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Review

Climate teleconnections among the Earth's three poles

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ABSTRACT

The Arctic, Antarctic, and Tibetan Plateau (TP) are often referred to as Earth's three poles, and they exert outsized influence on the global climate. The three poles have undergone accelerating loss of sea ice, ice shelves, and/or glaciers, accompanied by pronounced warming in the Arctic and TP and region-specific warming in Antarctica. Despite their geographical remoteness, the three poles exhibit evident linkages, yet substantial gaps remain in our understanding of their climate teleconnections. This review summarizes the interactions among Earth's three poles. The three poles are dynamically linked through a hierarchy of pathways. The Arctic–TP interactions are dominated by stationary Rossby-wave trains triggered by sea-ice and snow anomalies and reinforced by land-surface feedback over the plateau. The Arctic–Antarctic coupling relies on ocean heat transport through the Atlantic Meridional Overturning Circulation and on the modulation of tropical Atlantic temperature and the Intertropical Convergence Zone. The Antarctic–TP signals travel via sea-surface temperature anomalies in the Indian Ocean forced by the Antarctic Oscillation, which propagate northward and excite wave trains and transport moisture onto the TP. Closing the remaining knowledge gaps will require coordinated paleoclimate constraints, targeted field campaigns over the Southern Ocean and TP, and next-generation Earth-system models equipped with machine-learning techniques. Such integrative efforts are essential for more reliable projections of compound extremes and for informing adaptation strategies.

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1. Introduction

The Earth's three poles (Fig. 1), including the Arctic, the Antarctic, and the Third Pole, the Tibetan Plateau (TP), are the predominant components of the cryosphere and are characterized by frigid temperature, snow, frozen ground, and extensive terrains outlined by ice sheets [1–4]. These regions serve as habitats for unique species and reservoirs for Earth's freshwater resources and exhibit high sensitivity to climate change, which are key similarities among their natural environments and ecosystems [1,2,5].

Over the past four decades, all three poles have undergone pronounced and, in many cases, accelerating change. The Arctic has lost approximately half of its summer sea–ice extent [6–8] and is warming at more than twice the global average, a phenomenon known as Arctic amplification [9,10]. West Antarctica has experienced significant surface-air warming and rapid ice-shelf thinning, whereas East Antarctica remains relatively stable [11,12]. On the TP, high-elevation glaciers are retreating, permafrost is degrading, and an elevation-dependent warming pattern has emerged, with the fastest increases occurring at the highest altitudes [13–16].

Rapid warming across Earth's three poles is driven by powerful surface–albedo feedback. As sea ice, seasonal snow and glacial cover diminish, darker land, ocean and vegetation surfaces absorb more solar radiation, accelerating local heating in the Arctic [9,17], on the TP, where elevation-dependent warming enhances the snow–albedo effect [18,19], and on Antarctic ice shelves and coastal ice sheets, where melt-albedo interactions reinforce warming and mass loss [20,21]. This locally amplified heating intensifies

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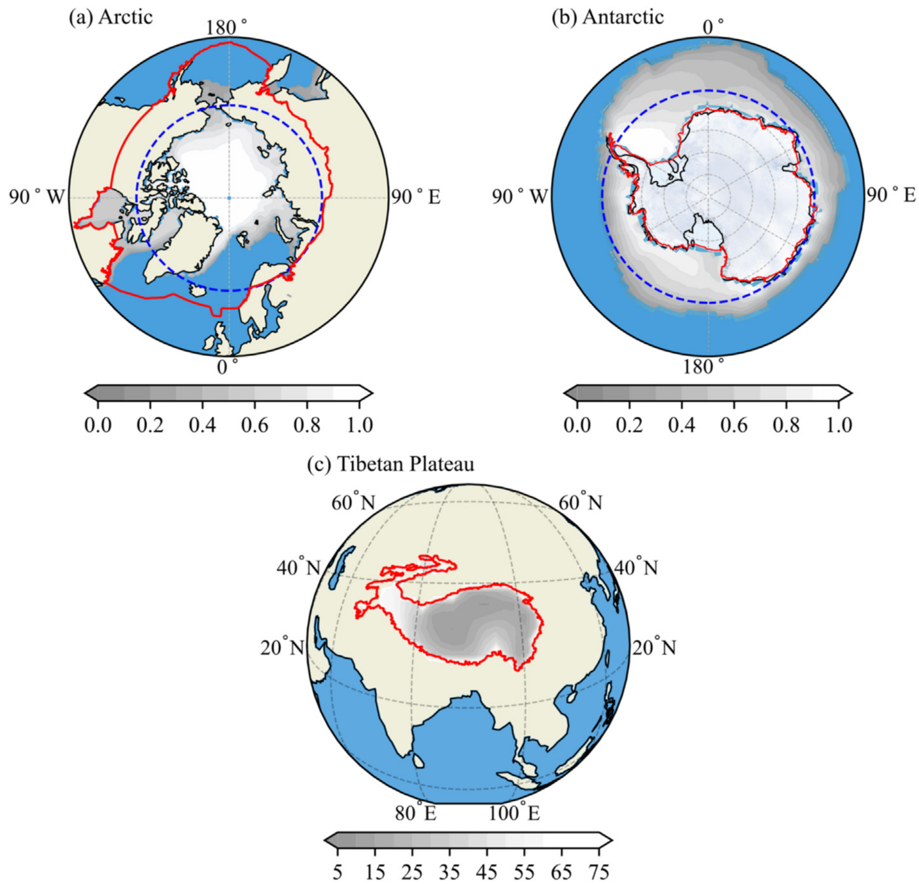

Fig. 1. Earth's three poles. Geographic areas of (a) the North Pole, (b) the South Pole, and (c) the Third Pole (Tibetan Plateau). The red line in (a) represents the Arctic boundary defined by the Arctic Monitoring and Assessment Program, whereas the blue line indicates the Arctic Circle. The red line in (b) represents the Antarctic ice shelf edge, and the blue line represents the Antarctic Circle. Shading over the ocean in (a) and (b) represents climatological sea-ice concentrations (1979–2023; units: 1) based on the Hadley Centre Sea Ice and Sea Surface Temperature dataset (Version 1.1). The red line in (c) indicates the 2500 m topographic contour, and shading indicates climatological snow cover (1979–2023; units: %) derived from the National Oceanic and Atmospheric Administration Climate Data Record.

meridional temperature gradients and excites large-scale planetary wave trains and jet-stream shifts that act as atmospheric bridges, linking anomalies at one pole to circulation changes at the other poles and to lower-latitude climates [22–24]. Concurrent oceanic adjustments, such as Atlantic Meridional Overturning Circulation (AMOC) responses to freshwater and heat fluxes, also transmit polar signals equatorward and across basins, completing a three-pole teleconnection network that couples cryospheric change at both ends of the planet with the high-altitude TP [25].

