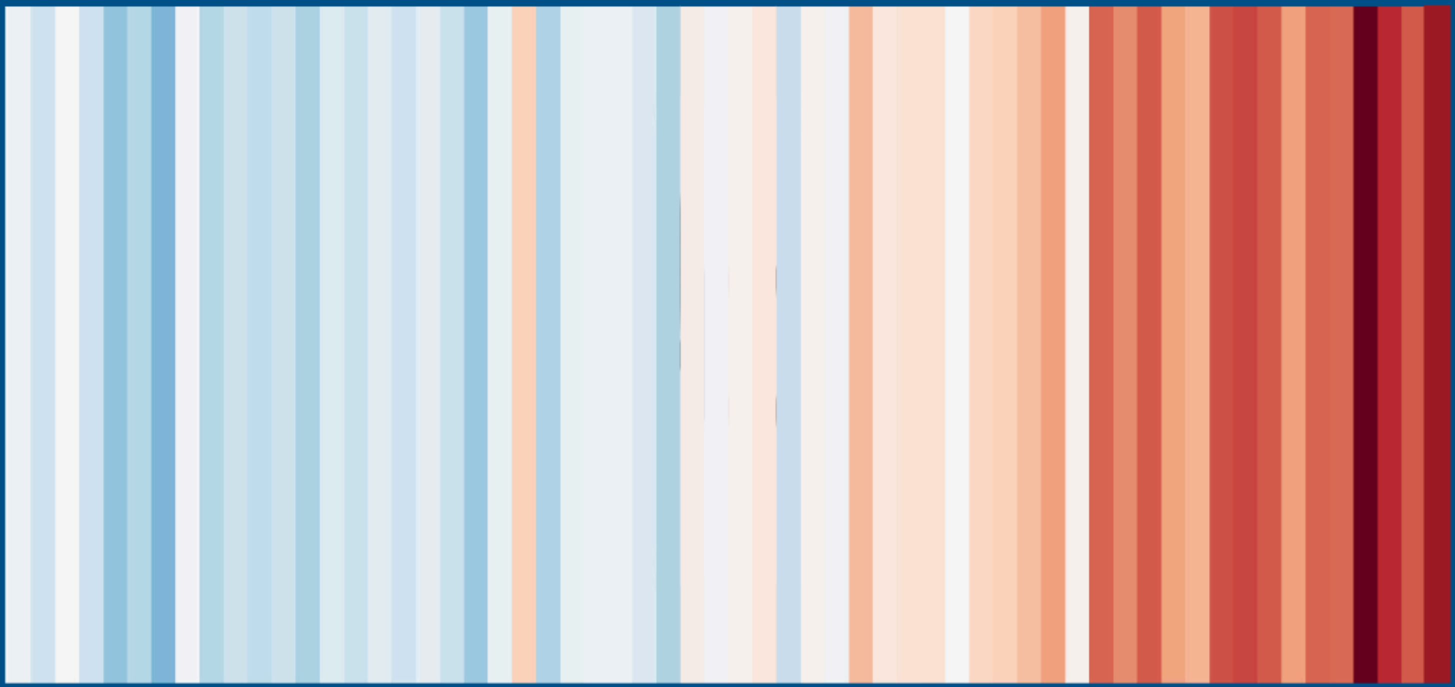
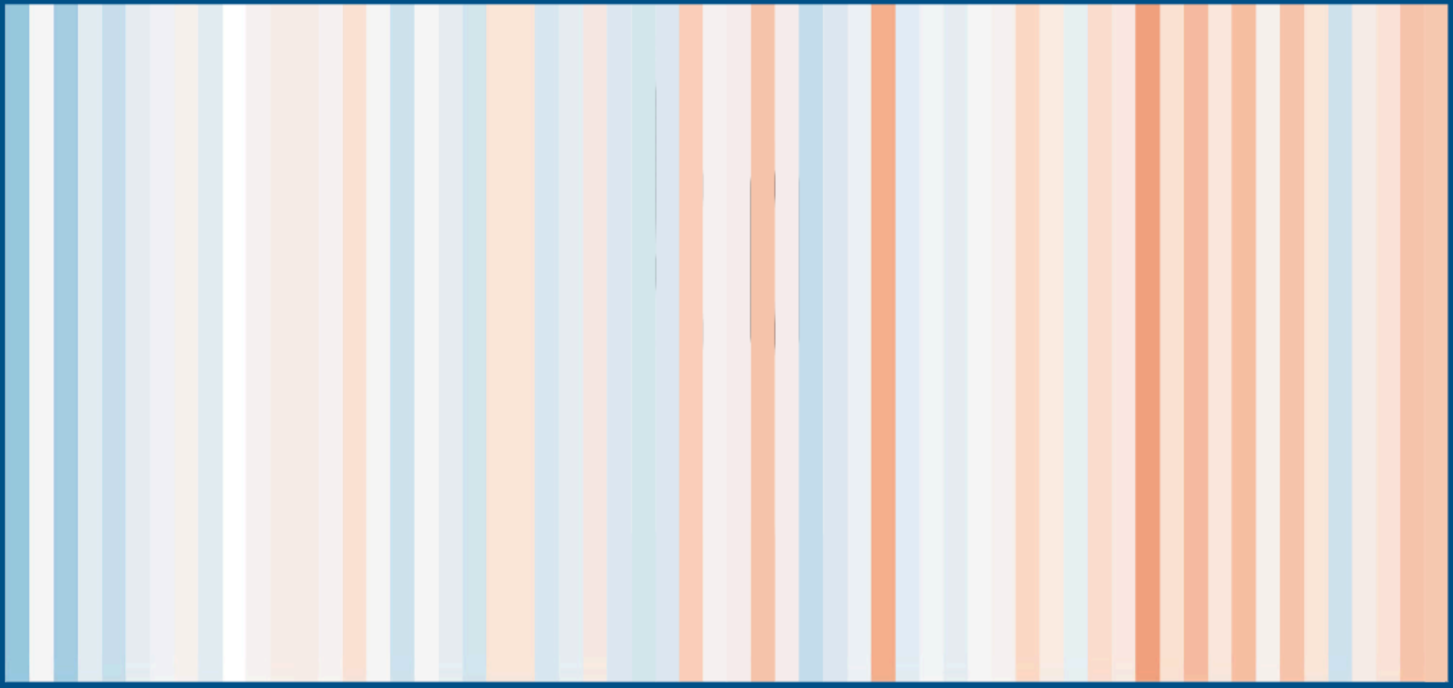


Polar Amplification of Climate Change Across Hemispheres and Seasons

A US CLIVAR Workshop
January 17-19, 2024
Boulder, Colorado



POLAR AMPLIFICATION OF CLIMATE CHANGE ACROSS HEMISPHERES AND SEASONS

Workshop Report

Workshop Sponsors:

BIBLIOGRAPHIC CITATION

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EDITORS

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FRONT COVER IMAGE

The Arctic and Antarctic Climate Stripes (Credit: Damien Ringeisen)

BACK COVER IMAGE

Arctic and Antarctic air temperature anomaly from ERA5 and sea ice thickness from PIOMAS (Arctic) and GIOMAS (Antarctic) by summer and winter season (Credit: Zachary Labe)

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EXECUTIVE SUMMARY

The polar regions of our planet have evolved in unique ways in response to anthropogenic climate change. Observations show recent, rapid, and, in many cases, unprecedented changes occurring in the Arctic that are outpacing the rest of the globe. On the contrary, observations indicate that the Antarctic has changed more slowly. In both regions, warming is uneven across the year, with greater warming occurring in winter than in summer, a feature that we now know is a fundamental aspect of polar amplification. While workshop discussions made clear that the Arctic and Antarctic systems are different in many ways, commonalities between the two polar hemispheres include the large spread in climate projections that exists amongst contemporary climate models and the substantial shortcomings in our capabilities to model these unique systems.

It is clear that the fate of the polar regions will impact everyone, no matter where we live on Earth. Changes in polar climate ripple across the globe, influencing global sea level (via melting glaciers and ice sheets), the global energy budget (via surface albedo change from melting snow and ice, as well as other radiative feedbacks), the carbon cycle (via permafrost thaw and methane release), and atmospheric and oceanic circulations. Physical changes in the polar regions have geopolitical and global economic implications. Thus, the ability to anticipate the pace and characteristics of polar climate change are needed for society to thrive on our changing planet.

A better understanding of the underlying mechanisms causing polar warming asymmetries requires expanded research and observations. This general workshop outcome rests on the shoulders of the extensive and sustained suite of observations from spaceborne, airborne, and ground-based sensors collected over the last 40 years that have undeniably expanded our understanding of polar amplification. The current observing system and modeling efforts have provided the basis against which we have confirmed fundamental aspects of polar amplification: the central role of sea ice, the ubiquitous occurrence of mixed phase clouds, the characteristic surface-based warming profile, fall-winter warming maximum, and the role of seasonal energy transfers from summer to fall by the ocean heat storage. We now understand that polar amplification is a coupled sea ice-ocean-atmosphere phenomenon that operates across the seasonal cycle. The observing system has enabled enhanced modeling capabilities that together are inspiring new hypotheses about how atmospheric and oceanic energy transport are interacting with sea ice and driving polar amplification. Coordinated modeling experiments designed to isolate sea ice loss have enabled credible estimates of the impacts beyond the polar regions. These key advances and the emerging science in polar amplification causality could not have been achieved without the current observing system, detailed process studies, and the investments made in modeling capabilities.

This US CLIVAR workshop was convened with the intent to identify specific observations, modeling studies, and community activities that could enable an acceleration of our understanding of the polar climate systems. This workshop brought together Arctic and Antarctic researchers with a range of disciplinary backgrounds and career-stages to present the latest research and discuss pressing unknowns confounding our attempts to reduce uncertainty in climate projections of polar amplification. Sessions covered the topics of observed and projected polar amplification, causes of polar amplification, the role of atmospheric and oceanic transport, drivers of sea ice trends and variability, and non-local effects of polar amplification. The goal of the workshop was to identify key knowledge gaps and formulate actions to address these gaps. Key knowledge gaps were identified relating to:

- the role of ocean heat transports and vertical mixing in polar amplification and sea ice variability;
- metrics and diagnostics for causal attribution of processes to polar amplification
- ice processes in mixed-phase clouds (nucleation, secondary ice production, aerosol-cloud interactions);
- effects of ocean mesoscale and sub-mesoscale processes on polar amplification and the representation of the mean state ocean circulation and sea ice properties;
- the sensitivity of ocean-atmosphere exchanges to sea ice properties;
- the influence of atmosphere-ocean interactions on sea ice variability and trends;
- quantification of the efficacy of ocean and atmosphere heat transports to sea ice melt and surface warming;
- mechanisms of remote impacts on and of polar change;
- influence of freshwater forcing on the Southern Ocean circulation and SSTs;
- precipitation and the role of snow in the polar systems;
- the role of the land surface on polar amplification;
- contributions of internal variability vs. forced trends to Antarctic sea ice variability; and
- understanding of the temporal and spatial nature of atmospheric heat transport and its influence on polar amplification.

