BAMS
Meeting Summary

Why Polar Winter Climate and Processes?

Xin Yang,[a] Xiangdong Zhang,[b] Xianda Gong,[c] Markus Frey,[a]
Sergi González-Herrero,[d] Alexandra Weiss,[a] Rainette Engbers,[d] Ola Persson,[e,f]
Martin Radenz,[g] Irina Gorodetskaya,[h] Thomas Bracegirdle,[a] and Romy Hall[a]

KEYWORDS:
Atmosphere;
Ocean;
Antarctica;
Arctic;
Climate;
Winter

Polar Winter Climate and Processes: Towards Filling Knowledge Gaps in the Understanding of the Coupled Climate System Recordings

What: Over 110 participants registered for this hybrid workshop, from 18 countries representing over 40 institutes, with 42 abstract submissions encompassing a wide array of topics. More than 40 participants attended in person, with many online. This workshop provided an interdisciplinary platform for scientists to present recent research, exchange ideas, identify knowledge gaps, and foster new collaborations in the study of polar winter climate.

When: 23–25 April 2025

Where: Cambridge, United Kingdom

DOI: 10.1175/BAMS-D-25-0216.1
Corresponding author: Xin Yang, xinyang55@bas.ac.uk
In final form 15 August 2025

AFFILIATIONS: [a] British Antarctic Survey, Natural Environment Research Council, Cambridge, United Kingdom; [b] North Carolina State University, Asheville, North Carolina; [c] Research Center for Industries of the Future, Westlake University, Hangzhou, Zhejiang, China; [d] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland; [e] Cooperative Institute for Research in the Environmental Sciences, University of Colorado Boulder, Boulder, Colorado; [f] NOAA/Earth System Research Laboratory, Boulder, Colorado; [g] Leibniz Institute for Tropospheric Research, Leipzig, Germany; [h] CIIMAR - Interdisciplinary Centre for Marine and Environmental Research, Porto, Portugal

1. Introduction

Our current understanding of the polar climate and its feedback mechanisms within the coupled global climate system remains incomplete (Goosse et al. 2018). Most polar scientific communities have primarily focused on summer weather processes because observations are easier to obtain. Due to the harsh weather conditions and logistical difficulties associated with conducting winter campaigns, our data coverage at both spatial and temporal scales for the polar winter is limited. This means that key processes vital to the coupled climate system are still not fully understood and investigated. To identify the knowledge gaps in our understanding of the coupled climate system, we organized a workshop centered on polar winter climate and processes. We aimed to bring together diverse research communities to showcase the current state of winter polar weather and climate research and its latest findings, exchange scientific ideas, and foster new collaborations. Our goal was to discuss the key physical and chemical processes often overlooked by models and field measurements across the interconnected atmosphere, cryosphere, marine, and terrestrial systems. Below are three key topics we expected to focus on during the workshop: polar winter aerosols, clouds, and chemistry; winter storms and sea ice; and large-scale teleconnections.

The Arctic is experiencing rapid warming, with surface air temperatures increasing 3–4 times faster than the global average (Rantanen et al. 2022), with the most rapid temperature rise occurring during boreal winter (December–February), not summer (Ma et al. 2024; Liu et al. 2025). This warming process remains not fully understood, and current climate models struggle to accurately represent polar weather and climate, particularly during winter. For instance, the largest biases between the Coupled Model Intercomparison Project phase 6 (CMIP6) simulations and satellite CALCLD cloud fractions (CFs) occur at high latitudes in both hemispheres (Vignesh et al. 2020), and the most significant model spread of CF is in winter (Wei et al. 2021). These significant discrepancies hinder the reliability of these models in predicting and projecting future conditions in the Arctic and Antarctica (Bock and Lauer 2024). One of the key factors contributing to these uncertainties is the limited knowledge and understanding of sources of cloud condensation nuclei (CCN) and ice nuclei particles (INPs), as well as aerosol–cloud interaction processes (Tan and Storelvmo 2019). For instance, current CMIP6 models fail to reproduce the winter peaks of primary sea salt aerosol (SSA) observed at high latitudes (Lapere et al. 2023). This is likely due to the absence of blowing-snow-sourced SSA generated through blowing snow events over sea ice, as proposed (Yang et al. 2019, 2008) and confirmed by field data from the Arctic (Gong et al. 2023) and Antarctica (Frey et al. 2020). The recently identified sea ice–sourced aerosols account for one-third of Arctic winter aerosols and significantly warm the surface by influencing cloud properties (Gong et al. 2023), a process that most current climate models overlook.

