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• Perspectives •

Polar Winter Processes: An Under-Represented Research Focus within the Coupled Earth System※

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ABSTRACT

Observing winter processes during the extended cold season is crucial not only for understanding polar and global coupled Earth system but also for enhancing capability of year-round prediction, especially in the context of Arctic amplification and the drastic decrease in sea ice extent and thickness at both poles. However, harsh environmental conditions and logistical challenges have left polar winter Earth system processes substantially under-observed compared with those during summer. This disparity creates major obstacles for studying these processes and their roles in shaping the state and variability of the Earth systems, as well as for accurately simulating them in Earth System Models (ESMs). Consequently, these limitations introduce considerable uncertainties in ESMs regarding the understanding, prediction, and projection of Earth system variability and changes. This study discusses key polar winter processes and evaluates critical

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knowledge gaps. It identifies three urgent research priorities for the near future: (i) sources, properties, and transport of polar winter aerosols and their interactions with clouds; (ii) polar storms and their interactions with the underlying sea ice and ocean; and (iii) persistent discrepancies in understanding and predicting large-scale teleconnections between polar regions and lower latitudes. To address these priorities, this perspective recommends strengthening coordinated, winter-focused, international and multidisciplinary observational efforts, for example, through initiatives such as the Fifth International Polar Year and the ongoing international Antarctica InSync programme. These initiatives would lay groundwork for designing future sustainable winter process observations.

Key words: polar winter processes, Earth system, aerosols and cloud processes, storms–sea ice–ocean interactions, polar-global teleconnections, climate model predictions and projections

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Article Highlights:

- Significant observational gaps exist during polar winters due to limited geographic accessibility and inaccurate remote sensing technology.
- The observational gaps cause an incomplete understanding of the Earth system and model representations for predictions and projections.
- Key research priorities include aerosol and cloud processes, storm–sea ice–ocean interactions, and polar–global teleconnections.
- Enhanced multidisciplinary winter observations should be internationally coordinated and integrated with numerical model improvements.

1. Introduction

Whereas the overall impacts of global warming at the poles are dramatic, the seasonal manifestations of those changes are complex and varied. While the whole Arctic has experienced rapid warming (Arctic Amplification) at an annual mean rate of approximately three to four times the rest of the globe, Antarctic temperature trends over recent decades have been spatially heterogeneous and seasonally dependent. Observational records and reanalyses generally show a warming trend over the Antarctic Peninsula and parts of West Antarctica with different magnitudes across the datasets, whereas much of East Antarctica has exhibited comparatively weak trends or even slight cooling (Ma et al., 2025), particularly during austral autumn and winter. In Antarctica, some of the strongest recent warming trends occur during austral spring (September–November; Wang et al., 2025; Bromwich et al., 2026), whereas in the Arctic, the largest surface warming occurs during boreal winter (December–February; Rantanen et al., 2022; Liu et al., 2025; Zhang et al., 2025). These contrasting seasonal and regional characteristics highlight the complexity of externally forced and internally operating Earth system processes and feedback mechanisms in both polar regions. Despite extensive research efforts, important aspects of these processes and feedback mechanisms remain unclear (Goosse et al., 2018; Rantanen et al., 2022; Bromwich et al., 2025; Zhang et al., 2025; Swain et al., 2026).

In particular, recent observational campaigns have collected new evidence emphasizing the importance of winter processes at the poles. For instance, in the Arctic, the year-round Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC; Shupe et al., 2022) provided valuable insights into the active physical and chemical mechanisms during the polar night. A key discovery was the confirmation of the proposed production of fine-mode (radius <100 nm) sea salt aerosols (SSAs) from blowing snow in the central Arctic and their potentially significant surface warming effect (Gong et al., 2023), rivaling that of Arctic haze in late winter/early spring (Garrett and Zhao, 2006). Dramatic changes in the Arctic and Antarctic environments, including sea-ice extent and type (from multi-year to first-year ice), snow physical and chemical properties, and atmospheric dynamics, may considerably influence aerosol size, number density, and composition (Willis et al., 2018; Schmale et al., 2022; Confer et al., 2023; Ranjithkumar et al., 2025; Dall'Osto et al., 2026). For example, increased first-year sea-ice coverage could notably raise snow salinity, leading to greater SSA production from blowing snow, which in turn may warm the surface through aerosol–cloud interactions. However, this feedback process remains neither fully understood nor rigorously quantified. In Antarctica, the winter-targeted observing periods conducted during the Year of Polar Prediction in the Southern Hemisphere (YOPP-SH; Bromwich et al., 2024) have provided insights into how enhanced radiosonde balloon observations help refine mixed-phase cloud microphysical parameterizations and improve model forecast accuracy in the less-observed polar regions. Such findings further highlight the need for a deeper understanding of polar winter processes.

