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EDITORIAL

Focus on Arctic amplification

Karen L Smith[1,*], **Nicole Feldl**[2], **Rodrigo Caballero**[3] and **Patrick Keys**[4]

[1] University of Toronto Scarborough, Toronto, Canada
[2] University of California Santa Cruz, Santa Cruz, CA, United States of America
[3] Stockholm University, Stockholm, Sweden
[4] Boston University, Boston, MA, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: karen.smith@utoronto.ca

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Abstract

Anthropogenic climate change has a disproportionate effect on the Arctic, with the Arctic warming at approximately 2–4 times the rate of the global average, a phenomenon known as Arctic amplification. The greater rate of warming in the Arctic is not only having profound local effects on ecosystems and Indigenous and other communities in the far North, but may also be causing remote effects on weather and climate at lower latitudes. While much has been learned about the climate feedbacks that drive Arctic amplification in response to increasing atmospheric carbon dioxide concentrations, there remain outstanding questions about the evolution of and interactions between climate feedbacks, the relative roles of different climate forcings and feedbacks and local versus remote processes. This focus collection includes 17 articles which contribute novel research findings on (1) the mechanisms driving Arctic amplification with new insights into the time-dependent nature of Arctic amplification and feedback interactions, (2) Arctic amplification across a wide range of CO_2 and non-CO_2 forcings and (3) new approaches to assessing the climate response of amplified Arctic warming and the role of sea ice loss.

1. Introduction

The Arctic is undergoing rapid climate and environmental change. Recent observational estimates indicate that the Arctic has warmed at 2–4 times the rate of the global average depending on the time period and the southern boundary of the Arctic region considered (Rantanen *et al* 2022). This enhanced warming in the Arctic relative to the global average in response to increasing atmospheric greenhouse gas concentrations, a phenomenon known as Arctic amplification (Holland and Bitz 2003, Serreze and Barry 2011) was predicted by some of the first global climate models (Manabe and Richard 1975) and has emerged from internal variability in the late-twentieth century (Najafi *et al* 2015, England *et al* 2021). The Intergovernmental Panel on Climate Change Sixth Assessment Report concluded that Arctic amplification will continue to be a dominant pattern of warming throughout the twenty-first century (Forster *et al* 2021).

Although extensive research has shed light on the nature of the climate feedbacks and processes contributing to Arctic amplification (Pithan and Mauritsen 2014, Goosse *et al* 2018, Previdi *et al* 2021, Taylor *et al* 2022) questions remain as to the relative importance, separability, and state dependence of various feedbacks and drivers; the sensitivity of Arctic amplification to different radiative forcings; and the response of the global climate system to a warming Arctic, including how to accurately quantify the role of sea ice loss. This ERCL Focus on 'Arctic Amplification' collects seventeen articles that explore these questions and help to advance our understanding of the changing Arctic. Improved understanding of how the Arctic climate has and will continue to change in the future is vital to informing global climate and Earth System Model development and regional resilience planning (Moon *et al* 2024).

2. Projections of Arctic amplification

This collection presents novel and comprehensive analyses of future projections of Arctic amplification (hereafter AA) from the Coupled Model Intercomparison Project Phase 6 (CMIP6), the most recent international modeling activity. Taking advantage of the linear scaling of Arctic warming with global warming, Hay *et al* (2024) show that AA across the CMIP6 models is nearly independent of scenario and relatively steady over time, with a best estimate of end-of-century annual mean AA of approximately 2.5 (the ratio of Arctic to global surface air temperature change). Small scenario and seasonal dependence is evident for the low emissions (SSP1-2.6) and high emissions (SSP5-8.5) scenarios, consistent with previous studies (Ono *et al* 2022). While previous work has suggested that a decline in AA with warming in autumn is related to a weakening sea-ice albedo feedback (Holland and Landrum 2021, Taylor *et al* 2022, Davy and Griewank 2023, Wu *et al* 2023), Hay *et al* (2024) show that AA in autumn is uncorrelated with sea-ice loss, highlighting the need to more thoroughly investigate the roles of various feedbacks in the seasonal shifts in AA with warming. While model uncertainty is larger than scenario uncertainty for most of the 21st century, irreducible internal variability also contributes to uncertainty in projections of AA, especially when uncertainty is determined by 30 year trends.