Synoptic-scale low pressure systems, or cyclones, are common polar weather phenomena, especially in winter, playing a vital role in the atmosphere's energy balance by transporting heat and moisture poleward (Wickström et al. 2020). They also influence sea ice dynamics through complex thermodynamic and dynamic interactions within the air–ice–ocean system (Watkins et al. 2024). Recent observational campaigns have begun to reveal winter processes in the poles. In the Arctic, the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) (Shupe et al. 2022) has provided valuable insights into the physical and chemical mechanisms occurring during the polar night. In Antarctica instead, the winter targeted observing periods (TOPs) performed during the Year of Polar Prediction in the Southern Hemisphere (YOPP-SH) (Bromwich et al. 2024) have provided information on how observations influence forecast accuracy in the less-observed polar regions. These campaigns enhance our understanding of winter processes. For instance, during midwinter cyclone events, enhanced longwave radiation associated with cyclonic activity warms the sea ice surface, reducing ice growth rates and destabilizing the atmospheric boundary layer (Watkins et al. 2024). This destabilization, particularly behind the cyclone's cold front, leads to intensified air–ice stress, resulting in significant ice motion and deformation, as well as upper-ocean mixing through frictional coupling. An increasing trend in the intensity and frequency of Arctic cyclones has been observed over the past decades (Zhang et al. 2023; Parker et al. 2022), likely associated with global warming. Atmospheric rivers (ARs) are closely linked to midlatitude Rossby wave breaking and blocking events (Wille et al. 2021), serving as a direct manifestation of teleconnection-driven energy and moisture transfer poleward, particularly into Antarctica (Maclennan and Lenaerts 2021; Turner et al. 2022). Atmospheric rivers also contribute to polar warm-air intrusions and extreme precipitation episodes, which exacerbate surface melt and destabilize regional ice cover.

There is a growing consensus that polar storm systems and related extremes (e.g., atmospheric rivers, warm intrusions, extreme winds, and polynya formation) are no longer purely local phenomena. Instead, they are increasingly influenced by a hierarchy of atmospheric teleconnections stretching from the tropics, across the midlatitudes, to the poles. The dynamical pathways involve shifts in jet stream positions and stratosphere–troposphere coupling (Wille et al. 2021; Turner et al. 2022; He et al. 2017). Conversely, high-latitude variability, especially sea ice changes, in both hemispheres may impact lower-latitude atmospheric systems, such as the Indian and East Asian monsoon precipitation (Azhar et al. 2023; Kim et al. 2020; He et al. 2017; Kulkarni and Agarwal 2024), European extreme weather events (Oltmanns et al. 2024), or Australian wildfires (Liu et al. 2024)—highlighting the bidirectional link between polar regions and lower latitudes.

2. Key themes and session summaries

The program was structured around four core themes identified as shown below. Each theme's session included a keynote lecture, several oral presentations, and breakout group discussions that involved both in-person and online participants. Additionally, there was a poster session featuring a 2-min lightning presentation for each poster presenter. Figure 1 shows participants on day 2.

a. Polar winter storms, sea ice, and climate impacts. A series of presentations addressed the complex interactions between polar storms, sea ice, and the broader climate system. The keynote speaker, Ola Person, reviewed air–ice–ocean coupling during Arctic cyclone events, emphasizing their role in modifying surface fluxes and ice dynamics. This was further explored through a climatological analysis of Arctic cyclones, outlining recent trends in their frequency and intensity and their influence on sea ice and upper-ocean structure. The subsequent two presentations discussed Arctic sea ice, including its internal variability and

Fig. 1. Participants of the workshop on day 2.

external forcing, as well as projections of ice-free conditions in a warmer climate. The Antarctic perspective was provided by two presentations focused on heat waves, analyzing their frequency, intensification, and duration through data and modeling. The session concluded with an introduction to the Churchill Marine Observatory.

b. Aerosols, clouds, and chemistry in the polar winter. This session focused on recent advances in understanding the sources of aerosols, aerosol–cloud interactions, and chemical processes in the polar winter atmosphere and snowpacks. Martin Radenz's keynote highlighted the importance of remote sensing in improving wintertime observations of aerosol–cloud interactions under low-light conditions. Several presentations examined potential sources of INPs in the Arctic, the Southern Ocean, and Antarctica, using data collected from recent field campaigns including MOSAiC (Shupe et al. 2022) and The Southern Ocean Clouds (SOC) project (https://www.bas.ac.uk/project/southern-ocean-clouds/). The representation of clouds in U.K. Earth System models for polar regions, including during cold-air intrusions in the Arctic, was discussed. The roles of blowing snow on Arctic INPs, sublimation, and air pollution production were reported in three presentations from observational, modeling, and data analysis perspectives. Additionally, three presentations detailed laboratory work on salt formation through sublimation and the increase in brine acidification caused by freezing. One presentation provided field evidence of the importance of nocturnal snow chemistry in regulating reactive nitrogen.