Earth System Models have advanced considerably in recent decades. However, substantial uncertainties and biases still exist at high latitudes, particularly during polar winter. These shortcomings arise from the limited understanding of processes, especially in representing air–sea ice interactions, atmospheric boundary layer dynamics, and cloud–radiation coupling. Recent research shows that the Coupled Model Intercomparison Project (CMIP) phase 6 models systematically overestimate sea-ice melt and growth compared to ice mass balance buoy observations (West and Blockley, 2025) and inaccurately depict Arctic sea-ice variability and the marginal ice zone (Cocetta et al., 2024; Selivanova et al., 2024). Simultaneously, models continue to struggle with boundary layer structure during polar winter, resulting in errors in surface energy fluxes and near-surface temperature evolution, especially over sea-ice-covered surfaces (Duffey et al., 2025). CMIP6 models also do not match observed seasonal cycles of sea-salt aerosols in the polar regions, likely due to the lack of wintertime sources such as blowing snow (Lapere et al., 2023). Cloud microphysics remain a major source of bias, with studies indicating persistent misrepresentation of mixed-phase clouds, their sensitivity to aerosols, and their radiative effects (Hofer et al., 2024; Herbert et al., 2025; Stauffer et al., 2025). Reanalyses and satellite data further reveal systematic errors in the occurrence of supercooled liquid clouds and snowfall (Hellmuth et al., 2025). Collectively, these findings highlight that winter polar processes are still inadequately captured in current models, limiting confidence in predictions of regional climate changes and global climate feedbacks.

These seasonal variations interact with longer-term changes caused by anthropogenic warming, making it difficult to distinguish between natural and anthropogenic influences. Furthermore, severe weather worsens the challenges of conducting winter field campaigns and performing retrievals in both visible and microwave bands. Notably, using reanalyses to fill data gaps is problematic, especially at high latitudes, as evidenced by the ERA5 warm bias in surface temperatures over the Southern Ocean (King et al., 2022). This substantial lack of observations results in a reliance on summer data for analysis and model improvement, highlighting the need to deepen our understanding of winter processes.

While Arctic and Antarctic winters share common physical processes, they differ fundamentally in geography, circulation patterns, and responses to anthropogenic forcing (Swain et al., 2026). Here, we do not focus on their differences; instead, we address both common and specific scientific questions to identify important knowledge gaps in our understanding of the polar winter system, where key physical, chemical, and biological processes are poorly observed in field campaigns and inadequately represented by ESMs across the interconnected atmosphere, cryosphere, ocean, and terrestrial systems. In this study, we define “polar winter” as an extended cold season spanning November–April in the Arctic and April–November in Antarctica, including the shorter traditionally defined transition seasons (spring and autumn) in the polar regions. This definition encompasses the broader period characterized by reduced solar radiation, extensive sea-ice coverage, enhanced atmosphere–ice–ocean interactions, and persistent cold-season processes that remain substantially less studied than their summer counterparts.

The remainder of this paper is organized as follows. Section 2 outlines the scientific challenges and research opportunities we face in current polar studies. Section 3 identifies three research priorities we recommend focus on. Section 4 sets out recommendations for action in the coming years. Finally, Section 5 summarizes the study.

2. Scientific challenges and opportunities

2.1. *Observational gaps in polar winter conditions*

A major challenge in both Arctic and Antarctic research is the limited availability of observational data over time and space, particularly from in-situ and remote sensing observations, for key atmospheric, oceanic, and land surface variables, such as aerosol abundance and composition, cloud properties, sea-ice evolution, turbulent fluxes, hydrographic properties, and many other factors, including bioactivity. The fundamental lack of winter season measurements, therefore, hampers understanding of atmosphere-ice–ocean-land interactions in the polar regions during a significant part of the year.

Severe winter weather in polar regions significantly complicates the measurement of atmospheric trace gases and aerosols, making estimates of CO_2 air–sea exchange (Watts et al., 2022), surface fluxes of reactive halogens (Custard et al., 2017), and sea salt aerosols (Frey et al., 2020) challenging. Consequently, most air-sea flux estimates depend on measurements taken during calm conditions or on indirect calculations and model simulations (e.g., Else et al., 2012; Ruiz-Halpern et al., 2014). Other observations, such as direct profile measurements from airborne platforms (tethered balloons, drones, aircraft), become hazardous and often impossible during blizzard or icing conditions. These issues highlight a significant gap in our capacity to characterize and quantify both the direction and magnitude of fluxes of climate-relevant species across the air-surface interface during polar winter (Watts et al., 2022; Yang et al., 2024).

Additionally, ship- or mooring-based measurements of hydrographic and dynamic properties beneath sea ice during the polar winter are far from comprehensive (Nielsen-Englyst et al., 2023; Toppaladoddi and Wells, 2025). For example, when studying the impacts of cyclones on sea ice, most research concentrates on atmospheric dynamics and thermodynamic processes (Clancy et al., 2022; Aue and Rinke, 2023). There is a notable lack of measurements to fully assess the ocean’s contributions to the total sea-ice energy budgets during cyclone development and movement. Currently, available observations rely mainly on a limited number of opportunistic observations. For example, a recent Arctic study demonstrated that cyclone-enhanced Ekman upwelling of Pacific-origin warm water can drive rapid sea-ice melt by increasing ocean mixing and ocean-to-ice heat flux (Peng et al., 2021). This finding was based on atmosphere and ocean profile observations gathered aboard the icebreaking research vessel *Araon*, which encountered an intense Arctic cyclone in August 2016. Quantifying such ocean hydrographic and dynamic processes requires direct winter observations.