Teleconnections among the three poles emerge along three principal corridors with distinct physical mechanisms. The Arctic-TP corridor transmits anomalies primarily through fast, stationary Rossby-wave trains that arc across Eurasia. For example, sea–ice decline in the Barents-Kara Seas can alter Tibetan snowfall and temperatures within a season, and feedback from TP snow can in turn reshape Arctic circulation [26–28]. The Arctic-Antarctic corridor relies on interhemispheric ocean heat transport by the AMOC, accompanied by shifts in the Intertropical Convergence Zone (ITCZ) and Hadley cells [29–31], producing the out-of-phase temperature and sea–ice swings known as the bipolar seesaw. The Antarctic-TP corridor is governed mainly by air–sea interactions in the southern Indian Ocean, where changes in the Antarctic Oscillation (AAO) alter wind stress, induce a north–south Sea Surface Temperature (SST) dipole, and excite Rossby-wave trains and modulate moisture transport toward the TP [32].

Viewing the Arctic, Antarctic, and TP as a coupled network is essential because their joint anomalies can reshape the climate far beyond high latitudes and altitudes. Recent events illustrate this leverage. In 2022, concurrent hydrothermal anomalies over all three poles intensified mid-latitude heatwaves and Asian extreme rainfall by altering the mid-latitude westerly jet and exciting Rossby-wave trains; the same tripolar signal also forced a southward, weaker Asian summer monsoon [33]. Earlier work has shown that Arctic sea–ice deficits and TP surface heating together accelerate the spring-to-summer transition of the South Asian monsoon [34] and modulate summer rainfall anomalies over eastern China [35]. A growing body of evidence even links tripolar covariability to subcontinental heat extremes. For example, the synergistic amplifications of the Arctic and TP explain much of the interannual variability in Yangtze River Basin heatwaves, with Arctic amplification chiefly controlling spatial extent and TP amplification governing intensity via a meridional tripole pattern and double-jet configuration over East Asia. This combined effect is significantly stronger than the individual contributions of Arctic or TP amplification, highlighting nonlinear amplification [36].

This article synthesizes recent advances in our understanding of the climate teleconnections among the Earth's three poles. We elucidate the physical mechanisms that couple the Arctic with the TP, the Arctic with Antarctica, and Antarctica with the TP. To conclude, we offer a succinct summary along with a forward-looking perspective.

2. Land–air–cryosphere coupled linkage between the Arctic and the TP

The interaction between the Arctic and the TP has attracted considerable attention, primarily because the two regions are closer to each other than the Arctic-Antarctic and Antarctic-TP interactions are [26,27,37–39]. The linkages within this corridor are not uniform: they operate across a spectrum of timescales, from subseasonal to long-term trends. The influence is also bidirectional, with anomalies in each region capable of forcing a response in the other through complex atmospheric and land-surface pathways. The conceptual framework for the interactions between the Arctic and the TP is shown in Fig. 2.

2.1. The impact of the Arctic on the TP climate

Observational data reveal that anomalies in Arctic sea ice and large-scale atmospheric modes such as the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) significantly impact various climatic variables on the TP, including surface air temperature [40], land-surface temperature [41], precipitation [42], aerosols [38], dust [43], sensible-heat flux [44], and snow depth [45], across different time scales. These teleconnections primarily operate through atmospheric Rossby-wave trains, which rapidly convey anomalous climate signals from high-latitude Arctic regions to the mid-latitude TP. Additionally, the persistence of climatic anomalies across seasons is maintained through land-surface processes (a "land-memory" effect), where signals induced by Arctic sea-ice and atmospheric circulation anomalies are stored in Eurasian snow cover and soil moisture, facilitating delayed climatic responses on the TP. The position and strength of the subtropical westerly jet vary seasonally and interannually, providing a critical atmospheric waveguide for determining the effectiveness of these teleconnections.

At subseasonal-to-seasonal timescales, the teleconnections typically depend on specific atmospheric conditions. For instance, a Rossby-wave train originating from the Arctic influences the TP predominantly when the AO exhibits a positive phase concurrently with a negative Western Pacific pattern in February. Under these circumstances, increased snowfall on the TP occurs, leading to persistent cold surface anomalies that continue into spring [27].

At the interannual timescale, Arctic sea-ice anomalies in the North Atlantic sector, particularly in the Greenland, Barents, and Kara Seas, substantially impact various climatic variables over the TP via Rossby-wave propagation and land-surface processes. For example, negative sea-ice anomalies in the Barents-Kara Sea (BKS) in May induced circumglobal teleconnection-like wave trains, significantly amplifying surface warming on the TP after 2001[41]. Spring BKS ice anomalies can also persist into summer, affecting summer precipitation patterns on the TP through Silk Road pattern wave propagation [42]. In addition, reduced winter sea ice in the Barents Sea directly modulates winter snow depth on the mid-western TP via Rossby-wave excitation [45]. Similarly, winter sea-ice anomalies north of Greenland persist into spring, generating anomalies in sensible-heat flux on the TP [44]. Although still controversial, negative autumn sea-ice anomalies in the Beaufort and Laptev Seas have been linked to increased extreme cold events over the TP in the subsequent winter, presumably via Rossby-wave propagation [46]. Moreover, through the mediation of Eurasian snow cover, the reduction in February Arctic sea ice in the North Atlantic region significantly facilitates the transport of aerosols from South Asia to the Tibetan Plateau in April [38]. Similarly, autumn sea-ice variability in the BKS influences winter dust over the TP through Eurasian snow cover acting as an intermediary [43]. Furthermore, BKS ice loss in spring induces a summer warm anomaly on the eastern TP because the signal is stored in Eurasian soil moisture [40].

