving Arctic winter warming (Bintanja et al., 2011). Recent research indicates that Arctic vegetation expansion not only triggers vegetation–atmosphere–sea ice and vegetation–cloud feedbacks that regulate near-surface temperatures, but also modulates AA by promoting permafrost thaw, which alters surface albedo and polar carbon and methane emissions. Additionally, sea ice loss may influence Arctic climate change by affecting ocean circulation, sea ice dynamics, and oceanic wind stress (Zhang F et al., 2025).

3.2 Temperature feedback

Temperature feedback, which includes the “Planck feedback” and the “lapse-rate feedback”, is considered a key factor regulating climate change in the Arctic region. According to the Stefan–Boltzmann law, an object at lower temperatures requires a larger temperature increase than a warmer object to achieve the same increase in longwave radiation needed to offset external radiative forcing, which is known as the Planck feedback. It has been suggested that the Planck feedback contributes approximately 1.75 K to AA, ranking only behind the lapse-rate and albedo feedbacks in magnitude (Pithan and Mauritsen, 2014). However, results from solar radiation management showed that the Planck feedback acted primarily as a general stabilizing background, damping Arctic surface warming at a strength of $-2.6 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ and thus suppressing AA (Henry and Merlis, 2019). Still, simulations under $4\times\text{CO}_2$ forcing revealed that the increases in CO_2 and water vapor dominated near-surface Arctic warming and AA, whereas atmospheric energy transport processes such as the Planck feedback contributed more to mid-and upper-tropospheric warming (Henry et al., 2021). Hence, quantifying the relative contribution of the Planck feedback remains uncertain with substantial variability across modeling

studies precluding a unified conclusion (Block et al., 2020).

The lapse-rate feedback refers to the influence of the vertical atmospheric temperature lapse rate on the efficiency of the Earth to transfer heat into space (Bony et al. 2006). The process primarily stems from the sensitivity between outgoing longwave radiation at the top of the atmosphere (TOA) and the vertical temperature structure of the troposphere. In low-latitude regions, near-surface water vapor is lifted by atmospheric convection to higher altitudes where condensation releases latent heat, warming the middle and upper atmosphere more rapidly, which reduces the vertical temperature lapse rate and thus creates a negative feedback effect (Boeke et al., 2021; Li M et al., 2024). In the Arctic, however, frequent temperature inversions suppress internal vertical heat exchange within the atmosphere. To offset increasing temperatures the warming surface emits more longwave radiation. Much of this radiation is trapped within the inversion layer, further amplifying near-surface air temperature rise, yielding a positive feedback. It has been indicated that this positive lapse-rate feedback enhances AA, with its contribution to warming being positively correlated with sea ice loss (Boeke et al. 2021; Dai and Jenkins, 2023). Some studies also suggested that the lapse-rate feedback influences the magnitude of AA by modulating the transition of the Arctic from a radiative-advective equilibrium (RAE) to a non-RAE state (Liang et al., 2025).

Although the contribution of the lapse-rate feedback to AA is widely acknowledged, its mechanisms remain debated. Its trigger is considered to be associated with surface properties, sea ice cover, atmospheric heat transport, and cloud processes (Hegyi and Taylor, 2017; Kay et al., 2008; Lauer et al., 2020; Taylor et al., 2013). Simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) revealed that the lapse-rate feedback in the Arctic is positively correlated with albedo feedback, representing a longwave radiation response to sea ice loss (Feldl et al., 2020). Furthermore, Arctic lapse-rate feedback may also be influenced by surface characteristics and seasonal transitions, characterized by significantly weaker positive feedback over land than over ocean and with its contribution being greater during the cold season compared to the warm season (Boeke et al., 2021). Regarding the contribution of the lapse-rate feedback to AA, most researchers consider albedo feedback to be the primary driver, with lapse-rate feedback acting as an important amplifying factor (Dai and Jenkins, 2023; Goosse et al., 2018; Screen and Simmonds, 2010). However, it has also been suggested that the lapse-rate feedback contributed about 6 K to AA, slightly exceeding the 5.7 K from albedo feedback (Pithan and Mauritsen, 2014). Based on the abrupt CO_2 quadrupling experiment in CMIP5 models, research found that the lapse-rate feedback dominated AA during the first three months of simulation, and its influence persisted as an important contributor to further warming on longer timescales (Previdi et al., 2020).

In summary, both the Planck feedback and the lapse-rate feedback contribute to AA. The lapse-rate feedback exhibits distinct regional differences, with its contribution to warming being significantly higher over ice-free ocean and sea ice retreat zones than over land. In contrast, the magnitude of the Planck feedback's contribution to Arctic warming remains less constrained, and quantitative estimates vary considerably across models (Block et al., 2020). Current research confirms that the lapse-rate feedback acts as a driver of near-surface Arctic warming, but it is still debated if it can replace albedo feedback as the dominant forcing of AA.

3.3 Water vapor, cloud and aerosol feedbacks

The Sun heats the Earth's surface, which then emits longwave radiation. The radiation is absorbed by greenhouse gases in the atmosphere, warming it and radiating heat back to the surface, a process known as the greenhouse effect and primarily driven by greenhouse gases (Caballero, 2014). Recent Arctic warming has increased near-surface moisture, which enhances the absorption of surface-emitted longwave radiation, establishing a positive water-vapor feedback in the region (Wu et al., 2019). Increased Arctic water vapor is an important factor behind the anomalous rise in regional downward longwave radiation flux in recent years, contributing to sea ice retreat and near-surface warming in the Arctic (Ghatak and Miller, 2013). Changes in the atmospheric circulation and resulting moisture influxes are significant drivers of increasing Arctic humidity that contributed to winter warming in the Arctic between 1979 and 2012 (Gong et al., 2017). This result aligns with model simulations, indicating that moisture transport from the Atlantic influences sea ice extent in the Barents–Kara seas (Vázquez et al., 2017). Moisture intrusions can trigger extreme warming events in the central Arctic, with local temperature increases exceeding 20 K, contributing to 45% of the near-surface warming and 30% of the sea ice concentration decline during December and January in the Barents Sea from 1990 to 2012 (Woods and Caballero, 2016). In summer, atmospheric rivers account for 36% of the increasing trend in Arctic atmospheric humidity since 1979, with local contributions exceeding 50% in rapidly warming regions, which may lead to significant Arctic melt events (Wang et al., 2024). Collectively, these studies demonstrate that water vapor acts as both a local feedback amplifier and a vehicle for remote moisture transport, playing an indispensable role in driving AA across all seasons.