Complementary to the study of Hay *et al* (2024), Linke *et al* (2023) also present best-estimates of future AA by leveraging observational constraints based on sea ice extent, concentration and seasonality in the present-day climate. Unlike previous work in the Southern Hemisphere (Bracegirdle *et al* 2015), Linke *et al* (2023) show that CMIP6 models with lower present-day sea ice extent and sea ice concentration enable greater future ice loss, Arctic warming and AA. The strong linear relationships between present-day sea ice metrics and AA result in an estimated 95% uncertainty range for 21st century AA of 2.47–3.34, consistent with Hay *et al* (2024).

Taken together these studies demonstrate that model uncertainty, rather than scenario uncertainty dominates the spread in projections of AA. They also demonstrate the use of an emergent constraint for narrowing the range of model uncertainty. These updated projections of AA will be key to informing the next IPCC report.

3. Mechanisms of Arctic amplification

While Linke *et al* (2023) focused on projections of annual mean AA, it is well-established that AA has a pronounced seasonality, with a maximum in AA in late autumn/early winter and a minimum in summer. Many previous studies have attributed this seasonality to the ice-insulation feedback: enhanced loss of sea ice in summer leads to greater absorption of short-wave radiation at the surface and a subsequent exchange of this additional heat from the surface to the atmosphere in the form of turbulent and long-wave heat fluxes in late fall/early winter (Screen and Simmonds 2010, Boeke and Taylor 2018, Feldl *et al* 2020). New analysis by Sejas and Taylor (2023) of the heating rates of different surface types (sea ice, ocean and land) in the Arctic highlights a new perspective on the processes driving temperature changes at the surface and the coupling with the overlying atmosphere. Their analysis of climate model output suggests that a slowing of the surface cooling rate in fall and an increase in the thermal inertia of the Arctic surface due to the loss and thinning of sea ice is the dominant mechanism driving the seasonality of AA, equivalent to the increased effective heat capacity mechanism of Hahn *et al* (2022). This surface signal is then coupled to the near-surface air via upward turbulent heat fluxes. Recent work has also identified differences in tropical versus Arctic thermal inertia as playing a key role in establishing AA following an abrupt increase in CO_2 concentration (Previdi and Polvani 2025).

Other research in this collection points to the fact that AA can establish itself on ultrafast timescales (<1 month), timescales over which the loss of sea ice is minimal. Using a large ensemble of instantaneous $4xCO_2$ climate model integrations, Janoski *et al* (2023) demonstrate that rapid AA primarily results from surface heat uptake due to different surface latent heat flux changes in the Arctic compared to the global average. This finding is consistent with the well-known rapid adjustment of the global hydrological cycle to an increase in atmospheric CO_2: a decrease in atmospheric radiative cooling is approximately balanced in the global mean by a decrease in latent heating from precipitation and, thus, a decrease in the upward surface latent heat flux (Allen and Ingram 2002, Bala *et al* 2010). On ultrafast timescales, the decrease in surface latent heat flux is much larger in the global average than the Arctic, quickly establishing AA.

While Janoski *et al* (2023) presents new insights into the transient evolution of AA, Bonan *et al* (2025), demonstrates a novel framework for assessing feedback interactions. Studies using the traditional feedback-forcing framework suggest that clouds do not contribute to AA in the CMIP5 and CMIP6 multi-model mean (Pithan and Mauritsen 2014, Hahn *et al* 2021). Bonan *et al* (2025) revisit the cloud locking experiments of Middlemas *et al* (2020) that contradict these findings and that show that the cloud feedbacks do contribute to AA. Using a new framework and cloud feedback locking model experiments, Bonan *et al* (2025) show that including the mid-latitude cloud feedback in a climate model does contribute to AA through quantifiable interactions with other feedbacks. These results contribute to the growing literature on the importance of feedback interactions (Middlemas *et al* 2020, Russotto and Biasutti 2020, Sledd and L'Ecuyer 2021, Beer and Eisenman 2022) and underscore the need for improved understanding of these interactions to better constrain model projections.