In polar terrestrial biology, microclimates, such as those in vegetation and surface soil layers, are often isolated from the macroclimate (a probable driver) by snow cover (Convey et al., 2018; Beltrán-Sanz et al., 2022; Coulson et al., 2023). These microclimates differ significantly from the sub-surface temperature profiles usually recorded at larger scales in permafrost monitoring studies (Convey et al., 2018). Very few cases worldwide establish a clear link between well-documented global or regional climate trends and changes in biologically relevant microclimates.

Despite advances in monitoring and modeling, large uncertainties persist in quantifying polar water cycling, particularly during winter. Polar darkness, harsh conditions (high winds, low temperatures), and sensor limitations restrict direct measurements of factors contributing to the surface mass balance (e.g., precipitation, sublimation, snow drift), resulting in large uncertainties in winter accumulation estimates at a sub-annual resolution (Souverijns et al., 2018; Pritchard et al., 2021). Satellite radars struggle to detect light or shallow precipitation, while ground-based observations remain sparse and intermittent (e.g., Radenz et al., 2024). A recent satellite-based study (from ICESat-2) revealed that blowing snow events are not only a snow-transport process, but also represent an important source of atmospheric moisture via sublimation (Robinson et al., 2025). The sources and pathways of moisture that supply inland snowfall, particularly in Antarctica, remain uncertain, with limited isotopic and reanalysis constraints (Sodemann and Stohl, 2009; Gao et al., 2025). These gaps hinder efforts to close the polar water budget and to project freshwater and sea-level changes.

2.2. *Complexities and model representations*

Although a solid understanding of the coupled climate system exists, and Earth System Models have achieved notable success in reproducing many features of essential climate variables and the evolution of the Earth system, substantial uncertainties and biases remain. Polar winter biases are evident in models across spatial scales, from microscale aerosols and cloud droplets to mesoscale clouds, storms, ice dynamics, and boundary layer processes, extending to macroscale atmospheric circulations (Hyder et al., 2018; Notz et al., 2020; Fiddes et al., 2022; Smith et al., 2022; Lapere et al., 2023; Ye et al., 2024; Valkonen et al., 2025). The inability of most current climate models to accurately represent these cross-scale interactions leads to persistent discrepancies in simulated weather and climate variability, particularly in polar regions where such coupled processes are especially sensitive (Nordling et al., 2019; Day et al., 2022; Yang et al., 2022; Vignon et al., 2026). Untangling these deeply interconnected processes, such as how microphysical-scale processes and mesoscale cloud biases feed back onto large-scale circulation errors, remains a major scientific challenge, especially in high latitudes (Bodas-Salcedo et al., 2012; Hyder et al., 2018).

Well-designed model experiments are crucial, along with field observations, for investigating fundamental processes, but such experiments can also be challenging. For instance, fully coupled sea-ice-atmosphere models, in addition to forced atmosphere-only models, should be encouraged to better identify and understand teleconnections (Zhang et al., 2008; Screen et al., 2018). Besides targeted process studies using well-constrained model experiments, model intercomparisons are vital for recognizing model uncertainties, with CMIP6 (Eyring et al., 2016) serving as a notable example. As discussed below, many model uncertainties in polar winter simulations were highlighted in the CMIP6 results.

3. Research priorities in polar winter studies

3.1. *Aerosol, cloud, and chemistry processes*

State-of-the-art climate models struggle to accurately simulate polar weather and climate, with the largest biases between the CMIP6 simulations and satellite observations of cloud fractions (CF) occurring at high latitudes in both hemispheres (Vignesh et al., 2020; Sardana et al., 2025), and the greatest model spread of CF during winter (Wei et al., 2021). These substantial discrepancies between model simulations and observations introduce large uncertainties into model projections of future Arctic and Antarctic climate (Bock and Lauer, 2024). Several key factors contribute to these uncertainties, including limited understanding of the sources, properties, and transport of cloud condensation nuclei and ice-nucleating particles (Raif et al., 2024; Li et al., 2025; Mallet et al., 2025; Dall'Osto et al., 2026; Wex et al.,2025), aerosol-cloud interactions (Kremser et al., 2021), and the mixed-phase clouds associated with supercooled liquid water (Bodas-Salcedo et al., 2019; Tan and Storelvmo, 2019; Sauerland et al., 2024).