Anthropogenic aerosol emissions not only alter the atmosphere's composition, but also modulate the Earth's energy budget, through direct and indirect effects by absorbing and scattering solar radiation, thereby influencing regional and global climate (Dobricic et al., 2019; Wang Y et al., 2014; Zhou et al., 2020). Aerosols in the Arctic originate primarily from local emissions and extratropical

transport from Eurasia, the Pacific, and the Atlantic (Abbatt et al., 2019; Ardyna and Arrigo, 2020; Quinn et al., 2008; Wang Y et al., 2014). Aerosol loading over the central Arctic, Greenland, Siberia, and the Canadian Arctic has been identified as an important factor affecting recent surface temperature trends and AA (Kuttipurath et al., 2024). Between 1955 and 1984, the trend in anthropogenic aerosol emissions was only 60% of that of greenhouse gases, yet aerosols contributed to a near-surface cooling of $(0.43 \pm 0.22) \text{ K} \cdot (10 \text{ a})^{-1}$ in the Arctic, exceeding the greenhouse-gas-induced warming of $(0.35 \pm 0.17) \text{ K} \cdot (10 \text{ a})^{-1}$ (Wu et al., 2024). This suggests that aerosols have exerted a stronger influence on Arctic climate compared to greenhouse gases. Community Earth System Model (CESM) results confirmed that secondary inorganic aerosols concentrations over Europe and North America declined, leading to a warming effect in the mid-high latitudes, whereas they increased over East Asia and South Asia leading to a cooling effect there from 1980 to 2007 (Zhou et al., 2020). Furthermore, it has been shown that the decline in European sulfate aerosols since 1980 has led to an additional energy absorption of $0.3 \text{ W} \cdot \text{m}^{-2}$ in the Arctic and a near-surface warming trend of $0.5 \text{ }^{\circ}\text{C} \cdot (10 \text{ a})^{-1}$, which is dominated by the direct radiative forcing of the aerosols (Acosta Navarro et al., 2016). This finding poses new challenges for Arctic climate projections, environmental protection, and the design of emission-reduction policies across Eurasia.

Black carbon (BC), formed through the incomplete combustion of fossil fuels and biomass, is a key component of aerosols and an important factor influencing climate change in the Arctic. The distribution and concentration of BC in the Arctic exhibit pronounced seasonal variations, influenced by global BC emissions and the large-scale atmospheric circulation (Schulz et al., 2019). Arctic BC originates from different dominant sources depending on altitude. Near the surface, BC concentration is dominated by local sources within the Arctic ($\sim 57\%$ in 2014–2018) and Russia–Belarus–Ukraine ($\sim 26\%$); long-range transport from Asia, particularly from the Indo-Gangetic Plain, can rapidly deliver BC over Central Asia into the high Arctic in as little as 7 d, altering BC concentrations aloft and affecting regional climate (Backman et al., 2021; Ren et al., 2020). BC particles influence the climate system through two primary pathways: in the atmosphere they absorb and scatter solar radiation and modulate cloud formation processes, while deposited on surfaces they reduce surface albedo and alter the regional energy budget (Bond et al., 2013; Ramanathan and Carmichael, 2008). In the Arctic, BC in the near-surface atmosphere induces a local radiative forcing of approximately $-0.2 \text{ W} \cdot \text{m}^{-2}$, whereas BC deposited on snow contributes a positive forcing ranging from $0.05 \text{ W} \cdot \text{m}^{-2}$ to $0.7 \text{ W} \cdot \text{m}^{-2}$ (Donth et al., 2020). Over the Arctic Ocean, the annual mean TOA radiative forcing due to the direct effect of BC exceeds $0.4 \text{ W} \cdot \text{m}^{-2}$, while BC in snow across the central Arctic reduces surface albedo,

adding approximately $0.2 \text{ W}\cdot\text{m}^{-2}$ to the regional energy budget (Schacht et al., 2019). Projections for coming decades suggest that Arctic BC emissions could decline by about 60% by 2050, which would reduce the total direct aerosol radiative forcing by roughly $0.44 \text{ W}\cdot\text{m}^{-2}$ (Kühn et al., 2020). Although these studies provide key insights into the role of BC in Arctic climate change, limited observational data and uncertainties in model simulations imply that the precise linkages between changes in BC concentration and Arctic climate mechanisms remain unclear.

Clouds form through the condensation of atmospheric water vapor onto aerosols and dust particles, generating suspended droplets or ice crystals that aggregate and grow into visible structures. In the Arctic, clouds generally influence climate by altering the regional radiative budget through reflecting solar radiation and absorbing terrestrial and atmospheric longwave radiation, and by transferring latent and sensible heat along with modifying surface albedo via phase changes during cloud formation and precipitation processes, ultimately affecting near-surface air

temperature (Zhang et al., 2022). Nakanishi and Michibata (2025) point out that changes in cloud phase and cover enhance cloud emissivity, causing surface warming that increases cloud liquid fraction, creating cloud emissivity feedback that promotes AA. Model simulations confirm that the transition from ice to liquid particles in Arctic mixed-phase clouds increases longwave radiation and strengthens AA, as shown in Figure 4 (Tan and Storelvmo, 2019). Polar stratospheric clouds also play a significant role in Arctic warming, with their contribution positively correlated with methane concentrations (Dutta et al., 2023). In addition to driving cloud emissivity feedback independently, Arctic clouds can interact with sea ice and the ocean to shape regional climate. It has been suggested that the cloud-ice feedback amplifies Arctic sea ice variability during summer and autumn (Kay and Gettelman, 2009), and increased cloud cover in October and November enhances sensible heat flux by approximately $15 \text{ W}\cdot\text{m}^{-2}\cdot(10 \text{ a})^{-1}$, contributing to seasonal sea ice loss (Philipp et al., 2020; Wendisch, et al., 2019). Over the summer and early fall, changes in cloud cover also affect near-surface Arctic temperatures by