c. Teleconnections between polar, midlatitude, and lower-latitude regions. This session emphasized atmospheric teleconnections and their role in driving extreme weather patterns and climate variability. Keynote speaker Irina Gorodetskaya delivered a review on the role of atmospheric rivers in Antarctica and their teleconnections to lower-latitude weather systems. The subsequent presentations covered AR activity across the Arctic and western North America, the dynamics of high-latitude atmospheric blocking, and the seasonal behavior of the Amundsen Sea low. It also included two presentations on the impact of polar sea ice variability on subtropical precipitation in the Indian summer monsoon and spring rainfall over South China. The sensitivity of Antarctic coastal fast ice to large-scale processes was also reported.

d. Knowledge gaps. This session addressed significant scientific uncertainties in polar climate research, highlighting emerging areas that demand targeted investigation and improved observational efforts. The keynote speech by Thomas Bracegirdle synthesized recent advances in understanding Antarctic weather and climate extremes, including the representation of synoptic processes and extreme events in climate models. The subsequent presentation reported findings on how complex terrain and synoptic forcing jointly influence near-surface wind variability in East Antarctica. Another presentation introduced the Atmospheric Water Cycle over Antarctica (AWACA) project (https://awaca.ipsl.fr/en/atmospheric-water-cycle-over-antarctica/), detailing radar-based snowfall case studies and instrumentation deployment strategies in challenging polar environments. While most presentations focused on physical processes, one showcased novel observations of microbial biodiversity in Antarctic precipitation, emphasizing the need for interdisciplinary studies and a deeper understanding of biogeochemical cycles and the potential for winter microbial transport. A further talk highlighted the ecological impacts of storm-driven rain-on-snow events during the polar winter, which affect snowpack structure, soil freezing dynamics, and terrestrial biodiversity. Extending the theme to the third pole, one report examined the role of dust deposition from South Asian dust storms in speeding up the melting of Himalayan glaciers.

3. Scientific challenges and research priorities

The discussions highlighted various scientific challenges, knowledge gaps, and new research priorities, emphasizing the importance of interdisciplinary collaboration to tackle these issues. The most significant research priorities identified are listed below.

a. Observational gaps in polar winter conditions. A significant obstacle in both Arctic and Antarctic research is the limited availability of observational data for key parameters such as winter sea ice thickness, snow salinity, and turbulent surface fluxes. The lack of wintertime measurements hampers the investigation and understanding of ice dynamics and atmosphere–ice–ocean interactions and feedback mechanisms. The workshop recommends expanding autonomous observational networks—such as drone and buoy deployments—to enhance winter data coverage in remote and logistically challenging regions.

b. Aerosol–cloud interactions and associated uncertainties. Uncertainties in aerosol–cloud coupling, especially during the polar night, represent a significant gap in knowledge. These issues are particularly evident in Antarctica, where data are limited. The workshop emphasized the need for continuous, year-round aerosol monitoring using remote sensing and autonomous platforms to address this. Additionally, improving the parameterizations for sea salt aerosol production over sea ice, cloud condensation nuclei, and ice-nucleating particle activity is essential for enhancing polar climate models and reducing uncertainty in cloud microphysical processes.

c. Complexities in teleconnections and model representation. Understanding the mechanisms behind polar–tropical teleconnections remains a vital challenge. Current climate models frequently fail to accurately represent these cross-scale interactions, leading to discrepancies in simulated climate variability. Workshop participants recommended coordinated multimodel experiments to evaluate teleconnection robustness across different modeling frameworks. They also supported targeted observational campaigns focused on atmospheric rivers and blocking events that influence polar systems.

4. Summaries

Polar winter plays a vital role in the global surface energy balance, atmospheric dynamics, and chemical processes. During winter, the poles undergo numerous changes, including sea ice growth, snow accumulation, and reduced solar radiation, among other processes. These seasonal variations interact with longer-term changes driven by anthropogenic global warming. The workshop highlighted the latest research on polar winter climate and processes across various disciplines, including observation, laboratory work, and modeling. Several key research priorities for the polar climate system were identified. For example, (i) the workshop emphasized the need for enhanced observational capabilities and improved modeling of storm-driven processes to better understand and predict the evolution of polar climate. (ii) The complex mechanisms behind polar aerosol production and aerosol–cloud interactions, as well as the necessity for better parameterizations and integrated observational strategies to reduce model uncertainties, were also highlighted. (iii) The workshop further stressed the importance of incorporating polar processes into global teleconnection frameworks to improve the predictability of climate impacts at mid- and low latitudes.