For instance, current CMIP6 models fail to reproduce the winter peaks of primary sea salt aerosol observed at high latitudes (Lapere et al., 2023), likely due to the absence of blowing-snow-sourced SSA over sea ice, as proposed by Yang et al. (2008, 2019) and confirmed by in situ observations from the Arctic (Gong et al., 2023; Ranjithkumar et al., 2025) and Antarctica (Frey et al., 2020). These newly identified blowing-snow-sourced aerosols account for one-third of Arctic winter aerosols and have the potential to significantly warm the Arctic surface by influencing cloud properties (Fig. 1 in Gong et al., 2023). In addition to aerosol effects, increased atmospheric moisture from blowing-snow sublimation, as indicated by remote sensing data (Robinson et al., 2025) and high-resolution Arctic modeling studies (Luo et al., 2021; Luo and Zhang, 2022; Zhang et al., 2023a), may enhance local cloud formation by supplying water vapor to the air, which can then alter surface mass balance and radiative fluxes. These blowing-snow-sourced aerosols and relevant sublimation processes are not represented in most current climate models. Furthermore, our understanding of blowing snow is mainly based on observations from inland locations (Budd, 1966; Schmidt, 1982) rather than from sea ice covered regions (Frey et al., 2020; Ranjithkumar et al., 2025). The parameterizations implemented in some modeling experiments to describe blowing snow events, such as threshold wind speed (Li and Pomeroy, 1997), sublimation flux (Rogers and Yau, 1989; Luo et al., 2021; Luo and Zhang, 2022; Gerber et al., 2023; Zhang et al., 2023a), and the fragmentation process (Comola et al., 2017; Huang et al., 2025), are largely semi-empirical or theoretical, lacking validation under a wide range of polar environmental conditions, and therefore remain incomplete. Some new findings, like bulk parameterization underestimation of blowing snow fluxes (Sigmund et al., 2022) or blowing snow metamorphism (Wahl et al., 2024), are not yet well quantified in the field nor even represented in models. Hence, comprehensive, high-resolution field observations of blowing snow, sublimation fluxes and resulting aerosol production rates are needed to improve and validate model representations of these processes. Additionally, well-designed laboratory investigations, for example, using wind tunnels, could provide vital data to constrain the parameterizations.

In the Arctic, winter atmospheric chemistry is primarily influenced by anthropogenic pollutants, known as Arctic haze (Shaw, 1995), which has a net surface-warming effect (Zhao and Garrett, 2015). In Antarctica, the increased particles observed at coastal sites during the austral winter, also called haze (Hara et al., 2025), are mainly natural in origin. Understanding the main sources and sinks of chemically active substances, such as aerosols, reactive halogens, and nitrogen (Schmale et al., 2022; Yang et al., 2024), as well as factors affecting snow and ice acidity (Veselý et al., 2024), is essential for accurately predicting atmospheric oxidative capacity (Tilgner et al., 2021). Current chemistry transport and climate models struggle to explain and accurately reproduce high-latitude, near-surface ozone and particle levels, especially during the polar winter-spring transition. For instance, surface ozone levels drop to their annual minimum in early spring (Bognar et al., 2020; Huang et al., 2020; Yang et al., 2020), and sodium concentrations reach their annual maximum during polar winter (Huang and Jaeglé, 2017; Yang et al., 2019; Lapere et al., 2023), highlighting the need for more in-situ data and modeling to verify the key mechanisms.

Finally, changes in sea-ice properties associated with the changing climate are leading to a more mobile ice pack with larger areas of open water, thereby promoting the formation of thin sea ice in winter (e.g., Barber et al., 2012; Stroeve and Notz, 2018). Variations in sea-ice extent and thickness, as well as snowpack properties (i.e., snow depth, salinity, and chemical composition), may influence snow-sourced aerosol production and their climate impacts. However, the relative contributions of marine aerosols, including primary organics and sea salts, from different sources (i.e., open ocean, open leads versus sea ice, and newly formed versus consolidated ice) to atmospheric chemistry, clouds, and radiation, remain largely unknown (Marelle et al., 2021; Swanson et al., 2022; Creamean et al., 2026; Ishino et al., 2026). Determining the relative contributions of locally sourced versus long-range transported aerosols to polar climate is challenging due to limited observations. Furthermore, how these aerosol contributions are evolving under ongoing climate change is even less well understood.

3.2. *Polar winter storms and their interactions with the surface*

Polar storms are primarily characterized by synoptic-scale (~1000 to 5000 km) cyclones, that is, low-pressure systems. They play a vital role in the atmospheric energy balance as they transfer heat and moisture towards the poles, especially during the polar winter when they are most intense (Zhang et al., 2004; Wickström et al., 2020). They affect sea-ice behavior through complex thermodynamic and dynamic