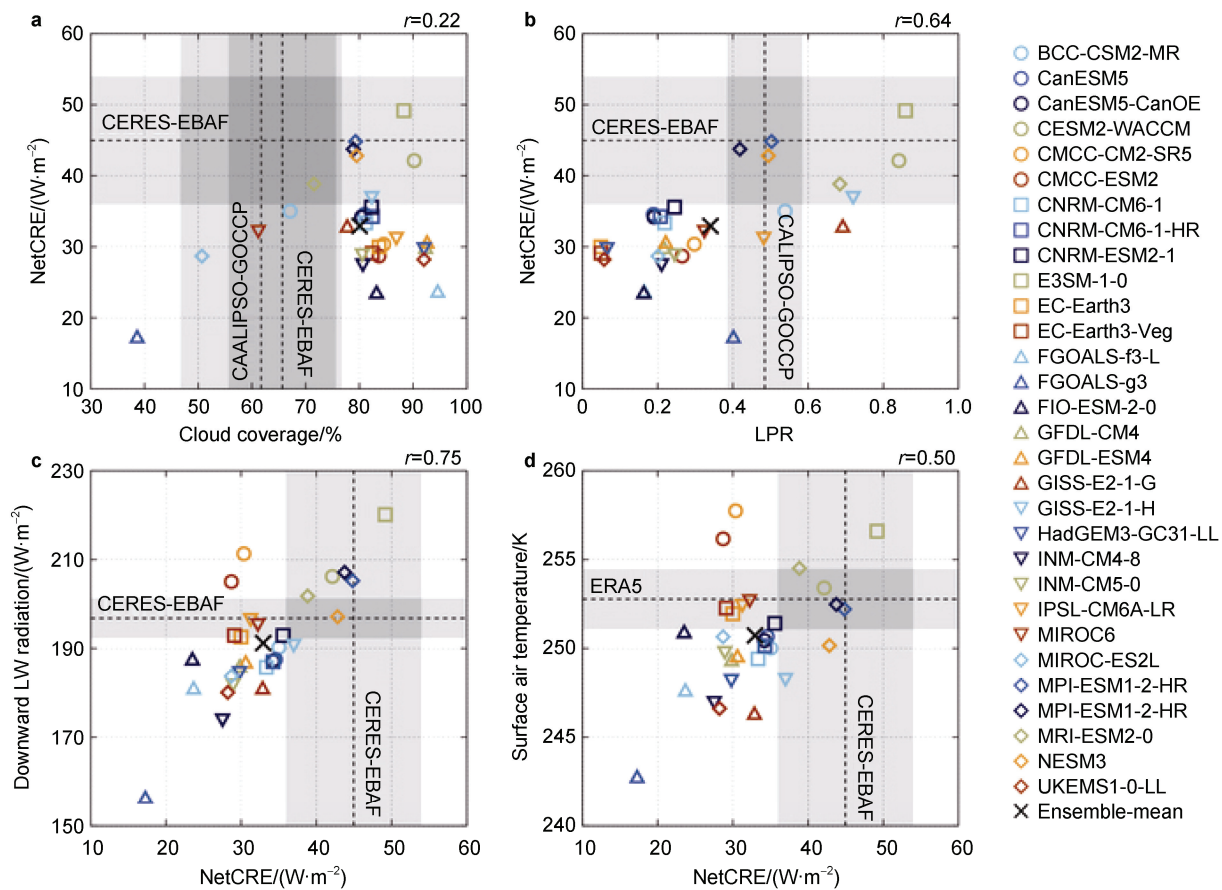


Figure 4 Multi-model simulated impact of the net cloud radiative effect (NetCRE) on NDJF (November–February) Arctic climate. **a**, correlation between cloud coverage and NetCRE; **b**, NetCRE versus liquid water path (LWP); **c**, correlation between NetCRE and downward longwave radiation; **d**, NetCRE versus surface air temperature. Correlation coefficients are given in the upper-right corner of each panel. Black dashed lines represent retrieval and reanalysis values, with uncertainties being shaded in gray. This figure is adapted from Nakanishi and Michibata (2025).

modifying radiative fluxes at the tropopause, as illustrated in the Laptev and East Siberian seas, where a 4%–6% reduction in cloud cover resulted in a forcing anomaly of the TOA shortwave irradiance exceeds $30 \text{ W} \cdot \text{m}^{-2}$ (He et al., 2019). Moreover, interactions between Arctic clouds and surface vegetation further modulate this amplification. During summer, when photosynthetic and respiration rates peak, Arctic vegetation evaporates substantial water vapor into the near-surface atmosphere, potentially triggering a water vapor–cloud feedback that intensifies summer warming and may weaken the seasonality of AA (Chae et al., 2015). Therefore, the complex coupling among clouds, the ocean, and sea ice, combined with insufficient accuracy in the representation of clouds in current climate models, significantly complicates the understanding of Arctic climate mechanisms and remains a major source of uncertainty in model simulations.

Based on the aforementioned studies, aerosols, water vapor, and cloud feedbacks all exert influences on AA, although their specific mechanisms differ. Water vapor and clouds primarily act through positive water vapor feedback, cloud emissivity feedback, cloud formation processes, and cloud phase changes. The net effect on downward longwave radiation depends strongly on cloud type, with low-level liquid-containing clouds generally warming the surface, whereas high ice clouds may have a weaker or even contrasting impact. These processes also deliver latent and sensible heat to the atmosphere, raising near-surface air temperature, thereby promoting sea ice loss and Arctic warming. Concurrently, changes in cloud cover produce shortwave-forcing anomalies that further amplify this warming. In contrast to water vapor and clouds, aerosols modulate the regional radiative budget mainly by absorbing and scattering solar radiation and by influencing cloud formation. Recent AA has been driven by a decline in overall aerosol loading, coupled with increased concentrations of iodine-containing aerosols and secondary inorganic aerosols. Furthermore, BC aerosols deposited on surfaces can accelerate the melting of snow and glaciers, reducing surface albedo and enhancing AA.

3.4 Poleward transport by oceanic and atmospheric circulations

The oceans serve as crucial carriers of mass and energy within the Earth system, regulating heat and moisture differences between high and low latitudes through oceanic circulation, thereby influencing regional climates. The Arctic Ocean is surrounded by continents, with inflows from lower-latitude currents entering primarily through the Fram Strait and the Bering Strait, transporting heat into the Arctic region (Aksenov et al., 2016). Research indicates that Atlantic inflows play a dominant role in warming the Arctic Ocean, and its heat transport is projected to reduce sea ice cover in the Barents Sea by more than 50% by the mid-21st century, whereas heat transport from the Pacific

Ocean mainly affects Arctic sea ice thickness (Cheng et al., 2025). Figure 5 shows the trends in net oceanic heat transport into the Arctic Ocean through the Bering Strait, the Barents Sea Opening (BSO), Fram Strait, and Davis Strait under the SSP585 scenario. The results reveal that heat inflow through these four passages has increased over the past three decades and is projected to continue rising until 2070, with the most pronounced increase occurring through the BSO (Shu et al., 2022). This trend is largely attributed to reduced sea ice import, which weakens oceanic stratification, enhances vertical mixing, and increases upward fluxes of heat and salt, leading to warming and sea ice loss in the northern Barents Sea (Lind et al., 2018). Furthermore, under a warming climate, reduced sea ice export through the Fram Strait allows more warm Atlantic water from lower latitudes to flow into the Nordic Seas and the Arctic Ocean, becoming a key driver of warming in the Atlantic water layer of the Arctic, forming a phenomenon known as Arctic Atlantification (Hordoir et al., 2026; Wang Q et al., 2020, 2024).