To address these and other knowledge gaps, several recommendations were generated from plenary and breakout discussions organized around the themes of observations, modeling, and community activities:

- Observational capabilities can be enhanced by increasing the number and depth of buoy measurements, by investing in autonomous measurement technologies for over, on, and under sea ice measurements, supporting focused process studies on winter sea ice-atmosphere-ocean interactions, and by establishing a program (e.g., Arctic supersite) to continually measure the ocean-atmosphere-sea ice column, spanning from the ocean mixed layer through at least the top of the atmospheric boundary layer across the full range of observed conditions.

- Modeling and diagnostics can be advanced by establishing a polar change model diagnostics US CLIVAR working group and promoting archival of high-frequency model output of sea ice, atmosphere, and ocean state fields.
- Finally, community collaboration is crucial to furthering these ambitious observational and modeling goals. Workshop participants recommended exploring a partnership with the Tara drifting station project, establishing an agreed-upon set of "essential and standard" variables for polar research cruises, and coordinating with modeling intercomparison projects to ensure essential model outputs.

1 INTRODUCTION

No matter where on Earth we live, we are connected to the polar regions. This connection is forged by the fundamental role the polar regions play in the global food web, economy, and physical climate system. Thus, climate variability and change in the polar regions are important not only for the local inhabitants and polar ecosystems but for global society. Changes in polar ice conditions and the polar energy budget have ripple effects with a global reach, influencing global sea level (via melting glaciers and ice sheets), the global energy budget (via surface albedo change from melting snow and ice, as well as other radiative feedbacks), the carbon cycle (via permafrost thaw and methane release), and atmospheric and oceanic circulations.

Observations show that the recent, rapid, and, in many cases, unprecedented changes occurring in the Arctic are outpacing the rest of the globe. Since 1979, observed near-surface temperatures in the Arctic have warmed 2-4x faster than the northern hemisphere mid-latitudes (Hahn et al. 2021; Smith et al. 2019; Chylek et al. 2022). On the other hand, the Antarctic has been changing more slowly than anywhere else. This polar warming asymmetry has perplexed the science community, and models do not generally simulate this feature of the polar climate well (Smith et al. 2019; Hahn et al. 2021). For instance, observations indicate a faster rate of Arctic warming than most models predict, but a slower rate of Antarctic warming and sea ice loss than models predict. Model projections of 21st century polar warming exhibit the largest intermodels spread in polar regions characterized by divergent projections of the magnitude of Arctic amplification and the timing of when Antarctic amplification will emerge (e.g., Lee et al. 2021). In addition to this hemispheric asymmetry, understanding the seasonal asymmetry, such as the lengthening period of ice-free conditions, in polar warming offers opportunities to explore the underlying mechanisms of polar climate change, the factors that contribute to the warming asymmetry, and the evolution with increased forcing. *Understanding the polar climate system and narrowing the expected range in future polar climate change is an urgent scientific and societal matter warranting the attention of US CLIVAR*.

Building upon previous polar amplification workshops, the objectives of the workshop are to:

1. identify knowledge gaps and deficiencies in model diagnostics that limit our understanding and simulation of the hemispheric and seasonal asymmetries of polar amplification;
2. prioritize these knowledge gaps as areas for future research;
3. identify strategies, approaches, and data needs (e.g., process studies, collaborative modeling activities, satellite missions) to address the identified knowledge gaps;
4. identify candidate observational constraints on the processes driving polar amplification; and
5. identify steps for enhancing community collaboration.

A unique aspect of this workshop was the focus on the seasonally-resolved processes that also relate to the asymmetries between Arctic and Antarctic amplification. As indicated by the results of previous Arctic and polar amplification workshops, expanding our focus beyond the atmospheric response to the oceanic response and sea ice loss is required to understand polar amplification more fully and reduce the inter-model spread in projections. The workshop brought together researchers studying Arctic and Antarctic climate change from observational and modeling perspectives (ranging from paleoclimate to future projections) to cross-pollinate ideas, forge new collaborations, and generate recommendations to accelerate our understanding of polar amplification. The sections that follow capture the key points of presentations and discussion. The report concludes with a summary of the key findings and action items.

1.1 The workshop

The workshop convened 111 scientists from 15 countries and represented disciplinary expertise across the atmosphere, ocean, sea ice, and glaciers and ice sheets. Nearly 50% of the participants self-identified as early-career researchers and students, demonstrating the vitality of this subfield of climate science.

The workshop focused on five thematic areas:

Observed and projected polar amplification: This session explored the observed changes in the polar climate systems and the fidelity with which contemporary climate models represent these changes. It included research addressing observed polar climate trends, model projections and biases, sources of model uncertainty, model diagnostic approaches (shortcomings and opportunities), and emergent constraints using present-day observations and/or paleoclimatic proxies.

Causes of polar amplification: This session explored the causes of polar amplification, its seasonal expression, and hemispheric differences. It included research on the processes that contribute to these features of polar amplification, including discussions on the relative roles of different climate forcings and feedback processes.

Role of atmospheric and oceanic transport in polar amplification: This session explored the dynamics and impacts of energy transports into the polar regions and their interactions with local feedback processes. It included research on the influence of dry and moist atmospheric energy transport, ocean heat transport, and episodic/synoptic phenomena (e.g., moisture intrusions, atmospheric rivers, and polar cyclones) on polar amplification.

Drivers of observed sea ice trends and variability: This session explored the causes of the sea ice variability and trends in the Arctic and Antarctic regions, with an emphasis on recent extremes such as the rapid decline in Antarctic sea ice observed in 2023.

Non-local effects of polar amplification: This session explored the non-local effects of polar amplification and sea ice changes, including their influence on mid-latitude or tropical atmospheric dynamics, ocean circulation, global sea-surface temperature patterns, global energy flows, and global warming from the observational, modeling, and theoretical perspectives.

These themes were the subjects of plenary, poster, and breakout sessions. During each plenary session, two invited speakers presented a broad overview of the progress on the themes and their perspectives on future directions. Additional oral and poster presentations covered a wide variety of subjects. All presentations are available via the online agenda at usclivar.org/meetings/polar-amplification-workshop-agenda.

Daily breakout sessions enabled focused discussion of the topics of the day. Participants were randomly assigned to one of five groups of approximately 20 people, such that each breakout session consisted of a newly formed and diverse group of participants. For each group, a facilitator was charged with leading the discussion and encouraging participation, and a rapporteur was charged with reporting a summary of the discussion in the next morning's plenary session. During the breakout sessions, participants shared their perspectives on the workshop objectives. The workshop concluded with a discussion of key outcomes and strategies for moving forward.

2 WORKSHOP SESSIONS

2.1 Observed and projected polar amplification

Observing the Earth's polar regions has advanced dramatically over the last 40 years, enabling scientists to track rapidly warming surface temperatures, the precipitous decline of Arctic sea ice, and the more gradual changes in the Antarctic. This observing capability has also captured unprecedented and unexpected events, including the dramatically low level of Antarctic sea ice in 2023, an Antarctic heat wave in 2022 (Blanchard-Wrigglesworth et al. 2023), and the Great Arctic Cyclone of 2012 (Simmons and Rudeva 2012). These observations have been used to confirm the seasonality and the vertical structure of polar warming first simulated by Manabe and Manabe and Wetherald (1975) and Manabe and Stouffer (1980). These observations have also advanced our understanding of polar climate change and resulted in substantial advances in modeling capabilities (e.g., Taylor et al. 2022). The focus of this session was the observed and model-simulated changes in the polar regions over the historical period to identify gaps within the observing system, modeling capabilities, and our understanding of polar climate change. *A clear outcome of this session is the substantial need for expanded observations of the polar regions to enable advances in understanding and modeling of polar climate change.*

While the scientific advances enabled by the historical record are foundational, the session highlighted several gaps in our polar observing capabilities that limit our process-level understanding of the polar climate systems. Specific areas of deficiency included ocean temperature, salinity, and heat transport profiles, sea ice thickness, snow depth on sea ice, sea ice surface albedo and melt pond evolution, lower tropospheric temperature and humidity structure, and cloud properties. This session emphasized the importance of capturing these observations simultaneously and over multiple years to understand the coupled ocean-sea ice-atmosphere processes that govern polar amplification. The presentations and discussion acknowledged field campaign/process study data and sustained and enhanced satellite instruments as necessary aspects of a complete observing strategy for enhancing polar modeling capabilities.

One observational enhancement identified as a high priority is measurements of ocean properties beneath sea ice (Figure 1). This could be accomplished in the Southern Ocean by adding ARGO buoys to the current complement and by increasing the depth of ARGO measurements to provide valuable missing perspectives on the vertical structure of ocean heat transport. An increased network of undersea ice salinity measurements offers insight into interactions within the Southern Ocean-sea ice system and aids in assessment of potential circulation regime shifts. Such observations would also help determine the influence of meltwater injection into the Southern Ocean from Antarctic ice sheet melt. Coupled climate models do not currently capture the ocean response to meltwater injection, a key model deficiency mentioned below.

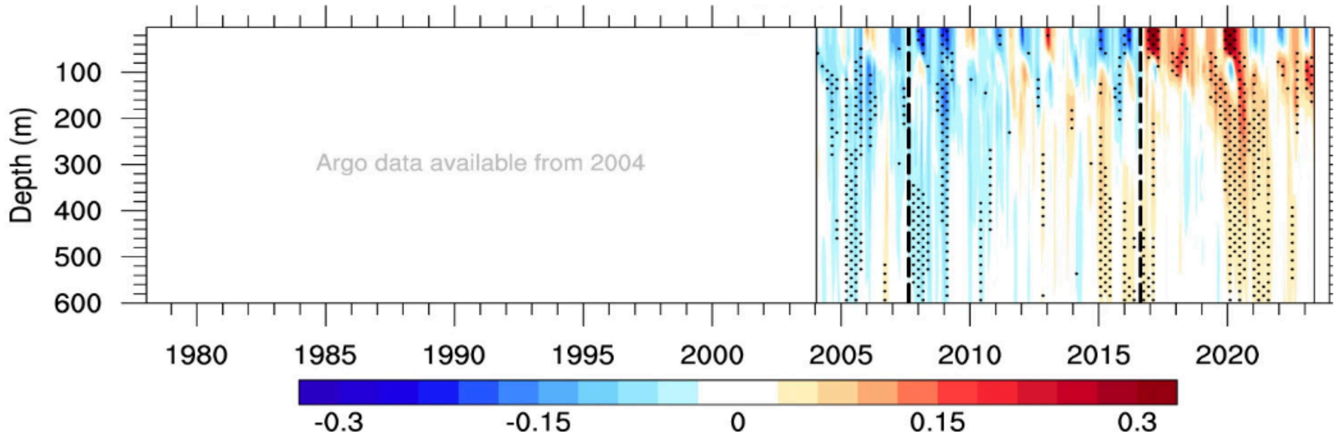

Figure 1. Observations show substantial changes in observed subsurface ocean temperature but are limited in time and depth. The figure illustrates observed ocean temperature anomalies with depth over the Southern Ocean since 2004. From Purich and Doddridge 2023.