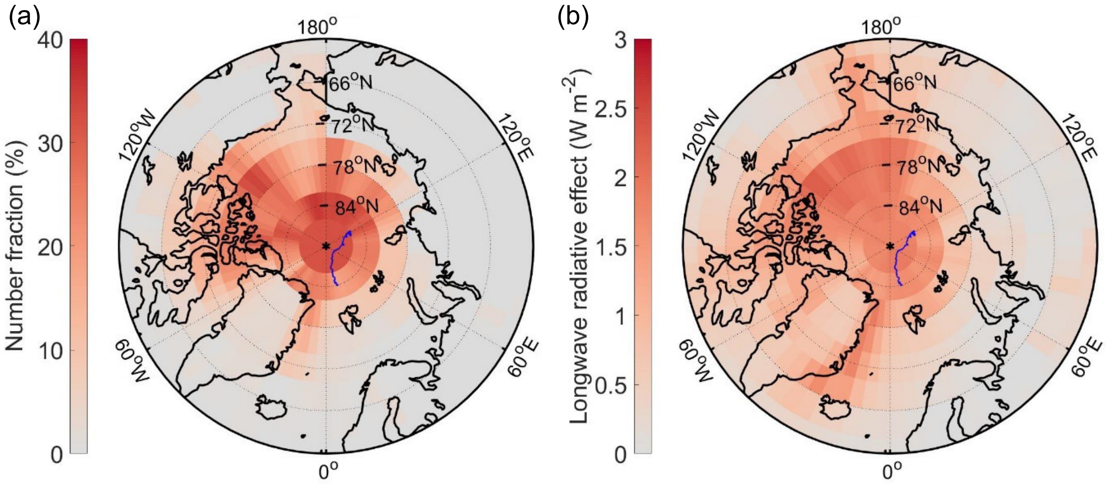

Fig. 1. Atmospheric amplification caused by winter blowing snow: (a) model-simulated percentage contribution of blowing-snow-produced sea salt particles to total particle number concentration in winter (November to April), and (b) simulated cloud downwelling longwave radiative forcing attributed to blowing-snow-produced sea salt particles [Reproduced from Gong et al. (2023)].

interactions within the air-ice-ocean system (Zhang et al., 2004; Aue and Rinke, 2023; Josey et al., 2024; Watkins et al., 2024). In recent decades, there has been an increase in both the intensity and frequency of Arctic cyclones (Parker et al., 2022; Zhang et al., 2023c). This trend is linked to sea-ice retreat, modifications in ocean conditions, and shifts in atmospheric circulation patterns, all of which are intensified by ongoing global warming (Parker et al., 2022; Zhang et al., 2023b; Zhang et al., 2024). In contrast, in Antarctica, the increase in cyclone intensity and frequency appears to be regionally dependent, notably over the Amundsen–Bellingshausen Seas, rather than a universal trend across all Antarctic cyclone zones. Furthermore, winter cyclone frequency in most Antarctic areas decreased from 1948 to 2017, although the number of intense cyclones increased (Zhan and Chen, 2023). The expansion of Antarctic sea ice, predominantly from the late 1970s, may have diminished thermal contrasts and enhanced surface stability, thereby hindering cyclogenesis. However, a significant decline in sea ice since 2016 (Wang et al., 2019; Suryawanshi et al., 2023) may reverse the trend of cyclone frequency. For instance, the record-low sea ice in Antarctica in 2023 caused ocean heat loss, and the primary regions of sea-ice decline closely corresponded with areas of heightened storm activity (Fig. 2; Josey et al., 2024). Nonetheless, the interactions between cyclones and the underlying sea ice and ocean are still not fully understood.

Atmospheric rivers (ARs) are closely linked to polar cyclones and to mid-latitude Rossby wave breaking and blocking events (Wille et al., 2021), enabling poleward warm-air intrusions and extreme precipitation. Recent studies indicate increasing trends in atmospheric river occurrence and intensity in polar regions, particularly in the Arctic and parts of Antarctica, with important implications for sea-ice variability, surface melt, and extreme precipitation and warming events (Wille et al., 2025). The warm-air intrusions and extreme precipitation associated with ARs lead to sea-ice melt and retreat in the polar marginal sea-ice zone. They also transport air pollutants into the Arctic, especially during winter (Dada et al., 2022; Liang et al., 2023; Zhang et al., 2023b). Over the Antarctic Peninsula, these events can cause intense surface warming, often strengthened by warm, downslope winds known as föhn effects (Gorodetskaya et al., 2023; Orr et al., 2023). Such warming has been linked to surface melting and ice shelf destabilization, including the collapses of the Larsen A and B ice shelves (Wille et al., 2021, 2022; Orr et al., 2023).

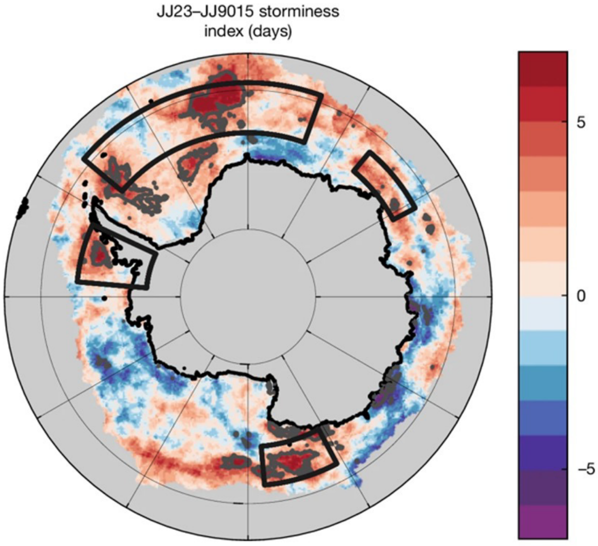

Fig. 2. Record-low winter sea ice in the Antarctic in 2023 increased ocean heat loss and storminess, as illustrated by the difference in storminess index (number of days with wind speed > 10 m s^{-1}) between June-July 2023 and June–July 1990–2015. Heavy grey contours show departures significant at the 95% level. Fields are derived from the ERA5 reanalysis. Boxes show the four main sea-ice-decline regions in the 2023 winter compared to the 1991–2020 climatological June-July mean [Reprinted from Josey et al. (2024)].