Overall, the workshop emphasized the importance of multidisciplinary approaches, year-round observation, and the integration of biological, chemical, and physical processes to address persistent knowledge gaps in polar and cryospheric science. Initiatives such as Antarctica InSync (https://www.antarctica-insync.org) and Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) (https://www.actris.eu) were highlighted as vital platforms for encouraging collaborative efforts across observational, modeling, laboratory, and theoretical communities. Strengthening these collaborations will improve understanding of polar processes and their global climatic impacts. Detailed information about this workshop can be found at https://www.bas.ac.uk/event/workshop-on-polar-winter-climate-and-processes/.

Acknowledgments. We gratefully acknowledge financial support from IASC (https://iasc.info) and the SURFEIT project (NE/X009319/1) (https://www.bas.ac.uk/project/surfeit/), sponsorship from CliC (https://climate-cryosphere.org/about-clic/), CATCH (https://igacproject.org/activities/CATCH), ICPM (http://www.icpm-iamas.aq), and the British Antarctic Survey (https://www.bas.ac.uk) for providing resources to host the workshop.

References

Azhar, S. S. A., S. N. Chenoli, A. A. Samah, S.-J. Kim, and N. Murukesh, 2023: The mechanism linking the variability of the Antarctic Sea ice extent in the Indian Ocean sector to Indian summer monsoon rainfall. *Climate Dyn.*, **60**, 2665–2685, https://doi.org/10.1007/s00382-022-06466-z.

Bock, L., and A. Lauer, 2024: Cloud properties and their projected changes in CMIP models with low to high climate sensitivity. *Atmos. Chem. Phys.*, **24**, 1587–1605, https://doi.org/10.5194/acp-24-1587-2024.

Bromwich, D. H., and Coauthors, 2024: Winter targeted observing periods during the Year of Polar Prediction in the Southern Hemisphere (YOPP-SH). *Bull. Amer. Meteor. Soc.*, **105**, E1662–E1684, https://doi.org/10.1175/BAMS-D-22-0249.1.

Frey, M. M., and Coauthors, 2020: First direct observation of sea salt aerosol production from blowing snow above sea ice. *Atmos. Chem. Phys.*, **20**, 2549–2578, https://doi.org/10.5194/acp-20-2549-2020.

Gong, X., and Coauthors, 2023: Arctic warming by abundant fine sea salt aerosols from blowing snow. *Nat. Geosci.*, **16**, 768–774, https://doi.org/10.1038/s41561-023-01254-8.

Goosse, H., and Coauthors, 2018: Quantifying climate feedbacks in polar regions. *Nat. Commun.*, **9**, 1919, https://doi.org/10.1038/s41467-018-04173-0.

He, S., Y. Gao, F. Li, H. Wang, and Y. He, 2017: Impact of Arctic oscillation on the East Asian climate: A review. *Earth Sci. Rev.*, **164**, 48–62, https://doi.org/10.1016/j.earscirev.2016.10.014.

Kim, I.-W., A. Prabhu, J. Oh, and R. H. Kripalani, 2020: Combined impact of Greenland Sea ice, Eurasian snow, and El Niño–Southern Oscillation on Indian and Korean summer monsoons. *Int. J. Climatol.*, **40**, 1375–1395, https://doi.org/10.1002/joc.6275.

Kulkarni, S., and A. Agarwal, 2024: Quantifying the association between Arctic ssea ice extent and Indian precipitation. *Int. J. Climatol.*, **44**, 470–484, https://doi.org/10.1002/joc.8337.

Lapere, R., and Coauthors, 2023: The representation of sea salt aerosols and their role in polar climate within CMIP6. *J. Geophys. Res. Atmos.*, **128**, https://doi.org/10.1029/2022JD038235.

Liu, G., J. Li, and T. Ying, 2024: Amundsen Sea ice loss contributes to Australian wildfires. *Environ. Sci. Technol.*, **58**, 6716–6724, https://doi.org/10.1021/acs.est.4c00051.

Liu, Z., C. Risi, F. Codron, G. Gastineau, X. Huan, H. Lan, W. Xu, and G. J. Bowen, 2025: Anthropogenic intensification of Arctic anticyclonic circulation. *Sci. Adv.*, **11**, eads4508, https://doi.org/10.1126/sciadv.ads4508.