The inclusion of observed meltwater fluxes in models has improved model-simulated ocean and sea ice properties and their variability. Meltwater fluxes are also a critical part of understanding the remote effects of Antarctic climate change (see Session 5).

Undersea ice measurements of ocean properties should also be a priority in the Arctic. However ARGO buoys are less useful for this purpose. Technological investment is needed to enable more extensive use of automated data collection systems for on- and under-sea ice measurements. This is crucial as Arctic amplification was shown to be sensitive to latitudinal ocean heat transport via the Bering Strait, Fram Strait, and Barents Sea (see Session 3). Enhanced monitoring of the vertical profile of ocean heat transport into and out of the Arctic and sea ice pack would provide an important observational constraint on models.

This session identified deficiencies in atmospheric and oceanic reanalysis as limiting our understanding. Figure 2 shows substantial disagreement in spatial patterns of regional surface warming derived from reanalyses poleward of 60S relative to GISTEMP. Improving reanalysis requires increased observational density (e.g., more radiosondes poleward of 60N and 60S would significantly improve reanalysis), improved physical parameterizations, and data assimilation advances to better incorporate hyperspectral satellite radiances. In addition, ice sheet processes and meltwater fluxes are important in explaining regional warming patterns and are missing from reanalysis.

Consistent multi-year data records in polar regions are needed to advance understanding of polar amplification processes and constrain models. The MOSAiC expedition was exemplary for its complete set of coupled ocean-sea ice-atmosphere system observations through the annual cycle. The concept of a semi-permanent Arctic drifting station ("SuperSite") garnered interest at the workshop. Performing such data collection annually and continuously with a consistent set of core observations by establishing an Arctic "Supersite" (e.g., Tara Polar Station; https://fondationtara-ocean.org/en/schooner/tara-polar-station/) would offer significant value as a means to provide a statistically representative picture of atmosphere-sea ice-ocean interactions and interfacial fluxes. Such activities would also be useful in the Antarctic, though they would come with unique logistical challenges due to the different character of sea ice in the region.

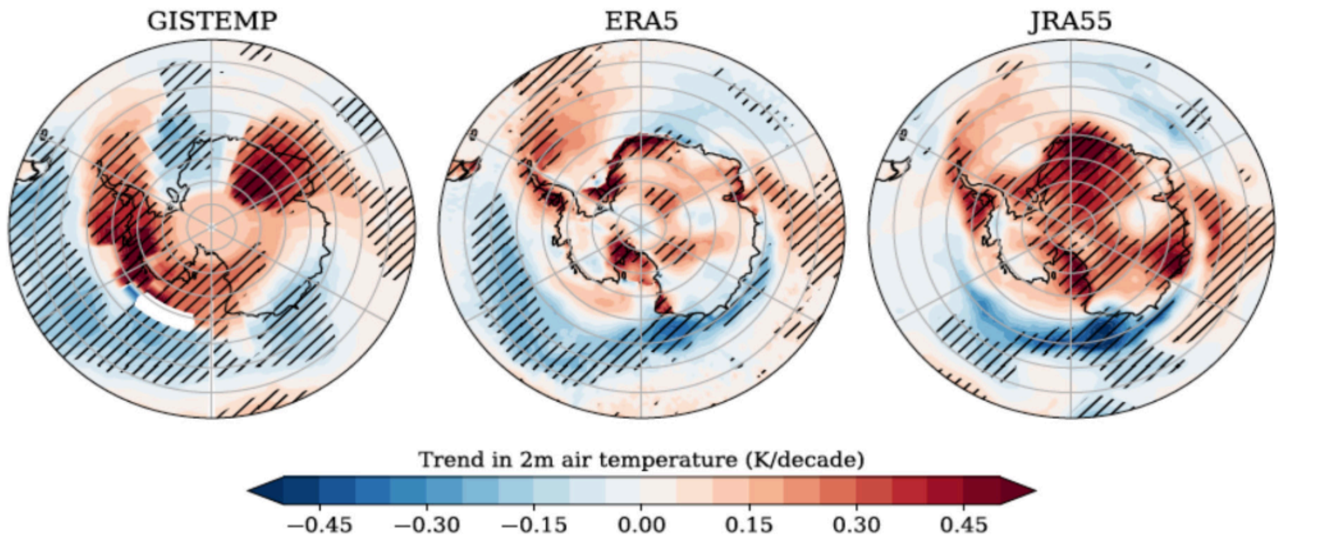

Figure 2. Substantial differences in the regional warming pattern across the Antarctic. Trends in 2-meter air temperature over the Antarctic for GISTEMP, ERA5, and JRA55. From Roach 2024.

Breakout sessions discussed the use of aircraft observations to track and revisit drifting Arctic sea ice parcels during polar night, with or without a "Supersite," with the specific intent to better understand the transition from first-year to multi-year ice and the factors that influence the likelihood of summer melt season survival. Discussions highlighted the need for improved coordination of the near-annual cruises in polar regions to help fill data gaps, such as the general lack of observations. An internationally agreed upon set of essential and standard variables, collected during any cruise regardless of the science focus, would facilitate continuity in high priority data records.

While climate models robustly show fundamental features of polar amplification, including seasonality and vertical structure, they struggle to adequately reproduce observed behavior known to be important to polar amplification. CMIP6 climate models generally outperform CMIP5 models in the simulation of sea ice thickness and other observed quantities (Notz et al. 2020). However, CMIP6 models consistently underestimate the Antarctic summer sea ice extent and warm the Antarctic faster than observed (Roach et al. 2020).

Consistent underestimation of the Antarctic summer sea ice extent is thought to result from model biases in Southern Ocean circulation and the lack of ice sheet-ocean feedback processes. However, this hypothesis cannot be tested because ice sheet models are not currently coupled with atmosphere-ocean general circulation models within simulations of the historical period or future scenarios. Internal variability may also be a substantial factor and varies greatly across models. Model simulations nudged to observed winds, sea ice drift, and freshwater forcing show improved agreement with observed sea ice properties (Blanchard-Wrigglesworth et al. 2021; Roach et al. 2022; Roach et al. 2023). While this session highlighted the need for improved physical understanding and physical parameterizations, this result suggests that improved parameterizations alone will not bring models into complete agreement with observations. Improved ocean model resolution is a potential pathway to improve simulation of the polar oceans and their response to forcing.

A key challenge that remains is separating forced response from internal variability. One recommendation to remedy this is the combined use of nudged experiments and analyses focusing on deconvolving forced trends on internal variability within the framework of known modes of variability (e.g., Southern Annular Mode, Arctic Oscillation, El Nino Southern Oscillation). Additionally, there is a need to continue and extend the use of single-model large ensembles to separate the forced response from internal variability. Moreover, a common practice is to use only the first ensemble member from a given model when performing multi-model comparisons. However, studies have shown that this does not necessarily represent the full model behavior. Increasing the number of ensemble members to at least ten improves model agreement with observations (Peings et al. 2021). The community should adopt the practice of including additional ensemble members.

This session, among others, highlighted the influence of model ocean circulation biases on simulated polar amplification. Model biases in the mean state of the global ocean circulation are a key uncertainty that influences polar amplification in both hemispheres. Increased ocean model resolution offers substantial improvement when simulating mean ocean circulation and small-scale processes, air-sea fluxes, and atmospheric jet stream variability. Ocean eddy-permitting simulations have also improved the simulation of Arctic sea ice by better resolving the pathways for ocean heat transport.

In summary, this session considered various observed and modeled features of polar amplification. The outcomes highlighted a need for continued and enhanced observational capabilities in both polar regions that capture the ocean-sea ice-atmosphere interactions at multi-year time scales and enable better constraints on the model representation of ocean circulation on sea ice variability.

2.2 Causes of polar amplification

A fundamental understanding of the physical processes underpinning polar amplification is required to improve model physics, reduce uncertainty in polar climate change projections, and guide observational needs. Due to the highly coupled nature of the climate system, isolating the processes responsible for polar amplification, its seasonal expression, and the asymmetry between the poles is challenging. Many studies have explored a plethora of potential causes of polar amplification, including the influence of atmospheric and oceanic heat transports, clouds, and the changes in mass, momentum, and energy exchanges that occur due to sea ice loss (Manabe and Stouffer 1980; Hall 2004; Sejas et al. 2014; Singh et al. 2017; Stuecker et al. 2018; Hahn et al. 2021; Chung and Feldl 2024). Many of these processes are important for a complete understanding of polar amplification (Figure 3), including its seasonal pattern (Laine et al. 2016; Kim et al. 2019; Hahn et al. 2022; Sejas and Taylor 2023; Chung and Feldl 2024) and hemispheric asymmetry (Zhang et al. 2023). The purpose of this session was to elucidate the processes that contribute to the magnitude and characteristics of polar amplification and identify gaps in our understanding and diagnostic frameworks. *The session highlighted the emerging consensus around the dominant role sea ice loss plays in polar amplification and the lack of a diagnostic framework to attribute causality to polar amplification processes.*

The presentations and breakout discussions emphasized five key knowledge gaps: (1) lack of a common framework for understanding the causes of polar amplification; (2) how to use observations to improve model projections; (3) the role of the mean-state polar climate in mediating change in a warming world; and the role of (4) clouds and (5) ocean dynamics in polar climate change.