The Atlantic Meridional Overturning Circulation (AMOC) is a key component of the global thermohaline circulation. Its changes, modulated by warmer sea surface temperatures and enhanced freshwater influx, are linked to sea ice loss in the Labrador, Greenland and Barents seas, and enhances seasonal warming in the Arctic (Mahajan et al., 2011). This connection operates through meltwater input from diminishing ice sheets, which increases freshwater in the ocean, suppresses the formation of deep water, and ultimately weakens AMOC, thereby influencing Arctic

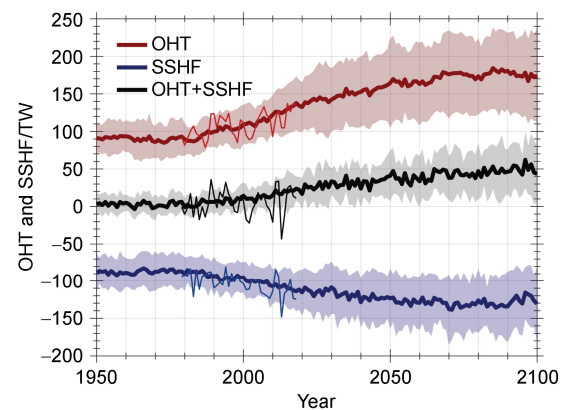


Figure 5 Variations of net OHT integrated across Bering Strait, BSO, Fram Strait, and Davis Strait, along with the Arctic Ocean-averaged sea surface heat flux (SSHF) and the sum of the both during 1950–2100. The upward trends in the red and black curves reflect the CMIP6-projected increase in poleward ocean heat delivery, a key driver of rising heat accumulation in the Arctic Ocean. Shaded areas indicate one standard deviation across CMIP6 models. Poleward OHT is defined as positive, while upward SSHF (representing ocean heat loss) is negative. Thin lines denote results based on the ORAS5 ocean reanalysis dataset. This figure is adapted from Shu et al. (2022).

climate dynamics (Deng and Dai, 2022; Duncan et al., 2020). In recent decades, the gradual weakening of AMOC has affected poleward energy transport, as shown in Figures 3 and 6 (Ditlevsen and Ditlevsen, 2023; Lee and Liu, 2023). CESM simulations show that the weakening of AMOC reduced the warming trend by $0.1\text{ }^{\circ}\text{C}\cdot(10\text{ a})^{-1}$ between 1901 and 2022, and is projected to lower average Arctic warming by about $1.37\text{ }^{\circ}\text{C}$ by the end of this century through its influence on sea ice melt, the Planck, cloud and water-vapor feedbacks (Lee et al., 2024). During 1980–2020, AMOC weakening has declined Arctic sea ice extent and volume by 36% and 22%, respectively (Lee and Liu, 2023). A negative feedback between Arctic sea ice melt and AMOC strength has been suggested, whereby freshwater input from melting ice enters the subpolar gyre, creating temperature and salinity anomalies that suppress deep convection and thus weaken AMOC (Liu et al., 2019; Madan et al., 2024). This

reduction in poleward oceanic heat transport can, in turn, favor a temporary expansion of Arctic sea ice cover (Liu and Fedorov, 2022). On the other hand, it has also been argued that a weakened AMOC may release heat previously stored in the Atlantic to the surface and overlying ocean, thereby amplifying Arctic and even global warming (Chen and Tung, 2018). Additionally, idealized model experiments indicate that an open Drake Passage relative to a closed one strengthens the Antarctic Circumpolar Current, which would strengthen AMOC and thereby enhance the northward oceanic heat transport, further promoting AA (Wang P et al., 2025). Clearly the evolution of AMOC and its impact on Arctic climate are highly complex, pointing at strengthening observational and modeling efforts and further elucidating the underlying mechanisms linking AMOC changes to Arctic climate variability is needed.

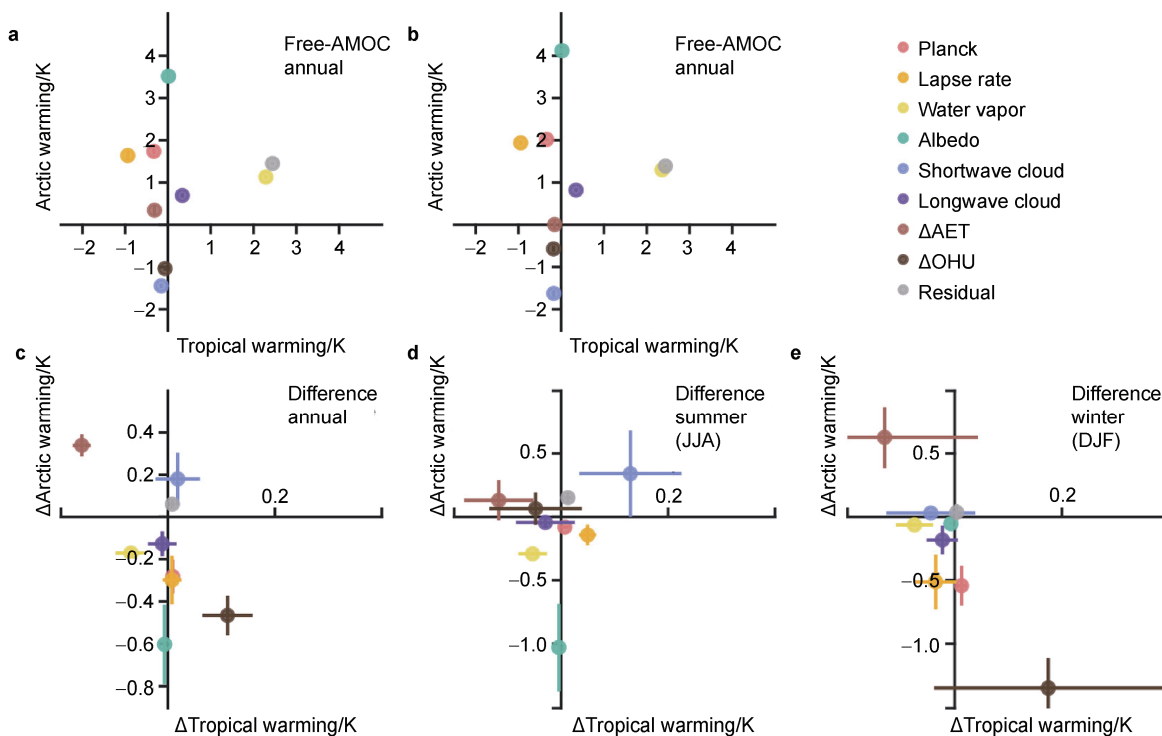


Figure 6 Impact of the AMOC on mean surface air temperature changes in the Arctic (60°N – 90°N) and the tropics (30°S – 30°N). The figure presents results from the free-AMOC simulation (a) and the fixed-AMOC simulation (b) for the period 2081–2100. c, the AMOC impact on annual mean temperature changes. Colored scatters represent partial temperature contributions from the Planck response, lapse rate, water vapor, short- and long-wave cloud feedbacks, atmospheric energy transport (ΔAET), ocean heat uptake/release (ΔOHU), and a residual term (residual). d and e display the same AMOC impacts as c, but for Northern Hemisphere summer (d, June–August) and winter (e, December–February) temperature changes, respectively. Error bars in all panels indicate one standard deviation of the differences across five ensemble members between the free- and fixed-AMOC simulations. This figure is adapted from Lee et al. (2024).