The AO and NAO also significantly influence the TP climate through Rossby-wave propagation at interannual scales. During summer, a positive AO phase generates a Rossby-wave train that establishes anticyclonic circulation over the northeastern TP, leading to warmer conditions, particularly on the eastern TP. The AO-temperature relationship over the TP has strengthened notably since the late 1990s because of a phase shift in the Pacific Decadal Oscillation (PDO) from positive to negative [40,47]. Similarly, the negative summer NAO (SNAO) phase triggers eastward-propagating Rossby-wave trains, increasing precipitation on the

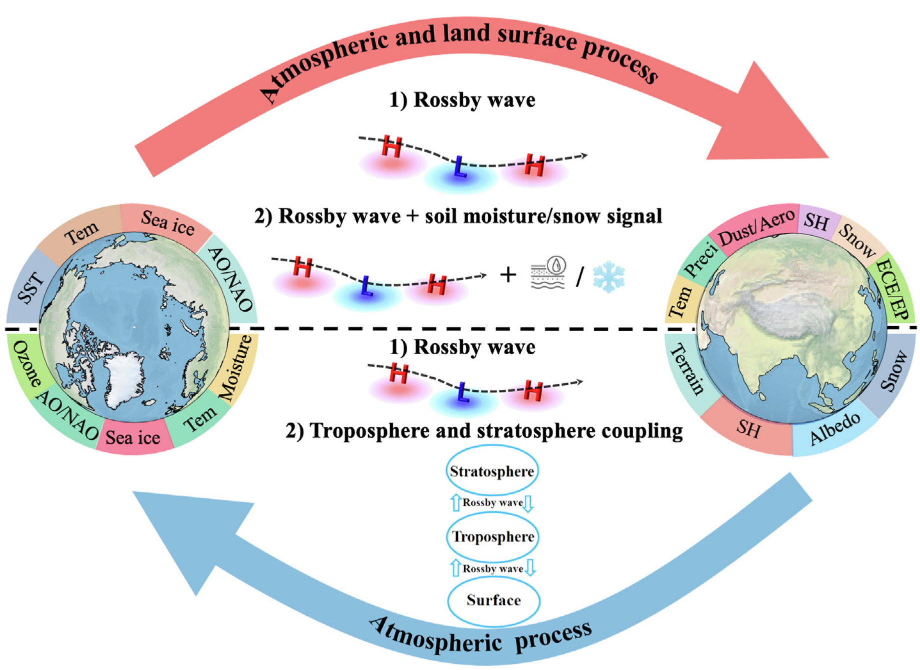

Fig. 2. Conceptual framework of the interaction between the Arctic and TP. The orange arrow represents Arctic influences (upper hemisphere) on the TP through atmospheric and land-surface processes. The blue arrow indicates the influence of the TP (lower hemisphere) on the Arctic through atmospheric pathways. SST: sea surface temperature; Tem: temperature; Preci: precipitation; Aero: Aerosol; SH: sensible heating; ECE: extreme-cold event; EP: extreme precipitation.

southeastern TP but reducing it in the northeast [28]. However, the strength of this SNAO-precipitation relationship has diminished since the late 1990s, likely because of the Atlantic Multidecadal Oscillation (AMO) transitioning from its cold to warm phase [48]. Additionally, winter sea-ice dipoles between the Barents-Nordic Seas and the Labrador Sea intensify negative NAO events, stimulating Rossby waves that lead to increased snowfall on the western TP [49].

On decadal timescales, sustained anomalies in Arctic sea ice and the AO/NAO state influence the TP climate predominantly through prolonged Rossby-wave activity. Persistent summer warming in the Labrador Sea triggers a Rossby-wave train, causing positive summer temperature anomalies over the TP [39]. Similarly, reductions in winter BKS sea ice significantly modulate winter extreme precipitation patterns over the TP, resulting in positive anomalies in the northwest and negative anomalies in the southeast, although the exact mechanism remains unclear [50]. In addition, a strengthened Arctic stratospheric polar vortex during winter associated with a positive AO phase can modulate the vertical propagation of planetary waves. This further influences tropospheric circulation by weakening the Siberian High and deepening the India-Burma Trough, thereby enhancing southwesterly moisture transport and leading to increased snowfall over the TP during winter and early spring [51]. The positive AO phase in spring similarly enhances snow accumulation over the TP via Rossby-wave propagation [52]. Similarly, a positive winter NAO phase strengthens the Asian subtropical westerly jet and regional circulation anomalies, enhancing moisture transport and subsequently increasing snowfall over the TP [53].

At long-term trend scales, continuous Arctic sea-ice reductions, particularly in the BKS region, significantly alter the climatic conditions of the TP through sustained Rossby-wave excitation. Persistent declines in winter sea ice in the BKS region notably amplify winter warming trends over the TP [26]. The winter Barents-Kara decline in recent decades can explain 18 %–32 % of the observed winter warming over the TP. Additionally, sea-ice reductions in the North Atlantic during late spring have been associated with a notable northwestward shift in summer precipitation on the TP, driven by delayed evaporation from anomalously wet soils near the Caspian Sea region, reinforcing teleconnections via soil moisture memory mechanisms [54].

The fundamental mechanism underlying Arctic-TP teleconnections is the excitation and propagation of atmospheric Rossby-wave trains. These wave trains serve as rapid conduits, transferring climatic perturbations from Arctic sea ice or AO/NAO anomalies toward the TP within days to weeks. However, the establishment of these wave trains requires specific atmospheric conditions. The subtropical westerly jet plays a crucial role, acting as a waveguide that channels wave energy efficiently toward the TP. Seasonal shifts in the latitude and strength of the jet critically influence wave propagation pathways and intensities. For instance, the propagation of a stationary wave train toward the Tibetan Plateau is most efficient when sea–ice anomalies develop in the Barents-Kara and Labrador seas, which sit along the preferred corridor for such waves. Conversely, anomalies in more remote Arctic sectors or less favorable jet conditions may weaken or disrupt the teleconnections.

The apparent discrepancies between the rapid propagation speed of atmospheric wave trains (subseasonal scale) and the longer-term climatic teleconnections observed (interannual to decadal scales) are largely attributable to the persistence of forcing anomalies in the Arctic region. Persistent sea-ice or SST anomalies, which may recur annually or sustain themselves over decades, continually excite these rapid wave trains, leading to robust, long-lived climate correlations at interannual and decadal timescales. Moreover, land-surface memory further extends the effects of teleconnection across seasons. Climatic anomalies induced by winter Arctic sea-ice reductions, for instance, can be stored in Eurasian soil moisture or snow cover, influencing subsequent seasons by altering surface albedo, diabatic heating, and moisture availability, thus reinforcing atmospheric circulation anomalies downstream. This interplay between rapid atmospheric dynamics and slower land-surface processes elucidates the complex temporal structures of Arctic-TP teleconnections and underscores the importance of clearly distinguishing among subseasonal, interannual, decadal, and long-term trend timescales.