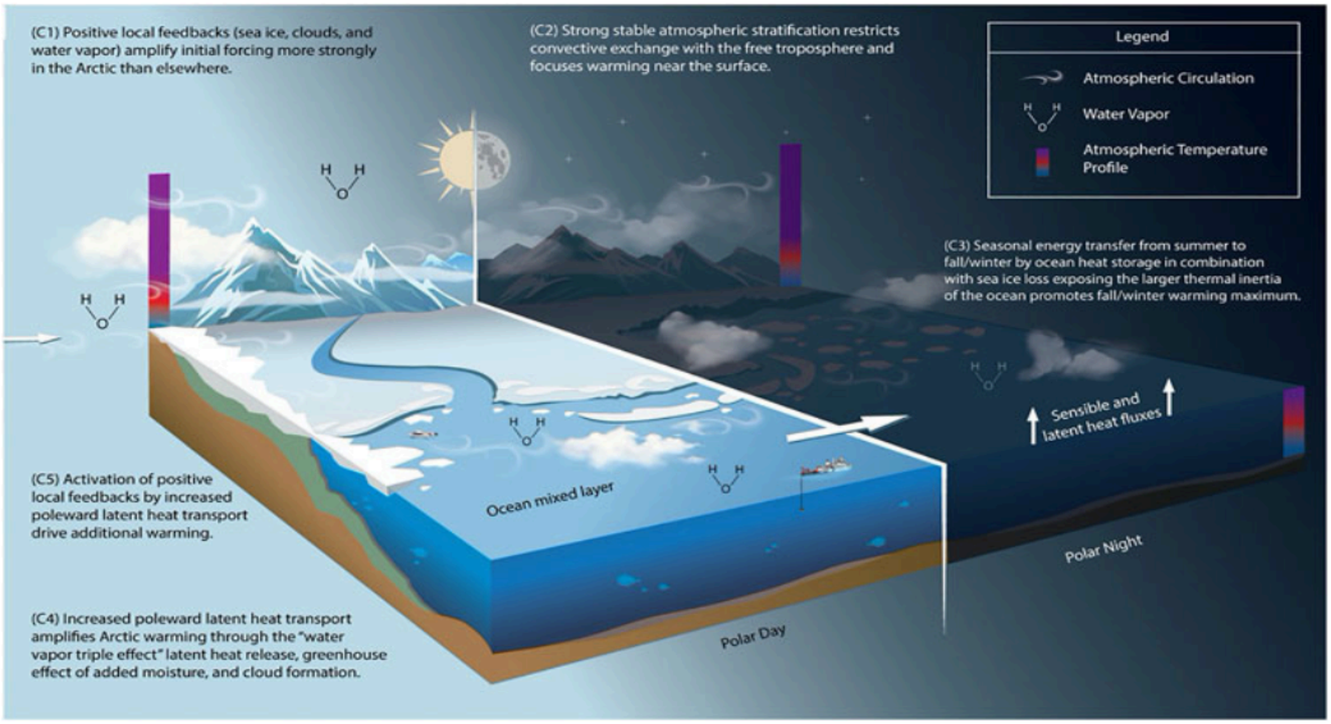

Figure 3. Causes of Polar amplification. Conceptual depiction of processes important for Polar amplification and its seasonal pattern. From Taylor et al. 2022.

Current diagnostic frameworks are insufficient for understanding the causes of polar amplification and its uncertainty. The Arctic is a highly coupled system of positive feedbacks, such that different methods highlight different causes. For example, Beer and Eisenman (2022) individually deactivate climate feedbacks in a moist energy balance model and find a key role for the water vapor feedback and no role for the lapse-rate feedback in driving Arctic amplification. In contrast, other studies that apply conventional feedback analysis to climate model experiments find a central role for the lapse-rate feedback (e.g., Pithan and Mauritsen 2014; Hahn et al. 2021), while others find that sea-ice loss and the albedo feedback ultimately drive the lapse-rate feedback and polar amplification (Graversen et al. 2014; Feldl et al. 2017; Feldl et al. 2020; Boeke et al. 2021). Furthermore, the perspective used to carry out the feedback analysis—e.g., budget analyses performed using radiative fluxes at the top of the atmosphere versus analyses performed using surface energy fluxes—can lead to different interpretations of the underlying causes (Pithan and Mauritsen 2014; Sejas et al. 2021). Even when these positive feedbacks are deactivated, a simple sea-ice model produces the key seasonal pattern of winter-amplified Arctic warming simply as a result of transitioning from sea ice to open ocean (Hahn et al. 2022). These examples illustrate the challenge of identifying causal mechanisms of polar climate change when there are several processes contributing to those changes and interacting with each other.

Observations have the potential to improve projections of polar climate change using emergent constraints, defined as physically explainable empirical relationships between characteristics of the current climate and long-term climate predictions that emerge across collections of climate model simulations (Hall et al. 2019). However, emergent constraints do not always identify the specific physical processes that produce these relationships, making it difficult to use emergent constraints to improve climate models. For example, Thackeray and Hall (2019) identify an emergent constraint based on present-day albedo, but it is unclear what drives model biases in present-day albedo (e.g., representations of regional sea ice patterns, snow on sea ice, melt ponds, snow on land). *The workshop highlighted the need to extend emergent constraint analysis to identify the underlying processes that contribute to model biases and improve those biases using targeted observations.*

Understanding the role of the base climate state for polar amplification emerged as a theme. Models with lower mean-state sea-ice concentration project stronger future ice loss and a more intense seasonal cycle in ice melt and growth, promoting more positive feedbacks and stronger Arctic amplification (Linke et al. 2023; this study also uses current sea-ice amount to provide an emergent constraint on future Arctic amplification). Sea-ice sensitivity in a single-column model depends strongly on initial sea ice thickness (Clemens-Sewall 2024). Experiments that apply positive and negative radiative forcing to the Arctic in different mean-state climates show that the climate response is strongly sensitive to the mean state (Hahn 2024). The existence of polar amplification in ice-free climates was shown to depend on mean state ocean heat transport (England and Feldl 2024, Zhu 2024). There is clear evidence that the polar base state mediates future warming and its uncertainty. Systematic investigations are needed to determine how the mean state climate and sea ice properties impact the simulated response to anthropogenic forcing across a range of model resolutions and complexities to better constrain future projections.

The role of clouds in polar amplification is a key uncertainty. Especially crucial is the need to assess and quantify microphysical processes in mixed-phase clouds, their radiative effect, and how both are influenced by retreating ice via changes in moisture, aerosols, and surface heat fluxes (Eirund et al. 2019; Taylor et al. 2022; Wendisch et al. 2019). To fully understand the role of clouds in polar amplification and the associated uncertainties, the following needs were identified:

1. improved observational approaches to measure cloud microphysical properties (e.g., size distributions and number concentrations of ice crystals);
2. collocated, long-term measurements of clouds, aerosols, and radiation with meteorological observations over sea ice and ocean surface types;
3. nudged model experiments leveraging available high-quality observations (such as from MOSAiC (Shupe et al. 2022); and,
4. cloud parameterization development to enable the accurate reaction of cloud properties to surface type changes.

Addressing these needs will enhance our process-level understanding of polar clouds to improve climate model projections.

The role of the ocean in polar climate change has been understudied relative to the atmosphere. Key high-priority actions needed to address the role of the ocean include leveraging higher resolution models to better capture ocean dynamical processes and investigate the impact of ocean model resolution on polar amplification (Chang et al. 2020; Docquier et al. 2019; Roberts et al. 2020). Observational needs include continued ARGO observations and new observations under sea ice and near the sea-ice edge, including during seasonal sea ice advance and retreat. Long-term monitoring with enhanced spatial and vertical sampling at important ocean gateways (Bering Strait, Fram Strait, and Barents Sea) is needed, as well as at ocean-atmosphere boundaries, to constrain high-resolution models (see Section 3).

2.3 Role of atmospheric and oceanic transport in polar amplification

Atmospheric and oceanic circulations have the potential to influence polar amplification by altering the poleward transport of heat and moisture; however, their role as drivers is obscured by their interactions with other components of the climate system. Total atmospheric energy transport into the Arctic is anti-correlated with Arctic amplification due to large decreases in dry energy transport, while moist atmospheric energy transport and ocean transport into the Arctic increase (Hwang et al. 2011, Figure 4). *This session focused on the dynamics and impacts of energy transports into the polar regions, as well as their interactions with local feedback processes.*

Moist and dry components of atmospheric energy transport interact in distinct ways with polar feedbacks. The decrease in dry atmospheric energy transport is coupled to amplifying polar feedbacks that promote a reduced equator-to-pole surface temperature gradient (Feldl et al. 2017, Henry et al. 2021). Much of the moisture transport into the Arctic occurs via short-lived, episodic events; increases in the frequency of these moist intrusions have contributed to wintertime Arctic warming and reduced sea ice growth (Woods and Caballero 2016; Graham et al. 2017; Hegyi and Taylor 2018; Dimitrelos 2023). In this manner, moist energy transport also interacts with polar feedbacks. When atmospheric energy transport is separated into its dry and moist components using popular diagnostic frameworks, moist atmos-pheric energy transport rises in prominence as a contributor to polar amplification in both hemispheres (e.g., Hahn et al. 2021, Figure 5) and may have a stronger influence on polar warming than suggested by energetic grounds (Graverson and Burtu 2016).

While the separation of moist and dry components of energy transports has yielded important insights on the influence and response of atmospheric circulations to Arctic surface climate, such metrics are limited by their vertically integrated nature. Stratospheric energy transport into the Arctic has little impact on the Arctic surface energy budget (Cardinale et al. 2021), while transport events that are bottom-heavy in their vertical structure have a greater efficiency, especially when they occur in an Arctic environment characterized by low stability, which promotes greater turbulent mixing and surface-troposphere coupling (Cardinale and Rose 2022, Kaufman and Feldl 2022). Reduced lower tropospheric stability, associated with decreased sea ice concentration, promotes an increase in high-efficiency transport events in a warmer climate (Cardinale and Rose 2023).

The role of episodic moist transport events, such as atmospheric rivers (ARs), in polar amplification emerged as a workshop theme. In the mid-latitudes, these narrow filaments of intense moisture transport are responsible for up to 90% of poleward moisture transport (Newman et al. 2012). An increase in the frequency of ARs penetrating into the Arctic accounts for 34% of the total decline in sea ice in the Barents-Kara Seas and central Arctic during the ice-growing season, with both anthropogenic forcing and tropical Pacific variability contributing to AR changes (Zhang et al. 2023). Other impacts of ARs include warm extremes and, for springtime events, the potential to initiate sea ice melt. Because impacts are sensitive to how ARs are defined, researchers are considering different thresholding methodologies for application to warmer climates (Thaker 2023). A key point raised in this session is that the inter-model spread in the structure and Arctic system response to ARs cannot currently be assessed because *the necessary high-frequency output is not available across climate models*. Additionally, the lack of high-frequency output within climate model projections hinders the ability to evaluate the role that changes in AR intensity and frequency play in the causality of polar amplification.

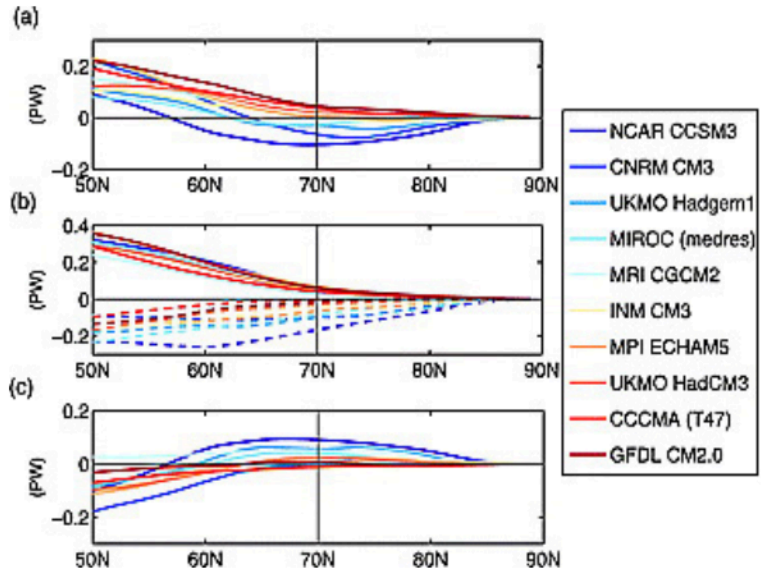

Figure 4. Changes in northward energy transport in the northern high latitudes for (a) atmospheric energy transport, (b) moist (solid) and dry (dashed) components of atmospheric energy transport and (c) ocean energy transport between 2081-2100 and 2001-2020 for simulations in the A2 scenario of CMIP3. From Hwang et al. 2011.