Ma, W., H. Wang, G. Chen, Y. Qian, I. Baxter, Y. Huo, and M. W. Seefeldt, 2024: Wintertime extreme warming events in the high Arctic: Characteristics, drivers, trends, and the role of atmospheric rivers. *Atmos. Chem. Phys.*, **24**, 4451–4472, https://doi.org/10.5194/acp-24-4451-2024.

Maclennan, M. L., and J. T. Lenaerts, 2021: Large-scale atmospheric drivers of snowfall over Thwaites Glacier, Antarctica. *Geophys. Res. Lett.*, **48**, e2021GL093644, https://doi.org/10.1029/2021GL093644.

Oltmanns, M., N. P. Holliday, J. Screen, B. I. Moat, S. A. Josey, D. G. Evans, and S. Bacon, 2024: European summer weather linked to North Atlantic freshwater anomalies in preceding years. *Wea. Climate Dyn.*, **5**, 109–132, https://doi.org/10.5194/wcd-5-109-2024.

Parker, C. L., P. A. Mooney, M. A. Webster, and L. N. Boisvert, 2022: The influence of recent and future climate change on spring Arctic cyclones. *Nat. Commun.*, **13**, 6514, https://doi.org/10.1038/s41467-022-34126-7.

Rantanen, M., A. Y. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma, and A. Laaksonen, 2022: The Arctic has warmed nearly four times faster than the globe since 1979. *Commun. Earth Environ.*, **3**, 168, https://doi.org/10.1038/s43247-022-00498-3.

Shupe, M. D., and Coauthors, 2022: Overview of the MOSAiC expedition: Atmosphere. *Elementa*, **10**, 00060, https://doi.org/10.1525/elementa.2021.00060.

Tan, I., and T. Storelvmo, 2019: Evidence of strong contributions from mixed-phase clouds to Arctic climate change. *Geophys. Res. Lett.*, **46**, 2894–2902, https://doi.org/10.1029/2018GL081871.

Turner, J., H. Lu, J. C. King, S. Carpentier, M. Lazzara, T. Phillips, and J. Wille, 2022: An extreme high temperature event in coastal East Antarctica associated with an atmospheric river and record summer downslope winds. *Geophys. Res. Lett.*, **49**, e2021GL097108, https://doi.org/10.1029/2021GL097108.

Vignesh, P. P., J. H. Jiang, P. Kishore, H. Su, T. Smay, N. Brighton, and I. Velicogna, 2020: Assessment of CMIP6 cloud fraction and comparison with satellite observations. *Earth Space Sci.*, **7**, e2019EA000975, https://doi.org/10.1029/2019EA000975.

Watkins, D. M., O. Persson, T. P. Stanton, A. B. Solomon, J. K. Hutchings, J. Haapala, and G. Svensson, 2024: Air-ice-ocean coupling during a strong mid-winter cyclone, Part 1: Observing coupled dynamic interactions across scales. ESS Open Archive, 170959964.40805357v1, https://doi.org/10.22541/essoar.170959964.40805357/v1.

Wei, J., Z. Wang, M. Gu, J.-J. Luo, and Y. Wang, 2021: An evaluation of the Arctic clouds and surface radiative fluxes in CMIP6 models. *Acta Oceanol. Sin.*, **40**, 85–102, https://doi.org/10.1007/s13131-021-1705-6.

Wickström, S., M. O. Jonassen, T. Vihma, and P. Uotila, 2020: Trends in cyclones in the high-latitude North Atlantic during 1979–2016. *Quart. J. Roy. Meteor. Soc.*, **146**, 762–779, https://doi.org/10.1002/qj.3707.

Wille, J. D., and Coauthors, 2021: Antarctic atmospheric river climatology and precipitation impacts. *J. Geophys. Res. Atmos.*, **126**, e2020JD033788, https://doi.org/10.1029/2020JD033788.

Yang, X., J. A. Pyle, and R. A. Cox, 2008: Sea salt aerosol production and bromine release: Role of snow on sea ice. *Geophys. Res. Lett.*, **35**, L16815, https://doi.org/10.1029/2008GL034536.

——, and Coauthors, 2019: Sea salt aerosol production via sublimating wind-blown saline snow particles over sea ice: Parameterizations and relevant microphysical mechanisms. *Atmos. Chem. Phys.*, **19**, 8407–8424, https://doi.org/10.5194/acp-19-8407-2019.

Zhang, X., H. Tang, J. Zhang, J. E. Walsh, E. L. Roesler, B. Hillman, T. J. Ballinger, and W. Weijer, 2023: Arctic cyclones have become more intense and longer-lived over the past seven decades. *Commun. Earth Environ.*, **4**, 348, https://doi.org/10.1038/s43247-023-01003-0.