2.2. Impact of the TP on the Arctic climate

Teleconnections originating from the TP significantly modulate Arctic climate across subseasonal, interannual, decadal, and longer timescales. On subseasonal timescales, rapid changes to the TP surface in late autumn and spring can disturb the midlatitude jet quickly enough for its footprint to reach the Arctic within a single season [22]. Reanalysis and numerical experiments show that rapid snow build-up intensifies local diabatic cooling, taps the subtropical westerly jet and excites a barotropic Rossby wave that arrives over the central Arctic in approximately ten days. The ensuing cyclonic sea-level-pressure anomaly accelerates equatorward ice drift and reduces spring sea-ice concentration by as much as 0.2×10^6 km^2 [22].

Subseasonal teleconnection also emerges in the "Impact of Initialized Land Surface Temperature and Snowpack on Subseasonal to Seasonal Prediction (LS4P)" Phase-I experiments. Initializing coupled models with a 1 °C cold anomaly in the May TP land-surface temperature triggers, within a week, a quasibarotropic wave train extending from the TP to the Rocky Mountains and the Bering Sea that persists into early summer. Most LS4P models reproduce a decrease in June sea-level pressure over the Bering-Chukchi seas and delayed seasonal ice recovery, demonstrating that high-mountain land temperature is a genuine subseasonal-to-seasonal predictor of Arctic circulation [55].

On interannual timescales, TP climatic anomalies have substantial effects on Arctic sea ice and atmospheric circulation. A dense snowpack over the TP in September-November deepens regional hydrological cooling, and the accompanying horizontal vorticity source launches a wave train that enhances ice growth in the Bering and Barents Seas but reduces it in the Sea of Okhotsk, explaining approximately 10 %–30 % of the interannual variance in Arctic sea-ice extent [56]. When the TP snow anomaly is out of phase with snow around Lake Baikal, dipole-like forcing occurs. This pattern involves two out-of-phase diabatic centers that generate dual Rossby-wave trains, one along the subtropical jet and another near 60° N, whose interference pattern amplifies the Arctic signal [57].

Latent heat release over the southern plateau provides a complementary moisture pathway. Atmospheric model sensitivity runs in which the summer monsoon condensation heating over the southern TP is increased to produce a poleward-arching wave train along the Japan-North Pacific, enhancing westerlies and increasing atmospheric river activity in the North Pacific [58]. This can lead to stronger melting of thin sea ice in the Arctic and hinder the seasonal recovery of sea ice [59].

On decadal time scales, satellite records reveal a plateau-wide decrease in albedo of approximately 0.03 per decade. Idealized surface-darkening experiments show that the resulting sensible- and latent-heat amplification sets up a stationary wavenumber-1 circulation anomaly pattern that warms the Atlantic sector of the Arctic and favors sea-ice loss, a darkening resonance whose magnitude is comparable to 15 %–20 % of the observed 1995–2024 Barents-Kara ice trend [60].

At the tectonic time scale, the uplift of the TP greatly strengthened the stationary planetary wave and favored Arctic cooling. The importance of TP orography is underscored by topography-removal experiments. Coupled modeling experiments indicate that the removal of TP topography or suppression of TP surface heating eliminates a crucial stationary wavenumber-1 ridge extending into the Arctic sector, resulting in Arctic cooling and increased sea-ice thickness. Conversely, imposed warming over the TP enhances the stationary wave amplitude, leading to significant Arctic warming and sea-ice thinning [61]. Additionally, the topography of the TP influences the Arctic via the stratosphere by generating stationary planetary waves (Fig. 3). The TP serves as a key topographic source of stationary planetary waves over the Northern Hemisphere. These waves propagate upward into the Arctic stratosphere, where their convergence releases energy and triggers stratospheric warming. Such warming weakens the circumpolar westerlies and may disrupt the polar vortex. When sufficiently intense and rapid, it can reverse the westerlies to easterlies within a few days, leading to a sudden stratospheric warming event [62–64]. Accordingly, the presence of the topography of the TP, relative to its absence, favors a higher frequency of sudden stratospheric warming events in the Northern Hemisphere. Moreover, planetary waves of Wavenumber 1 induced by the topography of the TP can displace the stratospheric polar vortex toward Eurasia [53], thereby facilitating the eastward propagation of wave trains from the North Pacific to the North Atlantic and promoting the development of the Aleutian-Low-Icelandic-Low seesaw pattern [52]. Moreover, stationary waves forced by the topography of the TP drive the Brewer-Dobson circulation (a hemispheric meridional stratospheric circulation) [65], which transports ozone from the tropics toward the Arctic stratosphere. This results in approximately 15 % higher ozone concentrations during the winter than in the absence of the topography of the TP [66]. However, the current understanding of the stratospheric linkages between the TP and the Arctic remains relatively limited, highlighting the need for further in-depth studies in the future.

Across all time scales, teleconnections from the TP to the Arctic fundamentally arise from the plateau's unique topography and its pronounced snow-albedo, land-surface temperature, and surface heat flux anomalies. These anomalies project onto the subtropical westerly jet, whose large meridional potential-vorticity gradient acts as a waveguide. Critical conditions for robust wave propagation include the alignment of these TP-generated anomalies with optimal jet stream configurations, facilitating efficient barotropic and baroclinic energy conversion and transient-eddy feedback that sustains wave trains to the Arctic. Wave-mean-flow interactions and transient-eddy feedback convert background barotropic energy into the propagating packet, enabling the disturbance to reach the Arctic in days to weeks. Once sea-level pressure is altered, sea-ice drift is redistributed. Ice-albedo feedback, together