As with the atmosphere, there are significant uncertainties about the role of ocean heat transport in driving polar amplification. In the Arctic, coupled models indicate that oceanic heat transport increases with shrinking sea ice coverage, as would be experienced under a warming climate that features significant Arctic amplification (e.g., Holland and Bitz 2003). More recent studies have demonstrated clear connections between changes in oceanic heat flux convergence in the mixed layer and changes in sea ice concentration in both hemispheres in fully-coupled simulations under forcing equivalent to a doubling of CO_2, and those changes also modulate other feedback mechanisms, such as the lapse rate feedback (Singh et al. 2017). New modeling protocols are needed to disentangle these highly interactive processes. Additionally, a more careful accounting of energy fluxes at the ocean-atmosphere-ice interface, as performed by Oldenburg et al. (2024), will help assess how much anomalous heat from the ocean directly translates to sea ice loss and how much is lost to the atmosphere. Direct model output of high frequency and monthly averaged ocean heat transport vertical profiles is also needed, as the role of ocean heat transport in the polar energy budget cannot be reliably calculated and closed from monthly averaged current and heat content information.

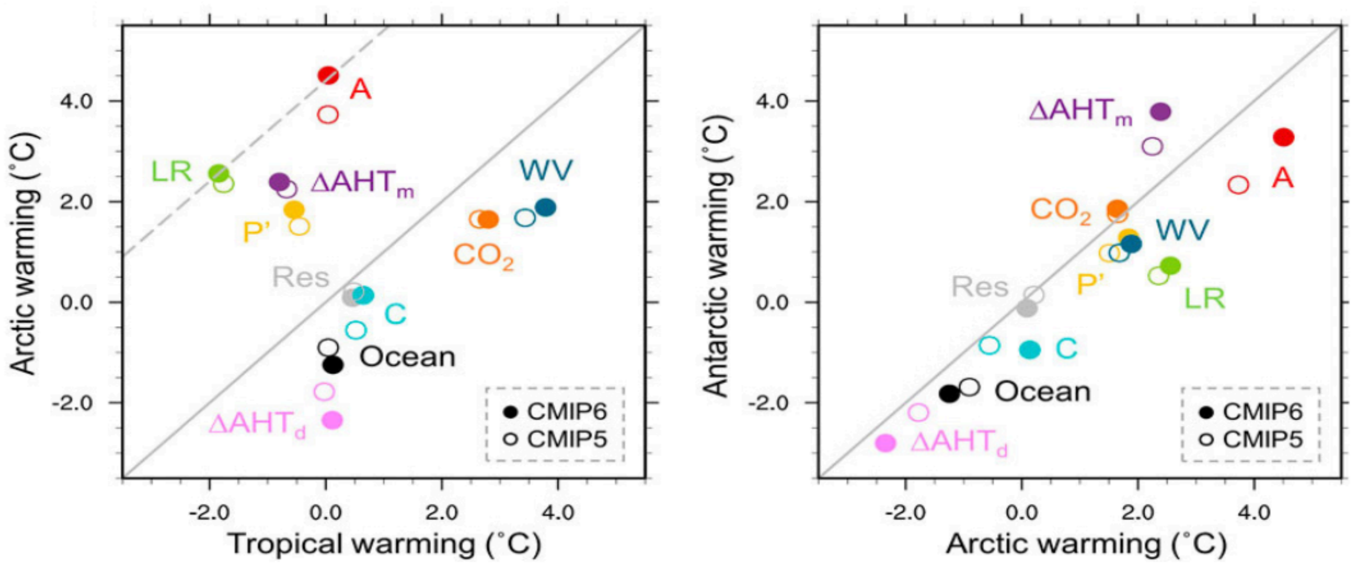

Figure 5. Contributions of feedbacks and transport processes to warming (˚C) following an abrupt CO2 quadrupling in CMIP6 (filled circles) and CMIP5 (hollow circles) models for the tropics relative to the Arctic and the Arctic relative to the Antarctic. Changes in moist atmospheric heat transport convergence (ΔAHTm) are an important contributor to Arctic and Antarctic warming. Warming contributions are also shown for the lapse rate (LR), surface albedo (A), water-vapor (WV), and cloud (C) feedbacks, the variation in the Planck response from its global-mean value (P'), effective radiative forcing (CO2), change in dry AHT convergence (ΔAHTd) and ocean heat uptake (Ocean), and residual term (Res). From Hahn et al. 2021.

However, there are indications that model-based results should be treated with care, given the relative dearth of observations available to evaluate ocean model performance at high latitudes. In combination with the high resolutions required to resolve and replicate the basic geostrophic turbulent flow of the high-latitude oceans, there are significant uncertainties about the performance of ocean models in handling some of the relationships discussed above. Increasing ocean model resolution from 1° to 0.1° significantly improves the simulation of oceanic heat transport through the Bering Strait and sea surface temperature in surrounding waters (Xu et al. 2024, Figure 6). Ocean heat transport through the Bering Strait exerts a more substantial influence on Arctic warming than previously recognized and is substantially larger in high-resolution than low-resolution models (Xu et al. 2024, Weijer 2024). Continuing efforts are needed to rapidly advance modeling capabilities to support high-resolution (0.1 degree) ocean simulations. As such, there is an additional need to develop parameterizations to appropriately represent oceanic turbulence at these scales.

Observations of the inflow through the Bering Strait have shown increasing trends since the 1990s. New gravity and altimetry data reveals that this increased flow has largely been driven by far-field pressure-head forcing (Peralta-Ferriz and Woodgate 2023). This increased inflow has been coupled with increases in oceanic temperatures and decreasing salinity. The increased pressure-head forcing is largely driven by changes in the East Siberian Sea during the summer months and by changes in the Bering Sea during the fall months. East Siberian Sea salinization resulting from increased advection of Pacific water is thought to play a role, based on ocean bottom pressure data from GRACE and dynamic ocean topography information from altimetry data, though the magnitude of salinization estimated for the East Siberian Sea is very sensitive to the version of GRACE data used. This result highlights a broader knowledge gap regarding the dependence of simulated phenomena, such as Bering Strait salinity and inflow, on different versions of assimilated observational data.

In summary, this session revealed that the character of heat transport is crucial to its efficacy in driving polar warming. It is insufficient to simply quantify the total poleward energy transport, or even its atmospheric and oceanic components, without also knowing whether, for the atmosphere, that transport occurs in moist or dry form, aloft or near the surface, and, for the ocean, through which oceanic gateway the energy enters the Arctic. Progress in this area requires a shift away from energy budget diagnostics to a more process-oriented approach that utilizes the high-resolution structure and temporal nature of heat transport, employs modeling hierarchies, and advances modeling capabilities such as numerical water tracers.

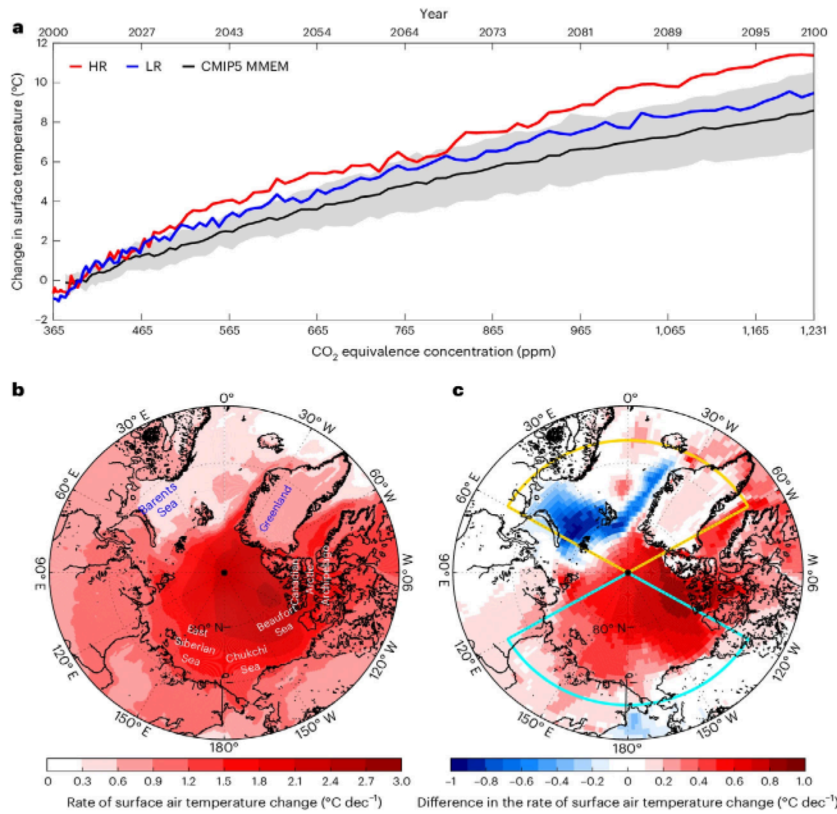

Figure 6. Impact of ocean model resolution on Arctic amplification showing a larger warming rate in high resolution (HR) relative to low-resolution (LR) and the CMIP5 multi-model mean (MMEM) simulations. The enhanced warming is primarily attributed to an increase in ocean heat transport through the Bering Strait. From Xu et al. 2024.

2.4 Drivers of observed sea ice trends and variability

Over the satellite record, there have been substantial changes in the sea ice extent (SIE) in both hemispheres. The Arctic has experienced a significant and continuous decline in SIE, while the Antarctic has experienced a small but significant overall increase (with regional cancellations) from 1979 through 2015, followed by substantial variability, including record extreme minima in sea ice extent in the summers of 2017, 2022, 2023, 2024 and the winter of 2023 (Figure 7). Accompanying the increased variability is the increased persistence of sea ice anomalies. The sea ice system is complexly coupled to the ocean and atmosphere, making it difficult not only to determine the primary drivers of this observed variability but also the pathways by which they influence sea ice variability. Therefore, the key aims of this session were to understand the sources of observed sea ice variability in both hemispheres by identifying the drivers and mechanisms responsible, the knowledge gaps that prevent us from achieving understanding, and how these knowledge gaps may be reduced/eliminated.