Model and reanalysis data indicate that winter ARs can trigger strong rainfall events over the Antarctic Peninsula (González-Herrero et al., 2023; Bozkurt et al., 2024). Recent regional climate models (RCMs) also exhibit high sensitivity in rain versus snow partitioning over Antarctic ice shelves under AR conditions (Gilbert et al., 2025). However, validation remains limited due to the scarcity of available in situ data. This highlights the need for winter precipitation measurements (including rain versus snow) in regions affected by ARs, as such data are essential for validating high-resolution models (Pritchard et al., 2021) and constraining surface mass balance estimates. Vertical profiling observations are also essential for studying atmospheric river activity, and enhanced radiosonde launches, such as those conducted during YOPP-SH (Bromwich et al., 2024), can substantially improve the characterization of AR thermodynamic and dynamical structures (Wille et al., 2025). Additionally, it is still uncertain how supercooled liquid precipitation in winter affects snow and firn, the older, compacted snow that has not yet turned into ice (Silber et al., 2019; Radenz et al., 2024). Winter "rain-on-snow" events in the Arctic (e.g., Svalbard) cause significant negative impacts on underlying terrestrial soil and vegetated ecosystems (Rennert et al., 2009; Pedersen et al., 2022). Changes in the patterns, extent, and timing of winter snow accumulation are similarly consequential (Coulson et al., 2023). The significance of these factors in the Arctic and Antarctica is likely to increase over the coming decades.

3.3. *Large-scale teleconnections in association with storms*

Polar storm systems and related extremes (e.g., atmospheric rivers, warm air intrusions, cold air outbreaks, extreme winds and polynya formation) are not purely local phenomena. Instead, they are driven or modulated by large-scale atmospheric dynamics, including teleconnections that stretch from the tropics across the mid-latitudes to the poles. The pathways of these teleconnections include the polarity of large-scale atmospheric circulation modes, such as the Arctic and Antarctic Oscillations (Li, 2024; Campos and

Castillo, 2025), transformed atmospheric circulation patterns, such as the Arctic Rapid Change Pattern, shifts in jet stream positions, and stratosphere–troposphere coupling (Thompson and Wallace, 1998; Zhang et al., 2008, 2023c, 2025; He et al., 2017; Wille et al., 2021; Turner et al., 2022). In a recent study of the 2024 winter heatwave in Antarctica (Tang et al., 2026), the authors demonstrated that polar vortex weakening contributed to the warming of East Antarctic surface air temperatures in winter. Furthermore, Fig. 3 illustrates teleconnections and a major sudden stratospheric warming (SSW), jointly excited by thermal anomalies in the Arctic, North Pacific, and North Atlantic, which led to three significant and impactful extreme-cold weather events across East Asia and North America during mid-winter 2020/21. The SSW resulted in a weakened stratospheric polar vortex (SPV), with the SPV center substantially shifted to the mid-latitudes, as shown by daily mean geopotential height (GHT; contours) and GHT anomalies (shading) at 50 hPa in the figure.

Furthermore, changes in the polar regions, such as the reduction of sea ice in both hemispheres, may influence or feed back onto the lower-latitude atmospheric circulation, impacting mid-latitude climate and weather (Kim et al., 2014; Screen et al., 2018; Zhang et al., 2018, 2022; Cohen et al., 2020; Overland et al., 2021; Oltmanns et al., 2024; Iles et al., 2025). For example, observations and model simulations have shown that winter Arctic sea-ice anomalies in the Greenland-Barents Seas can, in turn, influence the development and phase transition of the El Niño-Southern Oscillation in the subtropical Pacific (Chen et al., 2020, 2025). This influence can further extend to alter Indian and East Asian monsoon precipitation (He et al., 2017; Kim et al., 2020; Chandra et al., 2022; Azhar et al., 2023; Chandra and Sandeep, 2024; Kulkarni and Agarwal, 2024), and Australian wildfires (Liu et al., 2024). In the Southern Hemisphere, wildfire smoke may additionally impact stratospheric ozone depletion (Ansmann et al., 2022), emphasizing the broader, bidirectional links between polar regions and lower latitudes. Although many studies have demonstrated how polar climate change affects lower latitudes, significant seasonal differences and inconsistencies persist across studies. Notably, climate model responses to Arctic sea-ice changes tend to be considerably weaker than those suggested by observational analyses (Streffing et al., 2021; Screen et al., 2022; Smith et al., 2022).

3.4. *Feedback among the three research priorities*

As illustrated in Fig. 4, the three identified major research priorities not only address key knowledge gaps in the coupled polar Earth system but also are strongly interconnected through coupled processes and feedback loops. For example, intense winter storms (Priority 2) can bring strong winds to generate blowing snow, break up sea ice, and enhance heat exchange, thereby leading to the formation of primary sea-salt aerosol and ultimately influencing aerosol-cloud interactions and atmospheric chemistry (Priority 1). At the same time, aerosol and cloud processes can modify radiative fluxes and boundary-layer stability, thereby influencing precipitation and storms. In addition, the tracks, intensity, and persistence of storms are steered by large-scale atmospheric circulation patterns and teleconnections (Priority 3), while the storms themselves act as major agents of transient heat, moisture, and momentum transport that can feed back onto these large-scale circulation systems. Together, these interactions associated with the three priorities highlight the need for integrated, multi-platform observational and modeling strategies capable of simultaneously resolving processes across scales.