The predominance of the lapse rate feedback in attributions of AA (Pithan and Mauritsen 2014) has led to consternation because this feedback is calculated as a residual from the vertically uniform warming of the Planck feedback and, in the Arctic, cannot be tied to any one process. By illuminating the controls on the transient evolution of moist static energy in the Arctic, Miyawaki *et al* (2023) provide valuable insights on the Arctic temperature and water vapor feedbacks. Using the atmospheric energy budget, Miyawaki *et al* (2023) diagnose an Arctic energy balance regime transition with warming. Under present-day climate conditions, the Arctic is characterized by a balance between radiative cooling and advective heating, known as radiative–advective equilibrium (Cronin and Jansen 2016). By examining CMIP6 integrations following SSP5-8.5 out to the year 2200, Miyawaki *et al* (2023) show a clear wintertime regime transition from this two-way balance to a three-way balance, radiative-convective-advective equilibrium, in which radiative cooling and convective precipitation increase and moist advection decreases. Notably, the near-surface lapse rate weakens and approaches that of a moist adiabat. Sea-ice loss plays a key role in the time-dependent regime transition by enhancing radiative cooling and decreasing the moist static energy gradient via warming and moistening the atmosphere. Although, new research using reanalysis data in this collection shows an increase in Arctic atmospheric rivers and integrated water vapor transport into the Arctic in recent decades (Zhang *et al* 2023), Bintanja *et al* (2023) show a projected decrease in the fraction of wintertime precipitation associated with poleward moisture transport along preferred routes of atmospheric rivers in CMIP6 models, consistent with Miyawaki *et al* (2023).

Beyond the greater rate of warming, the Arctic is also projected to experience the largest relative change in precipitation in response to increasing atmospheric greenhouse gas concentrations (Pithan and Jung 2021). Bonan *et al* (2023) apply a similar atmospheric energy budget framework to examine individual feedback contributions to Arctic-amplified relative precipitation changes in the CMIP5 and CMIP6 models. The largest contributor is the Planck feedback, which is associated with atmospheric radiative cooling that is balanced by increases in latent heating from precipitation, followed by a decrease in the advection of dry static energy due to a weakened pole-to-equator temperature gradient. There is substantial compensation from the stabilizing positive lapse-rate feedback, however. As highlighted in Miyawaki *et al* (2023), additional warming can cause a transition to a radiative-convective-advective regime that will weaken this compensation and lead to enhanced convective precipitation in the Arctic.

The above studies reinforce that there is still much to learn about the processes determining Arctic-amplified warming and precipitation and that applying novel approaches to assess the transient evolution of and interactions between these processes provides valuable insights. Importantly, new findings on the time-dependent nature of AA suggest reassessing the utility of emergent constraints on AA (Linke *et al* 2023).