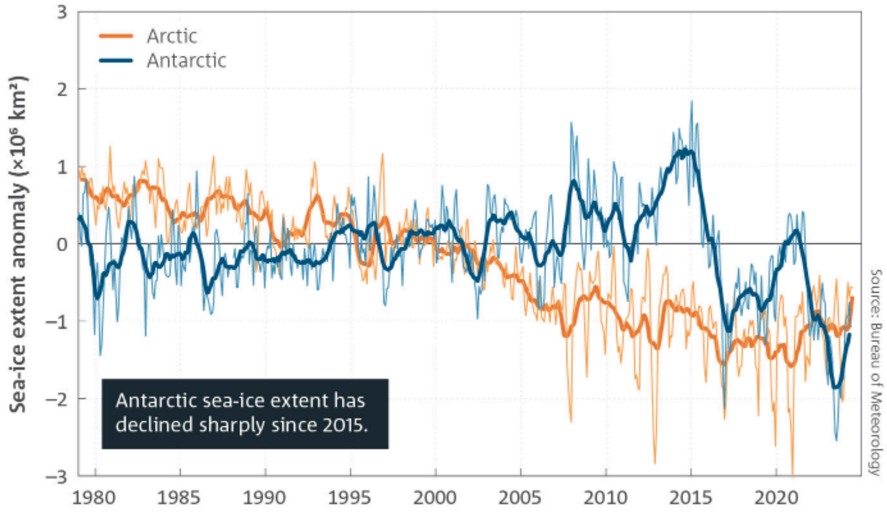

Figure 7: Total sea ice extent anomalies for the Arctic and Antarctic. From State of the Climate 2024, CSIRO and Bureau of Meteorology. © Copyright CSIRO Australia

Most research has focused on the atmospheric relationship with SIE, where sea ice change, especially in the short term, is driven by atmospheric circulation. For example, seasonal and decadal variability in Antarctic SIE is driven by the Southern Annular Mode (SAM) through its effect on the surface winds, which in turn influences vertical mixing in the ocean and the vertical transfer of heat, moderating SIE. However, there has been little change in the variability of the atmospheric modes suggesting that the current Antarctic sea ice variability is not solely forced by atmospheric circulation. Roach et al. (2023), using the ACCESS model, suggest that the sea ice response to atmospheric forcing has been reduced in the last few years. The warming of the Southern Ocean has become of primary importance in forcing the recent variability in Antarctic SIE (Fig. 1). The production of sea ice and, therefore, maximum SIE depends on the dominance of the ocean salinity profile over buoyancy. This has consequences for Antarctic amplification as negative feedback is related to the salinity regime. The workshop highlighted the need to enhance observations of the salinity profiles within the Southern Ocean.

Many knowledge gaps in our understanding of polar amplification were identified among the key components of the climate system—atmosphere, ocean, sea ice—and included the complexity added by their close coupling. One fundamental gap identified is in our understanding of interactions between heat transport in both the atmosphere and the ocean and sea ice variability and trends. Further, this session explored the efficacy of heat transports in driving sea ice changes with questions such as: how does the character of heat transport (on all timescales) influence polar change? Donohoe (2024) showed, using climate models and atmospheric reanalyses, that atmospheric heat transport convergence anomalies tend to lead Arctic sea ice concentration anomalies. Donohoe (2024) also showed that atmospheric heat transport divergence of approximately the same magnitude followed those concentration anomalies such that the total heat transport convergence does not change substantially when integrating over the course of a sea ice loss event.

We lack an understanding of how system components couple (e.g., the response of oceanic heat transport and salinity to freshwater/precipitation or two-way interactions between atmospheric heat transport and oceanic heat transport) and how this coupling differs between hemispheres. Our understanding of this coupling can be advanced through analyses of the temporal characteristics of events at higher frequencies than is commonly done in order to attribute the drivers of sea ice changes.

Our understanding of the causes of the overall increase in Antarctic sea ice (with regional cancellations) from 1979 through 2015 followed by substantial variability including record lows in recent years is another key knowledge gap. Recent work suggests that both atmospheric circulation and Southern Ocean freshening from Antarctic meltwater have played a role in long-term sea ice trends (Roach et al. 2023). Important questions were also raised about heat transport in the Southern Ocean, including on the processes that mix deep water upward or drive cross-shelf break transport. An unknown is the impact of vertical heat (and salinity) transport on sea ice and on polar amplification – how important is the deep ocean for sea ice in the Arctic and Antarctic? And how do atmosphere and ocean heat flux convergence interact and feedback on each other? Understanding the processes that cause variability in Arctic and Antarctic SIE would provide an important test of climate models.

A key sea ice knowledge gap concerned sea ice properties (thickness, snow cover, melt ponds, roughness) and how they influence the magnitude and time scale of the sea ice-atmosphere-ocean flux exchanges important for polar amplification. Additionally, the lack of understanding of sub-grid-scale sea ice processes, how they couple to the atmosphere and ocean, how this differs across the two hemispheres, and whether these processes impact sea ice sensitivity.

2.5 Non-local effects of polar amplification

Multiple teleconnection pathways exist for polar amplification to impact the global climate. In the atmosphere, the connections can be through circulation changes in response to meridional temperature gradients or through troposphere-stratosphere interactions, both at synoptic to sub-monthly timescales. Within the ocean-sea ice system, connections can be via turbulent air-sea exchanges of moisture and heat and seasonal and interannual timescale, basin-scale ocean gyre at decadal to overturning circulation at longer timescales (Liu and Alexander 2007).

The workshop highlighted that mechanistic understanding of teleconnection pathways requires synergistic observations and modeling efforts. Observation-based studies such as Kretschmer et al. (2016) support winter linkages between Arctic atmospheric anomalies and weather response at lower latitudes. Observations, however, are often sparse and insufficient to conclusively draw causality. Reanalyses suffer similar drawbacks as they rely on observations, in addition to difficulties in separating uncertain causal relations within these products from internal atmospheric variability. Forward modeling can be used to investigate linkages of, for example, (i) winter weakening of polar vortex on storm tracks and associated amplified stationary atmospheric planetary waves, which can lead to cold waves and floods at mid-latitudes in the winter, or (ii) summer Arctic warming on the shifted position of jet streams which can lead to heatwaves, droughts, and flood in the summertime (Cohen et al. 2020).

Models have large biases and results obtained from model intercomparison projects often show large spreads (Smith et al. 2022), leading to disagreement in even the sign between Arctic sea ice loss and remote responses. Due to these factors, there is low confidence in the predictive skill of the Arctic amplification impact on northern mid-latitude climate (Figure 2, IPCC AR6 WG1 Ch10).

In the Southern Ocean (SO), modeling results are even more uncertain, in general showing a positive trend (warming) in contrast to observed cooling (Smith et al. 2019). SO pacemaker experiments, where radiatively-forced response can be removed from historical simulations with perturbed SO cooling, show a general cooling response at most latitudes in response to SO-driven surface cooling (Zhang et al. 2021, Kang et al. 2023). In particular, the strong subtropical low-cloud feedback has been shown to lead to stronger tropical responses to SO-driven cooling (Kang et al. 2023; Kim et al. 2022). Simulated warming in the SO has also been shown to induce SST warming in the South Atlantic and tropical southeast Pacific (Zhang and Deser 2024), leading to low confidence in the SO's ongoing contribution to the projected evolution of tropical SSTs. To address this lack of knowledge in the teleconnection patterns, the session discussion suggested the expansion of SO pacemaker experiments to higher resolution ocean models and to atmospheric-ocean GCMs coupled to ice sheet models are critical to advance our understanding of the non-local effect of polar amplification.

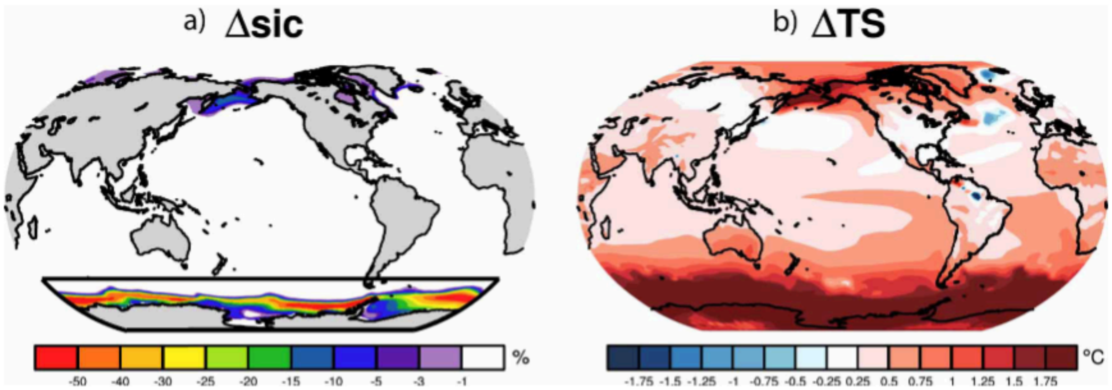

Figure 8. Annual mean response of (a) sea ice concentration (ΔSIC, %) and (b) surface temperature (ΔTS, °C) in response to perturbed Antarctic sea ice loss as shown in black-bordered box in (a). From England et al. 2020.

Despite observed near-surface atmospheric and associated SST cooling, a negative sea ice trend dominates (Zhang et al. 2021; Zhang and Deser 2024), with several record-breaking sea ice minima accompanied by observed ocean warming in the past decade (Purich et al. 2023). Given the role of the ocean, fully coupled atmosphere-ocean-sea ice models, not surprisingly, yield significantly stronger system dynamical response to projected Antarctic sea ice loss than uncoupled ones that use the ocean sea ice only as open boundaries (England et al. 2018; 2021). Cross-hemispheric responses include sea ice decline in the Bering Sea due to local surface temperature increase mediated by tropical warming (Figure 8, England et al. 2020). Overall, sea ice loss from the SO yields a significantly stronger tropical warming response than that from the Arctic (England et al. 2020). In addition, under several climate scenarios, the associated freshwater input from sea ice melt in the SO can give rise to a large range of local to global responses ranging from sea level rise, local atmospheric cooling, modified air-sea CO2 exchange, northward shifts of Southern hemisphere jet and ITCZ, reduced dense water formation and deep convection, as well as reduced Antarctic circum-current strength (Bronselaer et al. 2018; Swart et al. 2023).

The workshop highlighted ongoing work investigating the principal responses of polar amplification, using both complex coupled CMIP model types and idealized setups. For example, Kim et al. (2022) showed stronger responses of atmospheric energy transport and larger ITCZ latitude response when polar warming is imposed at a higher altitude. Extending this work, Chen (2024) used an idealized model set up to quantify dominant energy pathways and dynamics. Experiments with an imposed warming in the (A) summer and (B) winter in the atmospheric mixed layer show significant contrasts in local and non-local responses. Differences include higher local vertical extent of the warming in case (A) compared to surface-trapped of the forcing in (B), which triggers stronger atmospheric eddy responses and larger vertical eddy heat flux in (A) compared to a weaker atmospheric eddy response and decreased stability in (B), and subsequent higher anomalous eddy momentum flux divergence in the midlatitudes and convergence in the subtropics, leading to a weakened Hadley cell in (A). Researchers should extend these approaches to advance understanding of the non-local effects of polar amplification.