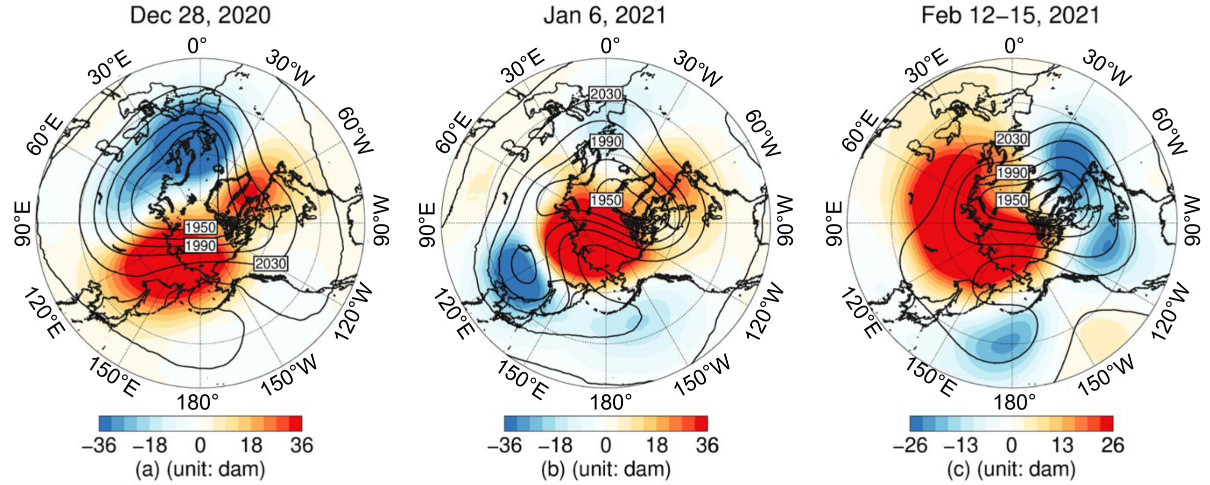

Fig. 3. Disturbance of the Arctic stratospheric polar vortex due to sudden stratospheric warming (SSW) driving three extreme cold events from East Asia to North America in Winter 2020/21. Daily mean geopotential height (GHT; contours) and GHT anomalies (shading) at 50 hPa on (a) 28 December 2020 and (b) 6 January 2021. (c) Average of daily mean GHT and daily mean GHT anomalies during 12–15 February 2021. The daily GHT anomalies were calculated relative to the daily GHT climatology constructed from 1979/80–2008/09 with units of 1 dam = 10 gpm. [Reproduced from Zhang et al. (2022) with permission from SNCSC]

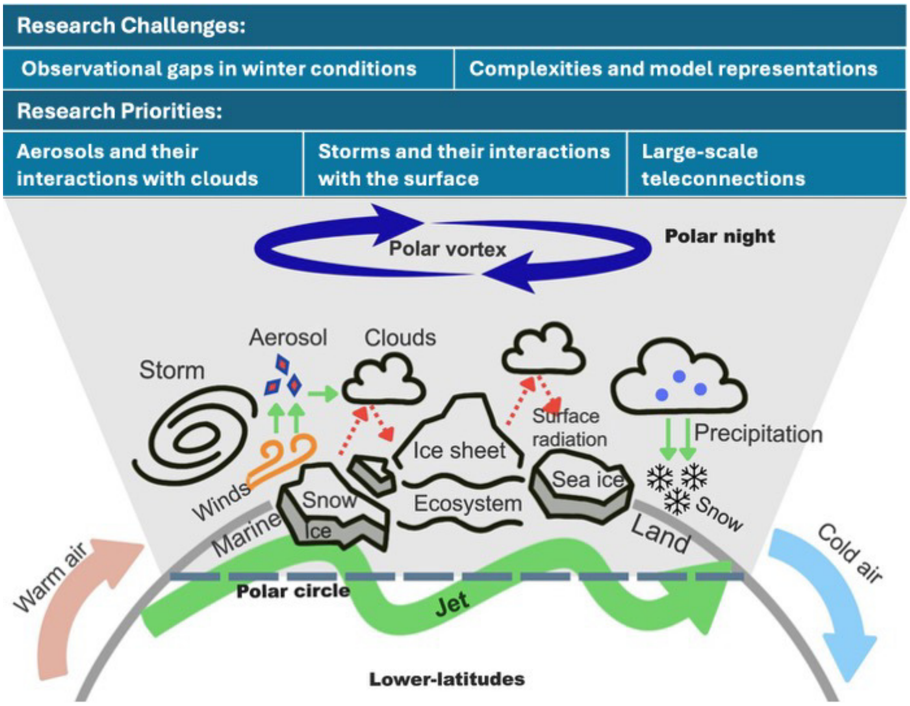

Fig. 4. Schematic of the research challenges and priorities identified in the study of polar winter climate and processes.