Uneven solar radiation distribution across the Earth's surface generates near-surface pressure gradients, which produce horizontal pressure gradient forces and drive advection. Under the influence of the Coriolis force, this flow organizes into global atmospheric circulation patterns. These circulation systems transport moisture and heat between high and low latitudes and represent a key factor

influencing climate change and ecosystem dynamics in the Arctic (Di Girolamo et al., 2025). Horizontal temperature advection, together with southwesterly air masses and moisture transport originating from the Pacific and Atlantic, significantly contributes to near-surface warming and sea ice loss in the Arctic (Clark et al., 2021; Vázquez et al., 2017; Wegmann et al., 2017). Specifically, the intensification

of a barotropic anticyclone over Greenland and the Arctic Ocean heats and moistens the lower troposphere, increasing downwelling longwave radiation over the ice and modifying summer atmospheric circulation, a process that has contributed about 60% to the decline in sea ice cover since 1979 (Ding et al., 2017). Kapsch et al. (2019) suggested that during spring, westward-extending negative geopotential-height anomalies favor the incursion of westerly jets into the Arctic, whose southwestern branch transports relatively warm and moist air from Siberia and the Kara Sea into the eastern Arctic, enhancing downward longwave radiation and triggering an earlier melt onset that, through ice-albedo feedback, carries the spring signal forward and ultimately promotes reduced sea ice concentration in September. In addition to transporting heat and moisture, atmospheric circulation delivers aerosols and pollutants from lower latitudes to the high Arctic, where they influence AA through aerosol-cloud interactions (Pernov et al., 2022; Zheng et al., 2024). Research further indicates that during spring, shifts in the polar vortex center and the presence of low-pressure systems over the northeast Atlantic, as well as variations in anticyclonic blocking north of Greenland, modulate pollutant transport, with low-pressure systems enhancing NO₂, aerosols and tropospheric CO over the Arctic while reducing O₃, and anticyclonic blocking tending to produce the opposite pattern (Thomas et al., 2021).

Atmospheric and oceanic circulation systems also modifying Arctic climate through air-sea coupling involving various circulation anomalies, such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), and the Arctic Dipole (AD) (Wu et al., 2006). In the Bering Sea, the PDO drives cyclonic anomalies that enhance northward heat transport and surface warming, promoting sea ice loss (Figure 7b, process (1); Figure 8, process “a”), whereas the North Pacific Gyre Oscillation drives anticyclonic anomalies that cause surface cooling and downwelling, leading to spring sea ice expansion after 2007 (Di Lorenzo et al., 2008; Yang et al., 2020). The AMO modulates AA on multidecadal scales by enhancing the release of latent and sensible heat from the North Atlantic during its positive phase (Figure 7b, process (2); Figure 8, process “b”), which strengthens sea-air interactions and thereby increases poleward ocean and atmospheric heat transport into the Arctic to amplify warming (Fang et al., 2022). Furthermore, in boreal winter, the AMO modulates the atmospheric circulation over the North Pacific by strengthening the westerly winds and the stratospheric polar vortex (SPV), partly through its influence on the AO and the AO-ENSO relationship, in which the ENSO teleconnection to the Arctic acts as a direct atmospheric bridge, thereby influencing Arctic climate (Figure 8, process “c”) (Gong et al., 2024; Tang et al., 2025; Zhu and Shi, 2025).

Numerous studies indicate that AO not only interacts

with AMO to modulate Arctic climate, but also drives other air-sea interactions that promote Arctic warming independently (Gong et al., 2024; Hegyi and Taylor, 2017; Wang et al., 2023). Recent studies have indicated that the positive phase of AO induces inflows of warm ocean water into the Arctic, heating the near-surface atmosphere and reducing lower-tropospheric stability, which then enhances vertical motion and establishes a positive feedback that reinforces the positive AO (Figure 7b, process (3); Figure 8, process “d”), promoting AA (Wang and Zhao, 2024). Furthermore, although the Arctic atmospheric circulation is dominated by the AO, especially in winter, anthropogenic warming and sea ice loss are driving a shift away from the classic AO pattern, a change manifested in the recent strengthening of the Barents-Kara seas anticyclonic circulation (Liu Z et al., 2025). The AO, together with the AD and PDO, influences sea ice drift and melt through anomalous heat and moisture transport, modulating surface albedo and thereby further amplifying Arctic warming. Sea ice motion data from 2001 to 2020 demonstrate that the concurrent positive phases of the AO and AD influences western Arctic sea ice loss and drift by causing the collapse of the winter Beaufort High and Arctic anticyclone, reversing drift and triggering anomalous ice export from the Beaufort Sea in 2017 and 2020 (Figure 7b, process (4); Figure 8, process “e”) (Zhang and Du, 2025). During periods characterized by a negative PDO phase combined with a positive AO phase, sea ice anomalies reached approximately -7.3% in the Beaufort and Chukchi seas, 4.9% in the East Siberian Sea, and -6.4% in the Canadian Arctic Archipelago (Figure 8, process “f”) (Bi et al., 2021). In recent years, the correlation between the AD and summer Arctic sea ice extent has strengthened significantly, has contributed substantially to variations in Fram Strait ice flux and to reduced sea ice concentration in the Pacific sector of the Arctic Ocean by modulating surface winds and the transpolar drift (Choi et al., 2019). The phase shifts of the NAO also play an important role in Arctic warming and sea ice loss (Chen et al., 2021; Wang C et al., 2025). The positive NAO phase served as the primary driver of anomalous warming in the northeastern Arctic during 1920-1925, as evidenced by climatic records and reanalysis data (Figure 7b, process (5); Figure 8, process “g”) (Rogers et al., 2004). Model simulations indicate that under a positive NAO phase, NAO intensity is negatively correlated with sea ice concentration in the Greenland, Barents, and Okhotsk seas, whereas the opposite pattern generally holds during a negative NAO phase (Figure 8, process “h”) (Dai et al., 2023). On the other hand, the positive NAO phase steers Atlantic storms into the Arctic, enhancing the Atlantic-Arctic tropospheric rapid daily warming pattern, which allows warm, moist air masses from lower-latitude Atlantic regions to enter the Arctic, contributing to Arctic winter daily warming events and near-surface temperature rise (Figure 8, process “g”) (Wang et al., 2023). The complex coupling between the ocean and atmosphere