One of the challenges when using models to interpret and establish causal relations of Arctic amplification is to distinguish between plausible physical and artificial forcing and responses, with the latter arising due to various reasons, including imperfect forcing physics, model physics and systematic model errors (Screen et al. 2018; Hay et al. 2022; Audette and Kushner 2022; England et al. 2022; Fraser-Leach et al. 2023). The community has developed methods to identify and negate spurious amplifications, e.g., tropical/polar amplification tug-of-war, through adjusted physics (e.g., sea-ice forcing scaling, lapse rate scaling) and energy balance while highlighting the importance of certain terms, e.g., latent heat transport, in the energy budget (Fraser-Leach et al. 2023; Merlis and Henry 2018; Hay and Kushner 2024). These challenges indicate the need to further explore and understand these systematic model errors.

3 RECOMMENDATIONS AND NEXT STEPS

The workshop successfully brought together Arctic and Antarctic researchers with a range of disciplinary expertise, including sea ice, atmosphere, and ocean, and facilitated discussions of the most pressing issues confounding our attempts to reduce uncertainty in polar amplification projections. The discussion identified a number of key knowledge gaps, listed below. This list is not exhaustive but represents the sentiments expressed by workshop participants across the oral and poster presentations and plenary and breakout discussions.

Key knowledge gaps:

- The role of ocean heat transports and vertical mixing in polar amplification and sea ice variability
- Metrics and diagnostics for causal attribution of processes to polar amplification
- Ice processes in mixed-phase clouds (nucleation, secondary ice production, aerosol-cloud interactions)
- Effects of ocean mesoscale and sub-mesoscale processes on polar amplification and the representation of the mean state ocean circulation and sea ice properties
- The sensitivity of ocean-atmosphere exchanges to sea ice properties
- The influence of atmosphere-ocean interactions on sea ice variability and trends
- Quantification of the efficacy of ocean and atmosphere heat transports to sea ice melt and surface warming
- Mechanisms of remote impacts on and of polar change
- Influence of freshwater forcing on the Southern Ocean circulation and SSTs
- Precipitation and the role of snow in the polar systems
- The role of the land surface on polar amplification
- Contributions of internal variability vs. forced trends to Antarctic sea ice variability
- Understanding of the temporal and spatial nature of atmospheric heat transport and its influence on polar amplification

Common themes emerged and re-emerged during the plenary and breakout discussions. This is reflected in the session summaries presented in Sections 2.1-2.5. We also present several recommendations within three topic areas: enhanced observing systems, modeling advances and diagnostics, and community activities.

3.1 Enhanced observational capabilities

The need for enhanced observations is a common refrain from scientists. However, the need for enhanced observations in the polar regions is greater than almost anywhere else. The observational needs expressed at the workshop go beyond "more" and "new" and highlight the need for coordinated, statistically representative observations of sea ice, ocean, and atmospheric properties and their coupled processes.

Before describing the desired observational enhancements needed to expand our knowledge of the polar climate systems, it is important to acknowledge the extensive, unprecedented, and sustained suite of observations from spaceborne, airborne, and ground-based sensors collected over the last 40 years. ***These observations have undeniably expanded our understanding of polar amplification and have enabled the confirmation of fundamental aspects of polar amplification***: including, the central role of sea ice, the ubiquitous occurrence of mixed phase clouds, the characteristic surface-based warming profile, fall-winter warming maximum, and the role of seasonal energy transfers from summer to fall by the ocean heat storage. We now understand that polar amplification is a coupled sea ice-ocean-atmosphere phenomenon that operates across the seasonal cycle. Our current observing system has also enabled enhancements in our polar system modeling capabilities that together are inspiring new hypotheses, such as how atmospheric and oceanic energy transport are interacting with sea ice and driving polar amplification. Testing these hypotheses, based upon the understanding gained from our current polar observing system, serves as the justification for the specific observational enhancements described below.

Ocean observation enhancements were highlighted as a need for both the Arctic and Antarctic, as ocean heat transports and mean state ocean circulation biases in models were identified as key contributors to polar amplification uncertainty that are not well-quantified. Increasing the number and the depth of ARGO buoy measurements would provide valuable information on the vertical profiles of temperature, salinity, and currents to monitor ocean heat and salinity transport profiles in the Antarctic. An increased network of under-sea ice salinity measurements would enable new studies of the key interactions within the Southern Ocean-sea ice system and tracking of meltwater injection into the Southern Ocean from Antarctic Ice sheet melt. Enhanced monitoring of the vertical profile of ocean heat transport into and out of the Arctic could be accomplished by providing a greater density of the moorings above the ones currently monitoring transport through the Bering Strait, Fram Strait, and Barents Sea. Technological investments are needed to enable the development of systems to perform sustained, autonomous measurements in the harsh polar environments, specifically of atmosphere and ocean properties over and under sea ice.

Advancing our mechanistic understanding of polar amplification requires statistically representative measurements of the ocean-atmosphere-sea ice column from the ocean mixed layer through to at least the top of the atmospheric boundary layer (a.k.a. the air-sea transition zone) across the full range of conditions. These measurements include ocean temperature and salinity, sea ice thickness, snow cover, and roughness, atmospheric thermodynamic and cloud properties, and interfacial fluxes. Providing such a set of measurements requires a systematic observational strategy involving long-term field campaigns (e.g., annual or bi-annual "MOSAiC-like" and/or a near-permanent Arctic Supersite) alongside autonomous in situ (e.g., deployed buoys/sleds/UAV/AUV) and satellite measurements (e.g., high spectral resolution lidar to detect cloud phase and tenuous aerosol layers, satellite-based winds over sea ice, satellite-derived hyperspectral surface reflectance/albedo data). Long-term observations are necessary to provide context for the spatial variability of these exchanges and over many different sea ice parcels/floes to provide robust statistics.

Recommended actions:

- Increase the number and depth of ARGO buoy measurements in the Southern Ocean with the under-sea ice sampling capabilities;
- Enhance the density of the Arctic moored buoy network monitoring heat and salinity transport through the Bering Strait, Fram Strait, and Barents Sea;
- Invest in autonomous measurement technologies for over, on, and under sea ice measurements
- Invest in satellite mission concepts to enable robust, long-term sampling of clouds, aerosols, and surface properties in polar regions; and
- Establish a program or capability (e.g., Arctic supersite) to provide statistically representative measurements of the ocean-atmosphere-sea ice column from the ocean mixed layer to at least the top of the atmospheric boundary layer across the full range of observed conditions.

3.2 Modeling advances and diagnostics

Meltwater forcing of the ocean circulation from glaciers and ice sheets is an important mechanism influencing sea ice variability, the spatial pattern of temperature changes, especially in the Antarctic, and potentially polar amplification. However, current atmosphere-ocean global climate models do not include interactive ice sheet models. Thus, the potentially substantial impact of meltwater forcing on internal variability and the forced climate response is unrepresented in projections by contemporary climate models (e.g., CMIP6). Meltwater fluxes are also a critical part of understanding remote effects of Antarctic climate change. There is a strong need to accelerate the coupling of ice sheet models within AOGCMs and Earth System Models (ESMs).

A wide range of model diagnostics and approaches for assessing the importance of mechanisms to polar amplification are found in the literature. However, each approach has nuances and tells a different story. There is a strong need to develop an approach or a small subset of approaches (diagnostics together with modeling protocols) that can be agreed upon to accurately portray cause and effect. As no approach currently exists, the workshop organizing committee recommends establishing an international or US CLIVAR working group to reconcile the different perspectives by systematically applying existing analysis approaches to the same hierarchy of model experiments where the "right" answer is known. The working group would organize and perform the intercomparison of polar amplification diagnostics under idealized model experiments (e.g., using an anomalous ocean heat transport in a global climate model), and the impacts could be studied from the perspective of top-of-atmosphere feedback analysis, surface feedback analysis, and feedback locking/mechanism denial. The activity would isolate differences between diagnostic approaches and describe them, resulting in a peer-reviewed perspectives article on "best practices" in interpreting causal mechanisms of polar change and potentially leading to new diagnostic approaches that could be applied to models and observations consistently to diagnose causality and potentially enable emergent constraints.

A related and unique recommendation is the need for high-frequency model output. Atmospheric and ocean heat transports are important mechanisms to polar amplification. However, the high-frequency model output required to quantify the influence of atmospheric and ocean heat transports to polar amplification, and the inter-model spread is unavailable. High frequency model output for sea ice, atmosphere, and ocean state information is needed across a wide range of climate models.

Recommended actions:

- Accelerate the coupling of ice sheet models with AOGCMs and ESMs;
- Establish a US CLIVAR working group on polar change model diagnostics; and
- Promote the archival of high-frequency model output of sea ice, atmosphere, and ocean state fields.

3.3 Community events

Research cruises, expeditions, and field campaigns represent an invaluable source of data on the polar climate systems. In many cases, these campaigns are the only way to gather certain data. Each year there are one or more research cruises into the central Arctic to repair a "fallen" buoy or gather data on a particular science interest. Because each cruise is unique and funded by different entities, the data gathered by each cruise varies from year to year, so they can not establish a consistent climate record. To enhance the utility of the data collected from these research expeditions and advance our understanding of polar amplification, an internationally agreed upon set of "essential or standard variables" to be collected during any cruise regardless of the science focus is needed.

Recommended actions:

- Establish an agreed-upon set of "essential and standard" variables for polar research cruises; and
- Explore collaboration/partnership with the Tara Polar Station project.