4. Sensitivity of Arctic amplification to climate forcings

Much of the research into the processes driving AA have analyzed instantaneous CO_2 doubling or quadrupling climate model experiments. These experiments provide equilibrated climate responses and do not involve model uncertainties associated with aerosol forcings. However, while extremely useful, these experiments may not capture the sensitivity of AA to a diversity of CO_2 and non-CO_2 forcings. In this collection, Zhou *et al* (2023) show that, over a wide range of atmospheric CO_2 concentrations (relative to preindustrial), AA is stronger when atmospheric CO_2 concentrations are decreased compared to when they are increased within a single climate model. The authors attribute these differences to a stronger lapse-rate feedback when CO_2 concentrations are decreased. Under increasing CO_2, the month of maximum warming shifts to later in the winter, consistent with the increased thermal inertia (Sejas and Taylor 2023). Complementary studies in this collection (Kay *et al* 2024) and elsewhere (Eisenman and Armour 2024) show that the southward expansion of the lapse-rate and sea-ice albedo feedbacks with sea ice growth contributes to greater AA when CO_2 concentrations are decreased. Notably, the timescales of AA emergence are slower for decreasing versus increasing CO_2 concentrations due to stronger vertical ocean mixing in the sub-polar regions and, therefore, slower southward sea ice growth, highlighting again the importance of examining the time dependence of AA to gain a deeper process understanding. The sensitivity of AA to varying CO_2 concentrations appears to differ from the relatively steady nature of AA over the 21st century across emissions scenarios described in Hay *et al* (2024). However, the magnitude of the CO_2 changes is considerably larger in Zhou *et al* (2023) and Kay *et al* (2024).

Moving beyond CO_2, Bushuk *et al* (2023) show that an increase in ozone-depleting substances (ODSs) in the late twentieth century has played a significant role in decreases of both Arctic sea ice extent and volume using single-forcing climate model experiments. These decreases represent approximately half and a third, respectively, of the impact of CO_2 alone over the same time period. This work augments earlier studies pointing to the outsized role that ODSs have on Arctic climate change (Polvani *et al* 2020, Liang *et al* 2022, Sigmond *et al* 2023).

Finally, recent work has highlighted that decreases in anthropogenic aerosol emissions from North America and Europe over the past several decades may also have contributed to AA (Yang *et al* 2014, England *et al* 2021). Using a suite of chemistry-climate model experiments in which different aerosol types in northern mid-latitude regions are reduced, Previdi *et al* (2023) confirm that almost all experiments exhibit AA. In these experiments, the dominant contributor to AA is poleward moisture transport (Merlis and Henry 2018, Graversen and Langen 2019, Krishnan *et al* 2020).

5. Climate response to AA and the role of sea ice loss

This focus collection not only consists of contributions addressing the processes, feedbacks and forcings driving to AA, but it also consists of contributions examining the climate response to AA (Barnes and Screen 2015). A comprehensive review by Hanna *et al* (2024) examines the potential influence of AA on mid-latitude blocking, the stratospheric polar vortex and associated cold-air outbreaks (CAOs). Although enhanced Arctic warming is associated with a reduction in the frequency and severity of CAOs (Russell and Fyfe 2024, Lo *et al* 2023, van Oldenborgh *et al* 2019), some studies have demonstrated dynamical linkages between Arctic warming and CAOs (Cohen *et al* 2021, Zheng *et al* 2022). Clarifying the role that Arctic warming has on CAOs is challenged by large internal variability, 'tugs-of-war' between the effects of high and low-latitude warming, observational and model uncertainties (Smith *et al* 2022, Blackport *et al* 2024) and differing modeling approaches. The review calls for the use of new dynamical frameworks and large ensembles of targeted climate model experiments.

As noted in Hanna *et al* (2024), the Polar Amplification Intercomparison Project, a coordinated international climate modeling activity, was established to overcome challenges associated with differing modeling approaches and to provide new insights into the response of the large-scale atmospheric circulation to polar sea ice loss (Smith *et al* 2019, 2022). The PAMIP experimental protocols aim to ensure that modeling groups perform similar and comparable experiments; however, recent work has identified spurious Arctic warming when sea ice is perturbed in coupled models following these protocols (England *et al* 2022), implying that the role of sea ice loss in global climate change may be overestimated in coupled climate model experiments. Two studies in this collection provide greater understanding of the cause of the spurious warming and how to address it.