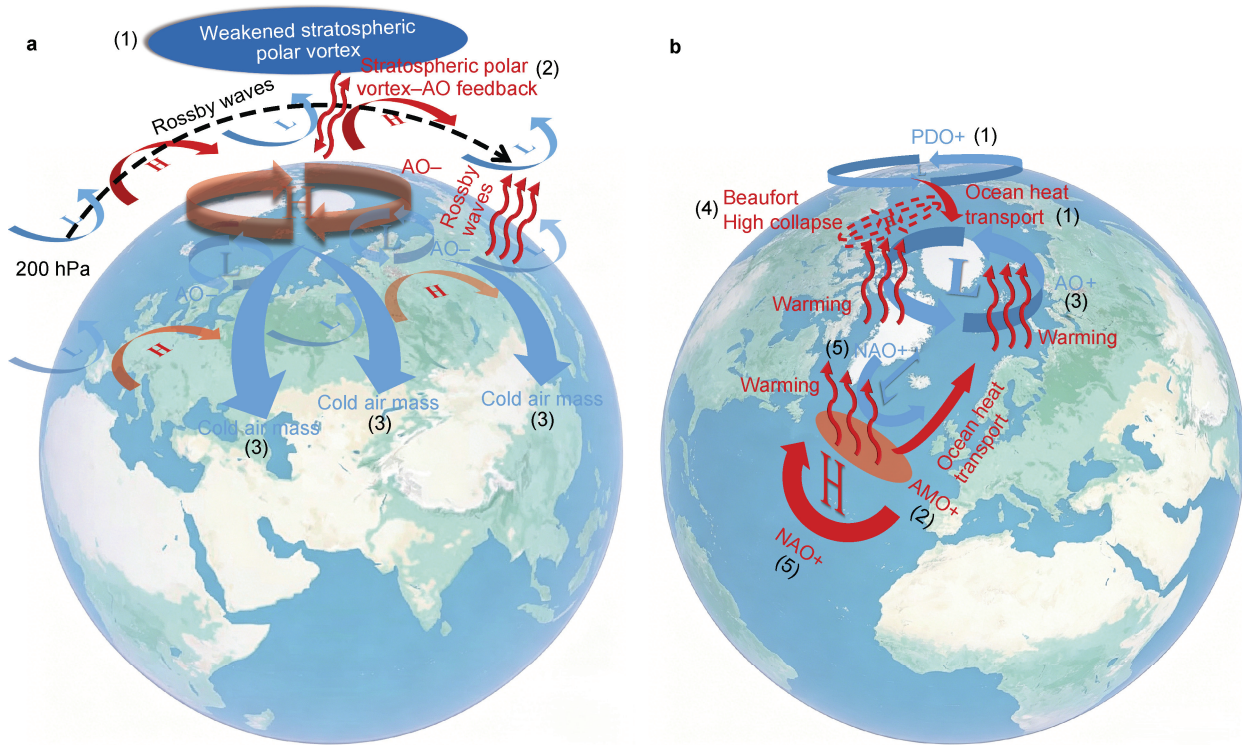


Figure 7 Partial processes of Arctic climate change within and outside the Arctic. The mechanisms contributing to Arctic warming and transmitting its climatic influence to mid-latitudes under global warming: **a**, primarily focus on the mechanisms involving the weakening of the SPV and its interaction with the positive phase of the AO, as well as its teleconnection with mid-to-low latitudes, which promotes cold conditions and cold waves in Eurasia; **b**, highlight the positive phase of the AO, NAO, AMO and PDO, along with the collapse of the Beaufort High, induce the inflow of warm seawater into the Arctic, intensifying Arctic warming.

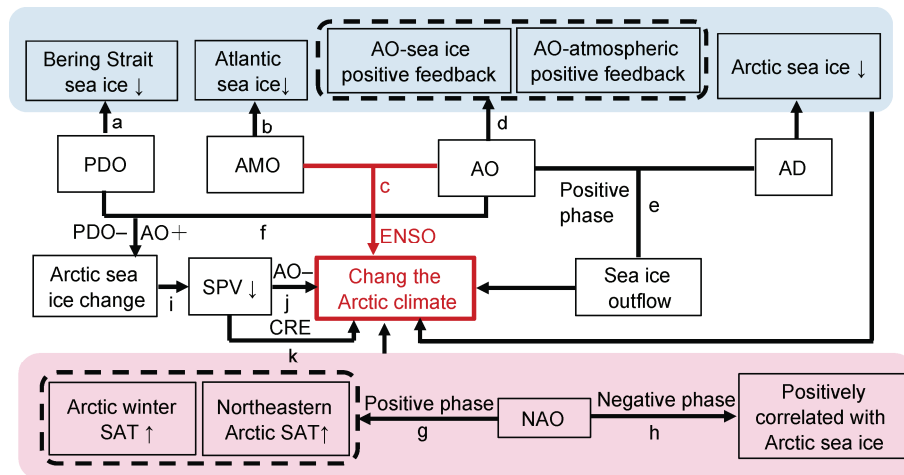


Figure 8 Mechanisms of five coupled modes influencing Arctic climate change. “↑” denotes increase, “↓” denotes decrease, “+” indicates positive phase, and “-” indicates negative phase. The letters from “a” to “k” denote different processes. AD, Arctic Dipole; AMO, Atlantic Multidecadal Oscillation; AO, Arctic Oscillation; CRE, cloud radiative effect; ENSO, El Niño–Southern Oscillation; NAO, North Atlantic Oscillation; PDO, Pacific Decadal Oscillation; SAT, surface air temperature; SPV, stratospheric polar vortex.

significantly increases the nonlinearity of Arctic climate change, posing challenges for clarifying the mechanisms of AA, improving simulation accuracy, and quantifying the contributions of individual drivers.

Besides tropospheric processes (AD, AMO, AO, NAO, NPO and PDO), the SPV and its interactions with the troposphere also affect Arctic sea ice and temperatures (Hu and Guan, 2018; Kim et al., 2014; Tang et al., 2025).