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Appendix A: Organizers

Scientific Organizing Committee

Patrick C. Taylor, co-chair, NASA Langley Research Center
Nicole Feldl, co-chair, University of California, Santa Cruz
Kyle Armour, University of Washington
Lily Hahn, Scripps Institution of Oceanography
Sergio Sejas, ADNET/NASA Langley Research Center
Gijs de Boer, University of Colorado, NOAA Physical Sciences Laboratory
Marilyn Raphael, University of California Los Angeles
An Nguyen, University of Texas at Austin

Program Organizing Committee

Alyssa Johnson, US CLIVAR
Mike Patterson, US CLIVAR
Shelley Raburn, UCAR CPAESS

Appendix B: Participants

Kyle Armour	University of Washington
Julian Arnheim	University of California, Irvine
Alexandre Audette	University of California, Santa Cruz
Ian Baxter	University of California Santa Barbara
Chloe Boehm	Colorado State University
Linette Boisvert	NASA GSFC
Dave Bonan	California Institute of Technology
Subrahmanyam (Subra) Bulusu	University of South Carolina
Tim Carlsen	University of Oslo, Norway
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Xiaodan Chen	Fudan University
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Tri Datta	University of Colorado Boulder ATOC
Gijs de Boer	University of Colorado Boulder
Michelle De Luna	University of California, Los Angeles
Neel Desai	San Jose State University
Clara Deser	NCAR
Minghui Diao	San Jose State University
Aaron Donohoe	University of Washington
Alice DuVivier	NSF NCAR
Ian Eisenman	Scripps Institution of Oceanography, University of California, San Diego
Izuchukwu Ezukanma	University of Florida

Nicole Feldl	University of California, Santa Cruz
Luke Fraser-Leach	University of Toronto
Sky Gale	University of Washington
Laura Gemery	U.S. Geological Survey
Melissa Gervais	Pennsylvania State University
Ash Gilbert	University of Colorado-Boulder
Michael Gooseff	University of Colorado Boulder
Ruijian Gou	Ocean University of China
Ashok Gupta	University of California, Los Angeles
Lily Hahn	Scripps Institution of Oceanography
Dörthe Handorf	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research - Research Unit Potsdam
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Mairka Holland	National Center for Atmospheric Research
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Laura Landrum	NSF NCAR
Yu-Chi Lee	Department of Earth and Planetary Sciences, University of California Riverside

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Xia Li	Princeton University and NOAA GFDL
Qian Li	Massachusetts Institute of Technology
Yu-Chiao Liang	National Taiwan University
Olivia Linke	Leipzig University
Maofeng Liu	University of Miami
Wei Liu	University of California Riverside
Xinlong Liu	University of Tasmania
Weiming Ma	Pacific Northwest National Laboratory
Parvathi Madathil Kooloth	Pacific Northwest National Laboratory
Wieslaw Maslowski	Naval Postgraduate School
Kyle Mattingly	University of Wisconsin–Madison
Nicolas Michaelzyk	LOCEAN - IPSL
An Nguyen	The University of Texas at Austin
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Jay Pillai	University of Washington Department of Atmospheric Sciences
Lorenzo Polvani	Columbia University
Jonathon Preece	University of Georgia
Marilyn Raphael	University of California, Los Angeles
Lettie Roach	Columbia University and NASA GISS
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Brian Rose	University of Albany (SUNY)
Kevin Rozmiarek	University of Colorado Boulder INSTAAR
Svenja Ryan	Woods Hole Oceanographic Institution
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Lauren Wheeler	Sandia National Laboratories
Molly Wieringa	University of Washington
Gaopeng Xu	Texas A&M
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Xiyue (Sally) Zhang	University of Nevada, Reno
Chen Zhang	University of Colorado Boulder CIRES
Pengfei Zhang	Pennsylvania State University
Wenyu Zhou	PNNL
Jiang Zhu	NSF NCAR

Appendix C: Agenda

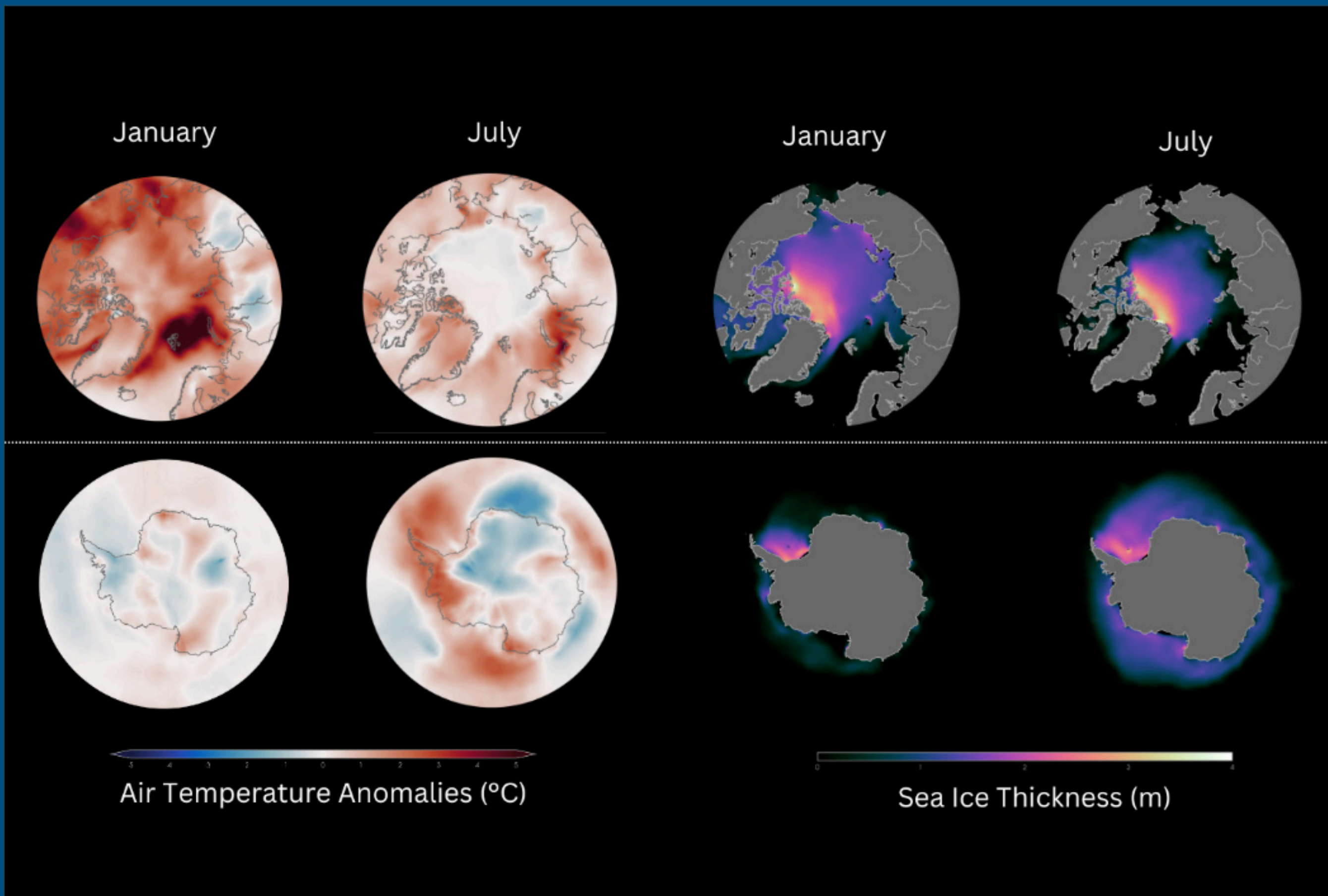
Wednesday, January 17, 2024		
Time (PST)	**Agenda**	**Presenter**
7:00 AM	Workshop registration and breakfast	
8:30 AM	Introduction	Patrick Taylor, (NASA Langley) and Nicole Feldl (UCSC)
8:45 AM	**Session 1: Observed and Projected Polar Amplification** Chairs: Patrick Taylor, Gijs de Boer	
8:45 AM	(Invited) A review of changes in the coupled Antarctic climate system in models and observations	Lettie Roach, Columbia University
9:15 AM	Comparing seasonal cycle and trend-based emergent constraints on future sea ice albedo feedback	Chad Thackeray, UCLA
9:30 AM	Steady but model-dependent polar amplification of the CO2-forced surface warming in CMIP6 projections	Stephanie Hay, University of Exeter
9:45 AM	Open discussion	
10:15 AM	Break	
10:45 AM	**Session 2: Causes of Polar Amplification Asymmetries** Chairs: Sergio Sejas, Lily Hahn	
10:45 AM	(Invited) Understanding seasonal asymmetry in Arctic climate change	Lily Hahn, University of Washington
11:15 AM	Sea ice loss, water vapor Increases, and their Interactions with atmospheric energy transport in driving seasonal polar amplification	Po-Chun Chung, UC Santa Cruz
11:30 AM	Sea ice sensitivity in the new Arctic	David Clemens-Sewall, NCAR
11:45 AM	Open discussion	

Wednesday, January 17, 2024 (continued)		
Time (PST)	**Agenda**	**Presenter**
12:15 PM	Lightning talks for virtual posters	
12:45 PM	Lunch	
1:45 PM	Poster session 1	
2:45 PM	Break	
3:00 PM	**Breakout Session 1: Causes of Polar Amplification Asymmetries**	
4:30 PM	End of day for virtual	
4:30 - 6:30 PM	Networking event	

Thursday, January 18, 2024		
Time (PST)	**Agenda**	**Presenter**
7:00 AM	Breakfast	
8:30 AM	Recap of Day 1 - each breakout group reports individually, 5 minutes each plus some quick comments	
9:00 AM	**Session 3: Role of Atmospheric and Oceanic Transport in Polar Amplification** Chairs: Nicole Feldl, Gijs de Boer	
9:00 AM	(Invited) The role of atmospheric and oceanic heat transport in polar* amplification: themes, thoughts, and opinions	Brian Rose, University of Albany
9:30 AM	More frequent atmospheric rivers slow the seasonal recovery of Arctic sea ice	Pengfei Zhang, The Pennsylvania State University
9:45 AM	Drivers of the increasing Pacific inflow to the Arctic through the Bering Strait: Insights from gravity and altimetry data, and possible reasons why models fail to simulate the increasing flow	Cecilia Peralta-Ferriz, Applied Physics Laboratory, University of Washington
10:00 AM	Open discussion	
10:30 AM	Break	
8:45 AM	**Session 4: Drivers of Observed Sea Ice Trends and Variability** Chairs: Marilyn Raphael, Kyle Armour	
10:45 AM	(Invited) Drivers of observed Antarctic sea ice trends and variability	Will Hobbs, University of Tasmania
12:00 PM	Seasonal and Decadal variability of Antarctic Sea Ice driven by the Southern Annular Mode	Qian Li, Massachusetts Institute of Technology

Thursday, January 18, 2024 (continued)		
Time (PST)	**Agenda**	**Presenter**
11:35 AM	Do changes in poleward atmospheric heat transport force or respond to polar amplification?	Aaron Donohoe, University of Washington
11:50 AM	Open discussion	
12:20 PM	Lightning talks for virtual poster	
12:45 PM	Lunch	
1:45 PM	Poster session 2	
2:45 PM	Break	
3:00 PM	**Breakout Session 2: Atmosphere and Ocean Heat Transport and Sea Ice**	
4:30 PM	End of day 2	

Friday, January 19, 2024		
Time (PST)	**Agenda**	**Presenter**
7:00 AM	Breakfast	
8:00 AM	Recap of Day 2	
8:30 AM	**Session 5: Non-local effects of Polar Amplification** Chairs: Kyle Armour, An Nguyen	
8:30 AM	(Invited) Non-local impacts of observed and projected high-latitude climate change	Sally Zhang, University of Nevada, Reno
9:00 AM	Role of Mean States on Atmospheric Responses to High-latitude thermal forcing and Arctic Warming	Yung-Jen Chen, National Taiwan University
9:15 AM	Correcting for artificial heat in sea ice perturbation experiments	Luke Fraser-Leach, University of Toronto
9:30 AM	Open discussion	
10:00 AM	Break	
10:30 AM	**Breakout session 3: Non-local effects of Polar Amplification**	
11:30 AM	Break	
11:45 AM	Breakout report-out	
12:10 PM	Conclusions and future steps	
12:30 PM	Workshop concludes	



usclivar.org/meetings/polar-amplification-workshop

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