4. Action recommendations

Previous successful year-round field campaigns, such as SHEBA (Surface Heat Budget of the Arctic Ocean; Uttal et al., 2002) and MOSAiC (Shupe et al., 2022), provide valuable experience to guide future polar winter studies. In particular, we need advanced detection technologies and innovative methods to overcome the harsh weather, strong winds, and cold temperatures during the dark months. Portable, durable instrumentation with low power requirements is necessary for long-term winter observations. Developing algorithms that utilize multiple satellite sensors to deliver more integrated information on atmosphere–ice–ocean coupled processes is essential to fill data gaps from localized sensors. We recommend year-round monitoring and expanding autonomous observational networks, including radar and lidar remote sensing, as well as measurements from drones and balloons, to improve atmospheric profile coverage in remote and logistically challenging regions, especially during polar winter. For ocean and sea-ice observations, higher-resolution data in both time and space are advised, using buoys, moorings, and autonomous underwater vehicles (AUVs). Meanwhile, coordinated inland measurements from multiple stations are vital to providing a comprehensive understanding of the internally connected polar climate system.

Enhancing numerical representations of polar winter clouds is essential for studies of surface energy, sea-ice evolution, and surface mass budgets. The lack of accurate descriptions of land-, marine-, and sea ice-sourced aerosols, along with the poor representation of mixed-phase and ice clouds, are two significant barriers. To address these issues, we recommend conducting targeted, intensive measurements and multi-model experiments. Additional laboratory work is needed to verify and constrain model parameterizations, as well as to reduce ongoing biases in simulations of polar winter climate.

A thorough understanding of polar winter processes is a prerequisite for accurately predicting and projecting climate in polar regions and for assessing risks to society and the environment. Improved knowledge and refined models of the sources and properties of aerosols, clouds, storms, and their interactions with the surface will enhance the accuracy of models representing critical climate variables. This, in turn, will strengthen the robustness of seasonal and short-term weather forecasts in regions influenced by polar teleconnections. Novel ocean and ice data, such as ice formation, polynya dynamics, and microscale turbulence, will provide insights into the drivers of sea-ice development, ice sheet instability, and sea-level rise, supporting better management of coastal hazards and climate adaptation efforts. Therefore, winter processes have a significant impact beyond the polar regions, influencing the global atmospheric circulation and affecting agriculture, energy needs, and ecosystem management worldwide.

Building on previous discussions, we identified three main research priorities for upcoming polar winter studies (Fig. 4): (1) sources, properties, and transport of winter aerosols and their interactions with clouds, (2) winter storms and their interactions with the underlying sea ice and ocean, and (3) ongoing inconsistencies and discrepancies in the understanding and prediction of large-scale teleconnections between the polar regions and lower latitudes. A practical way to integrate these priorities is through winter-focused campaigns in the Arctic and Antarctica, utilizing continuous observations across the atmosphere, ocean, ice, and land [for example, as planned with Tara Polaris (Ardyna et al., 2026) and Antarctica InSync (https://www.antarctica-insync.org)]. A comprehensive study of polar storms would offer insights into the dominant processes influencing polar winter weather and climate, as polar storms connect key microscale processes, macroscale feedbacks, and large-scale teleconnections. Critical processes affected by winter storms include locally produced and long-distance-transported cloud condensation nuclei and ice-nucleating particles; boundary layer processes; cloud microphysics, including mixed-phase and ice clouds; the underlying sea-ice and ocean, as well as polynya dynamics; coastal ice-sheet stability; and large-scale heat and moisture transport. Such a study would require well-coordinated efforts across latitudinal gradients and various platforms, including in-situ observations, remote sensing, and autonomous instruments. Profile data across the air, ice, and water, particularly during stormy periods, is urgently needed to unravel feedbacks among polar winter processes. Targeted modeling studies using a hierarchy of models, ranging from high-resolution (i.e., cloud- and eddy-resolving) to Earth System Models, alongside innovative laboratory experiments and theoretical advances, are essential to deepen our understanding and facilitate new discoveries. The identified winter research priorities and the proposed implementation complement and augment the recently published ICARP IV report (IASC, 2026), helping shape research themes for the next decade and the Fifth International Polar Year (IPY-5 in 2032–33; https://ipy5.info). Even before the IPY-5, the well-integrated, ongoing, year-round Antarctica InSync programme would serve as an excellent framework for implementing this strategy.

5. Summary

Enhanced, multidisciplinary, year-round research that fills key gaps in winter-process observations is critical to developing an integrated picture of the polar ocean-sea ice-atmosphere environment and its feedbacks with the global Earth system. The resulting improved understanding of polar winter processes would strengthen Earth system models, facilitating more credible climate change projections and assessments, such as those coordinated by the IPCC (Intergovernmental Panel on Climate Change; https://www.ipcc.ch/reports). This expanded knowledge would also improve risk assessments in the Arctic and Antarctic regions and support year-round, evidence-based adaptation strategies for vulnerable polar communities and beyond. International multidisciplinary initiatives, such as ACTRIS (Aerosol, Clouds, and Trace Gases Research Infrastructure; https://www.actris.eu) and ANTOS (Antarctic Near-Shore and Terrestrial Observation System; https://scar.org/science/cross/antos), can serve as crucial platforms for fostering collaboration among the observational, modeling, laboratory, and theoretical research communities. Strengthening such partnerships will improve understanding of these interconnected processes, elucidate their global climatic impacts, and enable robust future projections. Continued investment in research funding, including international cooperation, remains essential to achieve these challenging objectives.

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