Decreased sea ice cover during early winter months (November–December), especially over the Barents–Kara seas, enhances the upward propagation of planetary-scale waves with wavenumbers of 1 and 2, subsequently weakening the SPV in mid-winter (January–February) (Figure 7a, process (1); Figure 8, process “i”) (Hoshi et al., 2019; Kim et al., 2014; Xu et al., 2024). On one hand, this process favors a negative AO phase in winter, enhancing the poleward atmospheric heat transport and accelerating AA, which contributes a positive sea ice–SPV–AO feedback (Figure 7a, process (2); Figure 8, process “j”) (Ma et al., 2024; Nakamura et al., 2016; Ogi et al., 2016). On the other hand, a weakened SPV intensifies the Arctic–North European high, favoring colder midlatitude surface conditions and coldwaves particularly over Eurasia (Figure 7a, process (3)) (Hoshi et al., 2019; Zou and Zhang, 2024). However, recent study indicates that a weakened SPV decreases Arctic high-cloud cover, generating a negative net cloud radiative effect that amplifies Arctic Ocean warming and sea ice loss (Figure 8, process “k”) (Xia et al., 2026). Furthermore, the positive phase of the PDO increases the refractive index (a measure of wave propagation) in the upper troposphere at high northern latitudes, which impedes the propagation of planetary waves and thereby reinforces the polar vortex, leading to cooling of the Arctic stratosphere and ultimately influencing Arctic climate (Hu and Guan, 2018). These complex processes and opposing effects highlight the nonlinear and partly contradictory nature of the SPV’s influence on Arctic climate.

The above studies indicate that poleward energy transport by the ocean and atmosphere, along with air–sea coupling, are important drivers of AA. Oceanic and atmospheric circulation deliver heat and moisture directly into the Arctic, while also modulating regional aerosol and sea ice concentrations. The role of the AMOC in Arctic climate remains an active area of debate. Most studies indicate a positive correlation between AMOC strength and AA: A stronger AMOC amplifies Arctic warming through enhanced poleward oceanic heat transport, while a weakened AMOC reduces this heat supply and can temporarily mitigate warming or even favor sea ice expansion. Observations from recent decades suggest that a weakening in certain circulation anomalies has corresponded to reduced poleward energy transport, which appears to have further accelerated Arctic warming. Arctic climate change is further modulated by a suite of coupled ocean–atmosphere modes, notably the AMO, PDO, AO, AD, and NAO (Figures 7 and 8). When these modes shift phase, they can trigger a cascade of effects: altered convection patterns, stratospheric circulation anomalies, and a series of feedback processes across high northern latitudes. In addition to the ocean–atmosphere modes, the SPV provides another modulating factor, influencing Arctic sea ice and climate via sea ice forcing, cloud feedbacks, and AO modulation. However, its overall contribution remains uncertain due to the intricate nonlinear interactions involved.

From a mechanistic viewpoint, these interconnected dynamics represent fundamental factors promoting AA.

4 Discussion

Climate change in the Arctic region represents a critical component of global climate change, and is closely linked to the extreme weather events, circulation anomalies, and variations in precipitation and temperature observed in parts of the Northern Hemisphere mid-latitudes in recent years (Blackport et al., 2024; Hu et al., 2023; Liu J et al., 2021; Liu Q et al., 2025; Zhang C et al., 2025). Clarifying the mechanisms behind AA is therefore essential for addressing these issues. Although substantial research has advanced our understanding of AA in recent years, persistent limitations in models and observations continue to fuel the debate over the quantitative contributions of individual factors and their interactions, hindering scientific consensus. Current findings remain challenged in the following areas:

(1) Long-term, reliable observational data for certain key variables remain scarce. Advancements in observational technologies have now enabled long-term, precise monitoring of key Arctic variables, including sea ice concentration, temperature, vegetation coverage, and wind fields, yielding a series of robust observational datasets. In contrast, significant challenges persist in observing sea ice thickness, sea ice drift, and BC, leading to a notable lack of highly credible datasets to support research. The urgency of this gap is further heightened by the recent evolution in Arctic sea ice loss, which has shifted from a primary reduction in concentration to a pronounced decline in thickness, alongside increasingly frequent ice drift. This transition coincides with growing scholarly interest in clarifying the role of BC in Arctic climate change. Therefore, there is an urgent need to refine observational techniques to enhance data quality, thereby providing a stronger foundation for advancing mechanistic studies.

(2) The primary drivers and underlying mechanisms of several processes involved in AA remain unclear. In recent years, most studies have considered sea ice loss and the resultant surface albedo feedback to be the one of the key mechanisms in AA, with other drivers primarily modulating amplification by influencing sea ice melt (Dai A et al., 2019; Dai G et al., 2023). Still, it has been pointed out that AA persists even during periods without significant sea ice loss (Pithan and Mauritsen, 2014). As AA has continued in recent years, phenomena such as increased vegetation net primary productivity and permafrost thaw have become more frequent and are influencing AA through land–atmosphere coupling processes. However, relevant research remains limited regarding the interaction between vegetation and other driving factors, the contribution of vegetation to AA, and the coupling mechanism among vegetation, permafrost, and AA. Regarding aerosols, several key questions still require in-depth investigation. These

include the mechanisms of aerosol–cloud interactions, the role of emerging and secondary aerosols in the Arctic, and how changes in aerosol concentrations drive amplification (Acosta Navarro et al., 2016; Nakanishi and Michibata, 2025; Wu et al., 2024; Zhou et al., 2020). The evolving trajectory of AMOC and its influence on Arctic climate change represent particularly complex challenges, necessitating further research to unravel the underlying physical linkages. Beyond these factors, the mechanistic role of stratospheric processes in AA, though clearly relevant, remains poorly understood within the context of air–sea interactions. Moreover, the coupled processes involving clouds, the ocean, sea ice, and the atmosphere further complicate the nonlinear nature of AA, posing a significant obstacle in deciphering the mechanisms driving Arctic climate change. Clarifying the intrinsic workings of these processes is crucial, not only for understanding the causes of Arctic climate change but also for comprehending nonlinear dynamics within the global climate system.

(3) There is lack of exploration on the interaction mechanisms among different drivers. Due to persistent gaps in understanding its fundamental processes, studies have predominantly focused on analyzing individual factors and quantifying their isolated contributions. This approach often overlooks the combined, holistic effects arising from interactions between multiple drivers. While some studies have identified interactions among key local feedbacks involving albedo, temperature, and aerosol–water vapor–cloud processes (Clark et al., 2021; Vázquez et al., 2017; Wegmann et al., 2017), the specific mechanisms governing these relationships remain unclear. However, the connections between these local feedbacks and larger-scale processes, including extratropical air–sea energy transport, hemispheric or global circulation patterns, and regional changes in temperature and pressure fields, remain poorly understood. Future work should dissect the interaction mechanisms both within local feedbacks and between local and extratropical processes, by integrating sustained observations, paleoclimate reconstructions, improve modeling frameworks, and used advanced statistical separation techniques like Generalized Equilibrium Feedback Assessment to isolate independent footprints from complex, coupled noise. Advancing this understanding is crucial for unraveling the complex mechanisms behind AA and for improving the reliability of climate models.