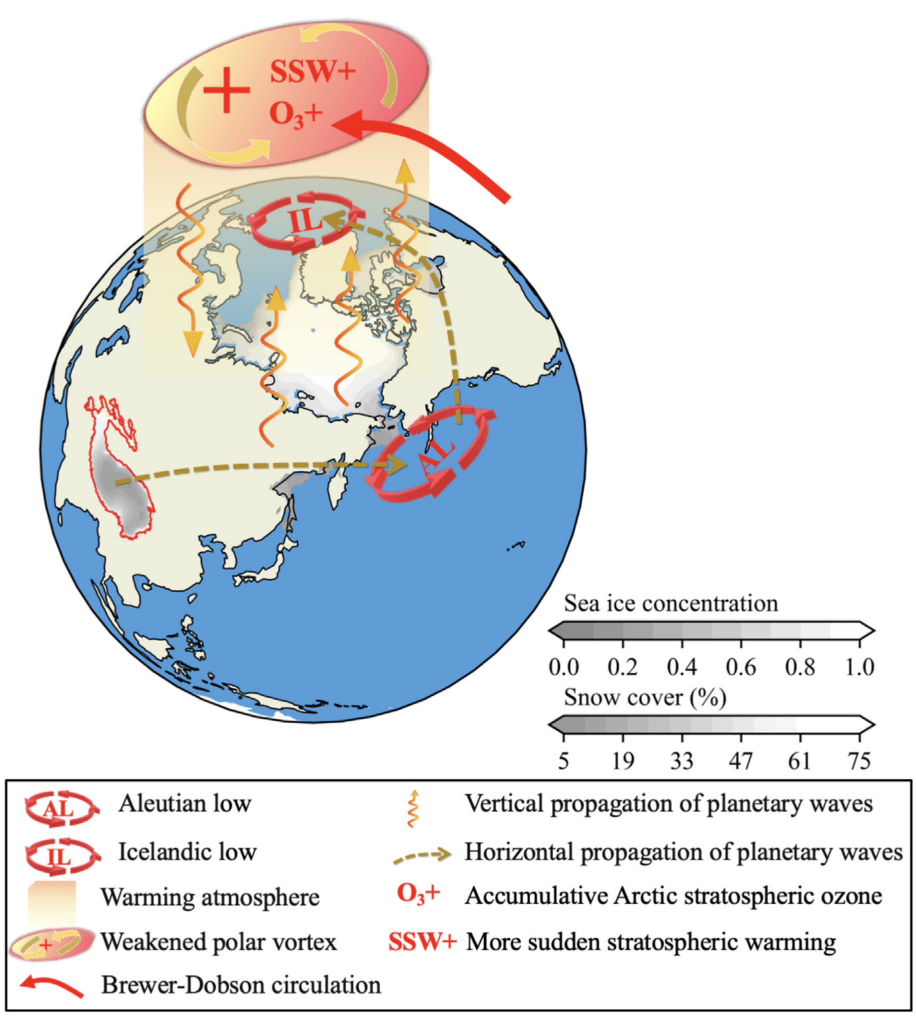

Fig. 3. Influence of the TP topography on the Arctic stratosphere. The TP topography intensifies both the horizontal and vertical propagations of planetary waves in the Northern Hemisphere, weakening the Arctic stratospheric polar vortex while strengthening the Brewer-Dobson circulation. This leads to more frequent sudden stratospheric warming events, increased stratospheric ozone, and a pronounced Aleutian-low-Icelandic-low seesaw pattern. The color shading over the TP and Arctic represents climatological snow cover (1979–2023, units: %) and sea-ice concentration (1979–2023, units: 1), respectively, and their data sources are the same as those in Fig. 1.

with slowly evolving TP surface properties (snow depth, albedo, and vegetation), integrates the signal into interannual and decadal variability. Finally, a portion of the wave activity penetrates the lower stratosphere, modulating the polar vortex and Brewer-Dobson circulation and thereby locking the teleconnection into the annular-mode framework.

3. Earth's farthest linkage spanning the Arctic-Antarctic

Despite their great geographical distance, the Arctic and Antarctic form an interconnected system [29–31,66–69]. The most representative linkage is the bipolar seesaw, demonstrated by asynchronous variations in Arctic and Antarctic sea ice and temperature [29,68]. Originally proposed in paleoclimate studies [70,71], the bipolar seesaw is evident in instrumental temperature data and ice-core records across millennial-centennial [31,72], interdecadal [68,69], and multidecadal [68,71] timescales.

The Arctic–Antarctic coupling operates through both oceanic and atmospheric pathways [29,30,67–70] (Fig. 4). On millennial-centennial time scales, high-resolution ice-core and marine-sediment archives reveal out-of-phase temperature swings between Greenland and Antarctica during the last glacial cycle, when abrupt Greenland warmings (Dansgaard-Oeschger events) coincided with slow Antarctic cooling, and the opposite pattern is also observed [29,71]. Stocker and Johnsen's simple thermodynamic model linked this antiphase to variations in AMOC, suggesting that a slowdown traps oceanic heat in the south, cooling the North Atlantic while warming the Southern Ocean, whereas a vigorous AMOC does the opposite [70]. As the AMOC is primarily responsible for northward Atlantic heat transport, any weakening would result in increased global ocean heat storage [73,74]. More heat is then retained in the Southern Ocean, increasing the Antarctic air temperature and reducing the temperature in the Arctic. Transient simulations and marine records sharpen that picture, suggesting that even modest freshwater pulses can flip the inter-hemispheric temperature gradient on millennial-centennial time scales [29,70,75]. Recent model experiments have further shown that meltwater discharged from the Antarctic Ice Sheet can weaken the AMOC, amplifying the thermal contrast between the poles [76].

On multidecadal and decadal time scales, instrumental records display a twentieth-century seesaw in which detrended Arctic and Antarctic surface temperatures vary in near-perfect antiphases. Two mechanisms dominate. First, in multidecadal SST modes, the AMO and PDO launch hemispheric Rossby-wave trains that increase the geopotential height in one polar cap while lowering it in the other, thereby flipping the sign of sea-ice and temperature anomalies, mainly through cloud-radiation and ice-albedo feedback [67,69]. Specifically, Atlantic warming related to the AMO can induce quasistationary Rossby waves that increase pressure south of Australia and lower it over the Amundsen Sea. This pressure change induces abnormal atmospheric circulation, which in turn affects the long-term trends of temperature and sea-ice distribution in the Antarctic region. Anomalies equivalent to one standard deviation of the North Atlantic SST can induce a 20 %–25 % change in the extent of Antarctic sea ice [67,77].