Fraser-Leach *et al* (2023) expand on the work of England *et al* (2022) by applying a pattern scaling approach to both an energy balance model and a coupled climate model to correct for the spurious warming in PAMIP-style sea ice perturbation experiments. The corrections show that the spurious warming leads to an overestimation of the climate response to sea ice loss and may suggest artificially strong 'tugs-of-war' between low latitude warming and sea ice loss on the zonal mean wind response. Also in this collection, a follow-up study by England *et al* (2024) presents a new modeling approach to isolate the impact of sea ice loss on the climate system. Consistent with Fraser-Leach *et al* (2023), accounting for the spurious warming results in a weaker zonal mean wind response to sea ice loss. Together these two studies present different but complementary solutions for addressing the spurious warming—statistical post-processing in the case of Fraser-Leach *et al* (2023) and additional model simulations in the case of England *et al* (2024)—and will help to inform potential future PAMIP experimental protocols.

Finally, Sigmond and Sun (2024) highlight the challenge of model uncertainty in identifying a robust large-scale atmospheric circulation response to Arctic sea ice loss. By altering the basic state of the zonal mean winds within a single climate model, the 'stratospheric pathway' and associated negative North Atlantic Oscillation response to sea ice loss can be eliminated. These results support previous work on the sensitivity of the large-scale circulation response to sea ice loss to the basic state (Sun *et al* 2015, Smith *et al* 2017, Liang *et al* 2024) and also emphasize the need to reduce model biases in order to better constrain this response.

6. Future directions

This collection brings together a diversity of new research on Arctic climate change and emphasizes the need for novel methodological and modeling approaches to make progress. Notably, this collection provides new insights on the time-dependent nature of AA, the importance of interactions among feedbacks and the sensitivity of AA to different climate forcings. This collection also underscores the challenges of modeling the global climate response to AA.

While the traditional feedback-forcing framework has allowed for greater understanding of the mechanisms driving AA, the inability to diagnose interactions among feedbacks, which are not explicitly quantified using this framework, has limited progress. Feedback locking experiments, such as those in Bonan *et al* (2025) provide a new avenue for better quantifying interactions between feedbacks. Future research on AA will continue to exploit feedback locking techniques to better understand local and remote feedback interactions.

Furthermore, we anticipate that additional insights into the mechanisms driving the time-dependence of AA and its unique seasonality will be gained by exploring a wide range of climates across multiple Earth System Models (Zhou *et al* 2023, Eisenman and Armour 2024, Kay *et al* 2024). Such simulations will help to clarify the role of sea-ice loss in the seasonal shift in AA with warming (Holland and Landrum 2021, Wu *et al* 2023, Hay *et al* 2024) and reconcile the steady versus evolving nature of AA with warming in the observational record (Davy and Griewank 2023) and in models (Dai *et al* 2019, Ono *et al* 2022, Hay *et al* 2024).

Identifying remote influences of AA on mid-latitude weather and climate has been a very active area of research over the past decade, but such research has been challenged by large atmospheric internal variability (Hanna *et al* 2024) and, more recently, by coupled sea-ice perturbation modeling protocols that introduce spurious heating (England *et al* 2022). New approaches to address the latter will prompt a revisiting of previous work (Fraser-Leach *et al* 2023, England *et al* 2024), but also a re-imagining of modeling protocols to isolate the influence of AA. Although alternative protocols, such as regional CO_2 forcing simulations, suggest a small atmospheric circulation response to AA, studies adopting this protocol with a focus on AA are limited (Shaw and Tan 2018, Stuecker *et al* 2018, Semmler *et al* 2020).

While much is known about AA, model uncertainty and internal variability continue to be large (Cai *et al* 2021, Bonan *et al* 2023, Linke *et al* 2023, Hay *et al* 2024). Research efforts that focus on reducing model biases, in the Arctic, but also globally, will help to better constrain future projections of AA.

Author contributions

Karen L Smith 0000-0002-4652-6310
Project administration (lead), Writing – original draft (lead), Writing – review & editing (lead)

Nicole Feldl 0000-0002-2631-1419
Project administration (supporting), Writing – review & editing (supporting)

Rodrigo Caballero 0000-0002-5507-9209
Project administration (supporting), Writing – review & editing (supporting)

Patrick Keys 0000-0002-7250-1563
Project administration (supporting), Writing – review & editing (supporting)

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