(4) Model simulations face challenges in quantifying the contributions of individual drivers, and certain processes still require further refinement. Numerous studies indicate that the limited ability of current climate models to simulate the multiple nonlinear processes and complex local feedbacks involved in AA can result in either underestimation or overestimation of key processes, depending on the time period, model, and analysis method employed, making it difficult to precisely quantify the relative contributions of different drivers (Cai et al., 2025; Gong et al., 2017; Goosse et al., 2018; Huang et al., 2019; Li et al., 2025; Morrison et

al., 2020; Schmale et al., 2021). Although some studies have employed control experiments, including fixed sea ice or cloud-locking simulations, to isolate and quantify the effects of specific drivers, results vary substantially across models and regions. Moreover, the limited accuracy with which current models simulate cloud processes and sea ice dynamics presents a persistent challenge, substantially complicating efforts to decipher the mechanisms of Arctic climate change and serving as a major source of simulation bias. Recent work has integrated daily Arctic sea ice drift, deformation, and thermodynamic changes into conventional sea ice thickness datasets, thus improving their accuracy and consistency, however, further studies are needed to verify these advances and clarify the underlying mechanisms (Ricker et al., 2025). Therefore, given that several underlying mechanisms of AA remain poorly understood, substantially improving model performance in the short term will require coordinated efforts from the international research community.

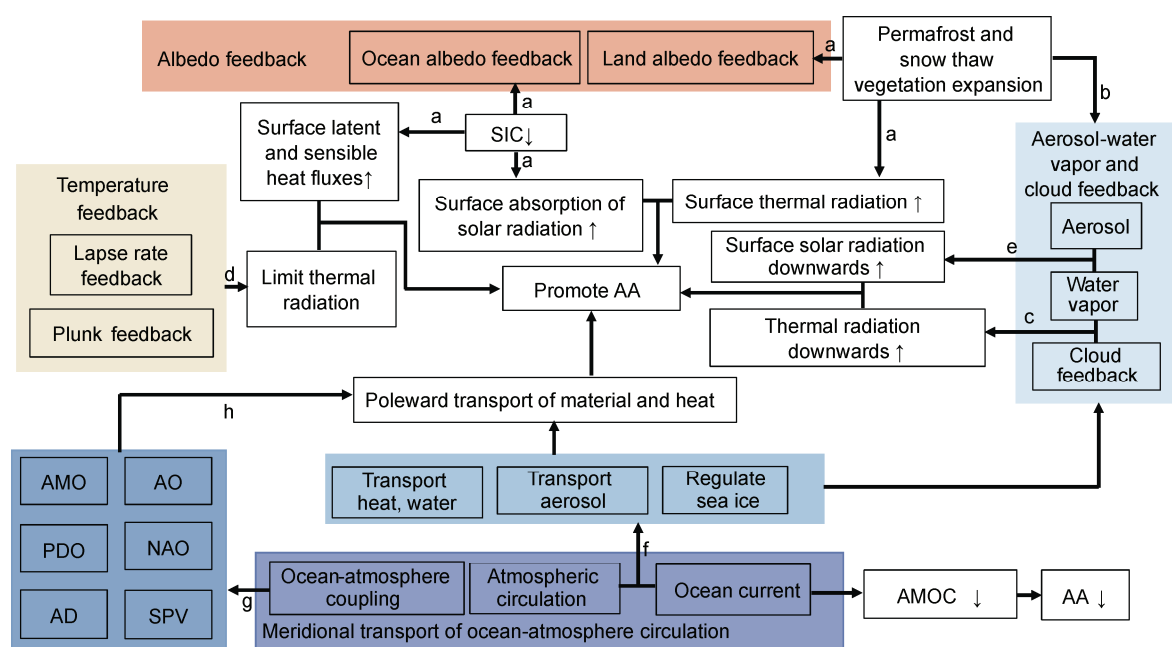
5 Conclusion

In recent decades, the Arctic has been warming at a rate three to four times the global average, accompanied by extensive cryosphere retreat and tundra expansion. In this paper, we provide a comprehensive review of the evidence for AA and the mechanisms that drive it, focusing on four primary factors. The results are summarized as follows:

(1) AA has increased significantly in the last four decades, exhibiting a strong dependence on surface type and pronounced seasonality, with the strongest amplification in winter. The most intense warming occurs in ice-retreat zones, while ice-free ocean areas show weaker warming and high-latitude Siberia undergoes anomalous cooling, forming the “warm Arctic, cold Siberia” pattern.

(2) The mechanisms driving AA involve complex interactions among surface albedo feedback, temperature feedback, water vapor–aerosol–cloud feedback, and poleward transport of energy and material (Figure 9). Driven by sea ice loss, land-surface changes (Figure 9, process “a”), and factors such as temperature inversions, these processes modulate the Arctic radiation budget (Figure 9, processes “a, c, d, e”), thereby forming feedbacks. These feedbacks, along with the poleward transport of energy and material (Figure 9, processes “h, f”) and coupled ocean–atmosphere circulation processes (Figure 9, process “g”), collectively influence Arctic climate. Moreover, some of these processes interact with one another (Figure 9, process “b”) to further amplify the feedback strength. Through these intertwined pathways, near-surface warming and sea ice loss reinforce each other, creating a networked set of feedbacks that collectively modulate the pace and spatial pattern of AA.

(3) Substantial uncertainty remains in how local feedbacks interact with each other and with large-scale processes. The coupling between local feedbacks (albedo feedback, temperature feedback, and aerosol–water vapor–cloud



feedback) and extratropical energy transport, hemispheric circulation patterns, and regional temperature–pressure field variations is still poorly quantified. The roles of vegetation–permafrost–climate interactions, aerosol–cloud–radiation linkages, and stratospheric processes within the coupled Arctic system are not yet fully understood, limiting our ability to predict the net effect of coupled feedbacks on AA.

Looking ahead, advancing our understanding will require improved observational data and models, more sophisticated analytical methods, and strengthened international cooperation. To this end, addressing these aforementioned uncertainties calls for sustained and enhanced observational data of key variables such as sea ice thickness, sea ice drift, and BC, alongside improved parameterizations of cloud-aerosol and land surface processes in climate and Earth system models, and the integration of sea ice drift dynamics into these models. Moreover, coordinated model intercomparisons, fixed-forcing experiments, and advanced statistical separation techniques are needed to isolate the contributions of individual drivers from complex coupled noises. Underpinning all these efforts, stronger international collaboration remains essential to accelerate process-level understanding and reduce the spread in climate projections.

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