High-latitude thermal forcing in one hemisphere can influence the polar climate of the opposite hemisphere by modulating the position of the ITCZ and hence the strength and latitude of the polar westerly jet [31,68,72,78]. Idealized modeling experiments have shown that polar–surface warming in one hemisphere can produce up to ~30 % of that warming in the opposite hemisphere [31]. Cooling in northern high latitudes, for example, displaces the ITCZ southward, weakens the northern Hadley circulation and strengthens its Southern Hemisphere counterpart. This intensified southern cell transfers more angular momentum to the Southern Hemisphere subtropics, accelerating the subtropical jet

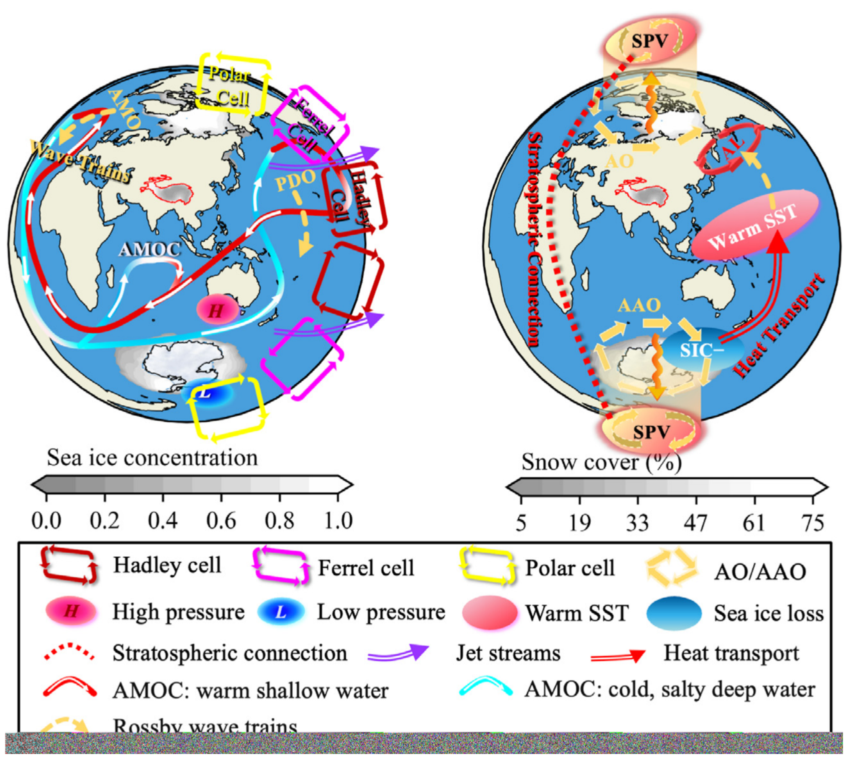

Fig. 4. Conceptual pathways linking the Arctic and Antarctic. AMOC mediates the oceanic pathway, whereas tropospheric processes, such as Rossby-wave excitation and shifts in atmospheric meridional overturning, provide the atmospheric route. Disturbances also spread across hemispheres through stratosphere–troposphere coupling. The SPV represents the stratospheric polar vortex. Color shading over the TP and polar regions represents climatological snow cover (1979–2023, units: %) and sea-ice concentration (1979–2023, units: 1), respectively, and their data sources are the same as those in Fig. 1.

stream and shifting the eddy-driven jet equatorward. Consequently, anomalous eddy momentum flux divergence develops in the high southern latitudes, inducing northerly winds and forming a counterclockwise meridional circulation. Within this pattern, subsidence over polar regions leads to adiabatic atmospheric warming [31,68,72,78].

On the interannual time scale, synchronization between the AO and AAO occurs in February and October. Reanalysis composites display a barotropic annular-mode pattern that extends from the surface to the lower stratosphere, implying a shared stratospheric driver [30]. Moreover, planetary waves generated by sea-ice and temperature anomalies can propagate upward, triggering sudden stratospheric warming that spreads globally [79–82] and inducing upper atmospheric and ionospheric anomalies in the Southern Hemisphere [83].

Projected warming in the Antarctic is likely to exacerbate warming in the Arctic on decadal time scales. The projected sea-ice loss in the Antarctic by the end of the 21st century can induce a 1°C increase in surface temperature in the Arctic and a reduction in Arctic sea-ice extent by approximately 0.5×10^6 km^2 [84]. This decadal Antarctic–Arctic teleconnection is routed through the tropics. First, the loss of Antarctic sea ice leads to enhanced surface warming and increased precipitation in the equatorial Pacific. The loss of Antarctic sea ice can induce cyclonic winds over the Southern Ocean and the associated northwesterly winds in the subtropics, which lead to Ekman suction at subduction latitudes, weaken oceanic subtropical meridional overturning cells, and allow more heat to accumulate in the tropical upper ocean, especially in the central and eastern Pacific [85]. Second, the resulting warming in the tropical Pacific excites a Rossby-wave train across the Pacific and intensifies the Aleutian Low in boreal winter, channeling warm air into the Arctic and contributing to sea-ice loss in the Bering Sea. Some studies [86,87] have reported differently routed tropical-Arctic links. The discrepancy appears to stem from the spatial pattern of imposed SST anomalies (particularly in the western Pacific), the season in which the forcing is applied, and climate model biases in simulating subtropical overturning and extratropical wave propagation.

The Arctic-Antarctic link operates through a set of distinct pathways, each most effective on a particular time scale rather than functioning as a continuous pathway at all times. On millennial to centennial horizons, the dominant mechanism is oceanic, as large changes in the AMOC redistribute heat between hemispheres and create the classic bipolar seesaw seen in paleoclimate archives. As the focus shifts to multidecadal and decadal variability, ocean memory becomes less influential, and a tropospheric bridge assumes greater importance. Persistent phases of the AMO or the PDO, along with sustained shifts in the ITCZ, generate cross-equatorial Rossby waves that impose pressure and temperature anomalies of opposite signs at the two poles. At the interannual scale, bursts of planetary wave activity or sudden stratospheric warming can synchronize the Arctic and Antarctic annular modes and cause the poles to respond almost simultaneously. Each bridge therefore requires a specific set of conditions, including substantial freshwater or buoyancy forcing for the overturning circulation, basin-wide sea-surface-temperature anomalies and a pre-existing hemispheric energy imbalance for the tropospheric route, vigorous wave activity and a receptive polar vortex for the stratospheric connection, and well-aligned subtropical jets for the brief atmospheric ducts. When these conditions overlap, for example, during a warm AMO phase combined with a positive AO, the two poles can behave like communicating vessels, but in their absence, the Arctic and Antarctic often evolve independently even under strong external forcing.

4. Cross-equatorial connection of the TP-Antarctica

Research on teleconnections between the TP and Antarctica is more limited than it is for TP-Arctic and Arctic-Antarctic links, yet recent work has confirmed a dynamic bridge. Observations and model simulations suggest that a teleconnection linkage does exist between the TP and Antarctic in which the AAO or the Southern Annular Mode (SAM), which is the most prominent atmospheric variability in the Southern Hemisphere [88,89], has been regarded as the key moderator of the climate of the TP [32,52,61,90–93].

The Antarctic-TP teleconnection comprises two distinct pathways (Fig. 5). The first interannual pathway involves combined atmospheric and oceanic bridge processes. During a positive AAO, a cyclonic anomaly spans the southern Indian Ocean, inducing SST anomalies through the wind-evaporation mechanism in boreal spring [32,91,94–96]. The resulting SST anomalies further induce an anticyclone over the northern Indian Ocean that transports water vapor to the TP [32]. Statistically, May AAO variability explains approximately 20 % of the June sensible-heat flux variance over the TP [32]. Additionally, diabatic heating related to tropical Indian Ocean precipitation anomalies stimulates a northeastward-propagating wave train and a resultant cyclonic circulation anomaly over the TP [91,97]. A recent study of Antarctic ozone variability revealed a second, longer-lag route that also relies on the southern Indian Ocean but is triggered months earlier. [98]. Positive stratospheric ozone anomalies over Antarctica in September-October favor a negative SAM in the following boreal winter. Changes in the SAM-related wind and clouds warm the southwestern Indian Ocean near Madagascar. Owing to the ocean's thermal inertia, this warm pool survives into boreal spring. Meridional overturning then exports heat toward 15°N, increases land-surface temperature over Indochina and, through land-atmosphere feedback, builds a persistent heat source that intensifies the southwesterly monsoon in early summer. The strengthened monsoon moisture flow and its associated Rossby response increase rainfall from the eastern Tibetan Plateau to East Asia and account for approximately 20 % of the interannual precipitation variability on the eastern Tibetan Plateau.

The second interdecadal pathway is a purely atmospheric bridge. The AAO-related northward wave train travels to northern Australia, leading to high-pressure anomalies and altering the quasimeridional overturning circulation spanning northern Australia and the TP [57]. Moreover, AAO-induced tropical Atlantic SST anomalies can modulate high-latitudinal Atlantic SST anomalies via the Hadley circulation, and the resulting pattern excites a stationary Rossby-wave train from the Atlantic to the TP on interannual timescales, further impacting the TP via moisture transport [90,94,96].

On the tectonic time scale, the rise in the topography of the TP disturbed both the atmospheric circulation and oceanic circulation in the Antarctic [66,93]. Removing the TP in the model experiments generates anomalous cross-equatorial flow during the austral winter and triggers an SST dipole pattern in the Indian Ocean. Stationary waves then channel energy southeastward from the tropical Indian Ocean toward Antarctica, promoting a Rossby-wave train that encircles the continent. Moreover, the absence of the TP could substantially increase Antarctic bottom water formation by initiating Rossby-wave trains that extend from the tropical Indo-Pacific to the Amundsen-Bellingshausen Seas. These experiments highlight the significant role of the TP in far-field climate regulation.

Research on the Antarctic-TP link remains limited because there are no atmospheric wave guides across the equator, and more attention has been given to the Arctic-TP link. Any disturbance that begins over Antarctica must first survive the equatorial belt, where

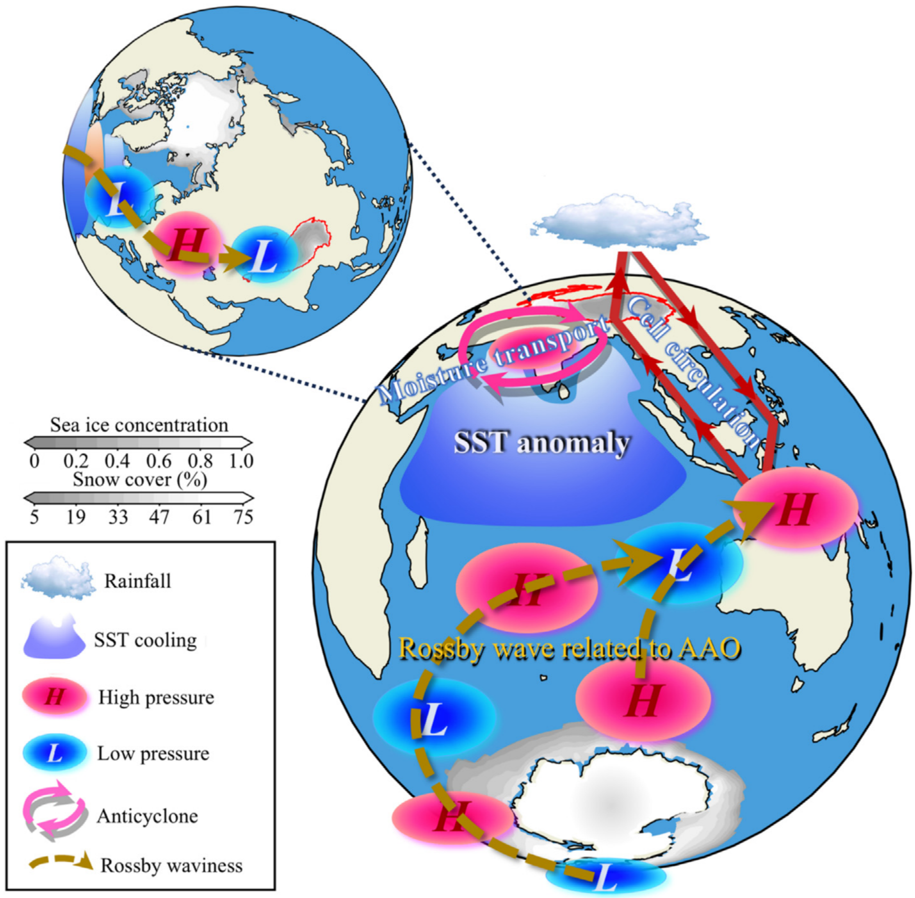

Fig. 5. Teleconnection linkage between Antarctica and the TP. Two pathway impacts of the Antarctic Oscillation (AAO) on the TP. The first pathway is through the circumpolar wave train and the tropical Indian Ocean. The second is from a northward-traveling wave train across Australia. The upper left panel shows the influence of AAO-induced tropical Atlantic SST anomalies on the Tibetan Plateau through high-latitudinal Atlantic SSTs and Rossby-wave trains. The color shading over the TP and Antarctica represents climatological snow cover (1979–2023, units: %) and the color shaded in the Arctic sea and around Antarctica represents sea-ice concentration (1979–2023, units: 1), and their data sources are the same as those in Fig. 1.

the mean meridional temperature gradient is weak and the subtropical jets are discontinuous in longitude. Only rare combinations of seasonal jet alignment and wave phase speed allow Rossby energy to cross from one hemisphere to the other without destructive interference. Even when a pathway is open, the transmitted anomaly is typically an order of magnitude weaker than the original perturbation; thus, it can be masked by monsoon variability, ENSO events or mid-latitude eddy noise around the TP. Finally, climate studies targeting the TP have often focused on its influence within the Northern Hemisphere, whereas Antarctic studies traditionally emphasize Southern Ocean feedbacks; hence, few studies have been designed specifically to trace a pole-to-plateau link. These physical hurdles explain why the literature on the Antarctic-TP teleconnection is much less common than it is for Arctic-related links, even though recent work indicates that the pathway is physically plausible.

5. Summary and future perspective

5.1. Summary

The three poles form an integrated, globe-spanning network, but the signals that bind them together travel mainly along three pairwise corridors, each with a distinctive physical fingerprint.

Among the linkages, the Arctic-TP corridor is the most dynamically active. Sea–ice and SST anomalies in the Barents-Kara Seas, Labrador Sea, or northern Greenland excite planetary waves that arc across Eurasia; alter the subtropical jet; and modulate TP surface winds, precipitation, and snow cover on subseasonal-to-decadal scales. Land-surface memory via Eurasian snow and TP soil-moisture anomalies extends the Arctic imprint well beyond the life-span of the initial forcing. The coupling is bidirectional, where enhanced TP snow or sensible–heat release can, in turn, trigger AO-like circulation and even accelerate regional Arctic sea–ice melt through wave-train-induced wind stress. Stratospheric processes add a further tier of interaction, as TP-forced planetary waves weaken the Arctic polar vortex, increase Brewer-Dobson upwelling, and feed back onto tropospheric flow that deepens snow over the plateau.

The Arctic-Antarctic bipolar seesaw operates through both oceanic and atmospheric conduits from millennial to interannual time scales. Variations in the AMOC redistribute heat between hemispheres, producing out-of-phase SST and sea–ice anomalies that can persist for centuries. In the atmosphere, shifts in the ITCZ and Hadley circulation alter the strength and latitude of polar jet streams, whereas Pacific and Atlantic decadal oscillations spawn Rossby–wave pairs that induce opposing pressure and temperature signatures at the two poles on decadal time scales. Stratospheric links in the synchronicity of the AO and AAO phases and in planetary-wave coupling during sudden–stratospheric–warming events provide a rapid, vertically coherent bridge that complements the slower AMOC signal.

The TP-Antarctic teleconnection has two main routes: a combined ocean-atmosphere bridge in the Indian Ocean and a purely tropospheric wave train that arcs across northern Australia into Asia. In the former, AAO-induced wind stress drives Indian Ocean SST dipoles, which trigger Rossby waves and moisture transport onto the plateau. In the latter, a poleward-propagating wave train alters the meridional overturning circulation between Australia and the TP. Topographic experiments emphasize reciprocity, showing that removing the TP generates cross-equatorial flow, an Indian Ocean SST dipole, and Rossby waves that encircle Antarctica, underscoring the plateau's far-reaching influence on Southern Ocean dynamics.

5.2. Challenges

Despite the advances in the intricate interactions among the three poles, several compelling challenges continue to stimulate scientific inquiry.

(1) The mechanisms governing heat exchange among the three poles remain uncertain, with the Southern Ocean highlighted as a key area of interest. It is often considered a heat capacitor that plays a remarkable role in Southern Hemisphere warming, especially during periods of AMOC weakening or collapse. Nonetheless, recent studies have challenged this view by questioning the precise locations of heat storage, potentially extending beyond the Southern Ocean to include the South Atlantic and other oceans [29].

(2) The role of tropical oceans in three-pole teleconnections needs further investigation. Although the Indian Ocean has been identified as a mediator connecting the climate in the Antarctic and the TP, the contributions of the tropical Pacific and Atlantic to Arctic-Antarctic or TP-Antarctic interactions remain largely unexplored. Insights from recent advances in tropical-polar teleconnections can provide insights into how tropical oceans influence three-pole teleconnections [99].

(3) The uncertainty surrounding whether the tipping elements in the three poles have surpassed their thresholds requires further investigations into the cascading effects these changes may have on the global climate. Recent studies [25,100] have indicated that critical tipping points for Arctic sea ice, the Antarctic ice sheet, and the Atlantic gyre may have been reached, suggesting a departure from previous climatic stability and the onset of a new climatic era. This shift raises crucial questions about the extent to which abrupt changes in one pole can trigger similar abrupt transitions in another, thereby influencing the global climate.

5.3. Future perspective

The future of research into three-pole interactions holds great promise. The construction of a 3-D observational system based on in situ stations, satellite retrievals, digital twins, and novel data assimilation products across the TP and polar oceans opens exciting avenues for investigation. For instance, a recent study leveraged continuous oceanographic records from beneath the East Antarctic ice shelf to elucidate critical insights into ice-shelf warming and the effects of subpolar westerlies and sea-ice changes [101].

Moreover, promoting interdisciplinary collaboration between the paleoclimate and modern climate research communities is crucial. While instrument data span only approximately a century, the rich paleoclimate archives at the three poles (including ice cores and marine and lake sediments) offer an extended timeline that can illuminate climate teleconnections over decadal to millennial scales. These extensive records provide a unique opportunity for modern climate scientists, who possess a deep understanding of climate dynamics, to assist in the interpretation of paleoclimate data. Such collaborations can ensure that hypotheses based on paleoclimate records are rigorously examined for physical validity.

Expanding research tools, including causal inference and machine learning, combined with state-of-the-art numerical models are gaining prominence [102,103]. These approaches help identify potential causal links among the three poles, accelerating progress in unraveling their interconnected mechanisms. High-resolution climate models, particularly those equipped with advanced interacting ice-sheet modules, hold promise for more accurately simulating ice-sheet mass variability across the three poles, thereby enhancing our ability to investigate three-pole teleconnections.

Collaboration across diverse disciplines, including climatology, oceanography, biogeochemistry, and remote sensing, is essential for advancing three-pole interaction research. This interdisciplinary approach promises a holistic understanding of the intricate connections among these geographically distant regions, especially for comprehending the tipping elements in the three poles. These synergistic elements offer a compelling trajectory for unraveling the complexities of Arctic, Antarctic, and TP interactions, with profound implications for our understanding of Earth's climate system and our ability to address the challenges posed by a changing climate.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Anmin Duan conceptualized the review and identified the themes to be covered. Anmin Duan, Xin Li, Tao Che, and Guoxiong Wu led the discussions and coordinated inputs. Anmin Duan, Wenting Hu, Jun Hu, Yuzhuo Peng, Chao Zhang, Die Hu, Yuheng Tang, Zhulei Pan, and Qilu Wang wrote the first draft. All the authors reviewed and edited the manuscript before submission.

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