PNAS COMMENTARY

Turning up the heat on asymmetries in lake ice phenology

Eric Post[a,1]

It may be tempting to regard ice cover as lifeless and inanimate, suggestive of winter dormancy and the seasonal period when biological activity is rendered largely quiescent. But, in reality, ice cover in both marine and lacustrine systems is a vital component of the Earth system, providing critical physical substrate for human transport, enjoyment of nature, and food acquisition related to traditional and nontraditional livelihoods (1–3). As well, many nonhuman animals depend on seasonal ice cover for travel, rest, offspring production, foraging and hunting, as well as refuge from predators (4–7). The physical properties of ice, such as its thickness and color, influence seasonal light penetration and reflectance, with important consequences for biological activity in the water column (5, 8). These properties also interact with the thermal environment to influence aspects of the phenology of ice cover such as the annual timing of its thinning, melting, and disappearance in spring and summer (5, 7, 9). The annual timing and duration of the seasonal ice-free period, and the physical characteristics of ice, interact to influence the composition and functioning of marine and freshwater communities and ecosystems,

Author affiliations: [a]Department of Wildlife, Fish, and Conservation Biology, University of California, Davis, CA 95616

Author contributions: E.P. wrote the paper.

The author declares no competing interest.

Copyright © 2026 the Author(s). Published by PNAS. This article is distributed under Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 (CC BY-NC-ND).

See companion article, "Rapid acceleration of ice-cover loss from Northern Hemisphere lakes above critical air temperature thresholds," 10.1073/pnas.2610752123.

[1]Email: post@ucdavis.edu.

Published September 14, 2026.

Fig. 1. Onset of spring ice break-up on an arctic lake, Aajuitsup Tasia, east of Kangerlussuaq, Greenland, in late May 2026. The study by Zhou et al. in this issue indicates far greater temperature sensitivity of ice break-up than of ice freeze-up processes, and suggests that far northern lakes may become the last refuge of seasonal lacustrine ice in the Northern Hemisphere as more southern lakes transition into partial or completely ice-free conditions with future warming.

regulating the timing of their ecological processes, species interactions, and taxonomic composition (8, 10, 11). And ice cover extent and seasonality can influence ecological and abiotic conditions in adjacent systems as well, including, in the case of sea ice, temperature, precipitation, and vegetation on land (7), and, in the case of ice melt and runoff from northern lakes, freshening and thermal properties of water in the Arctic Ocean (12). Ice cover dynamics in both marine and lacustrine environments have thus attracted considerable and growing attention in the context of climate change impacts to them and feedbacks from them through, for example, altered albedo effects (7, 9, 13–16). In a remarkably comprehensive assessment, Zhou et al. (17) add to such work and its context by highlighting important phenological asymmetries in lake ice phenology related to warming across the Northern Hemisphere (Fig. 1).

The analysis by Zhou et al. demonstrates that the timing of annual melt onset and ice-free conditions were markedly more sensitive to warming than were the timing of the onset of ice formation and complete ice-over.

The consequences of warming for the timing and duration of the annual ice-free period across the sample of 724 lakes included in the assessment by Zhou et al. largely bolster and expand the conclusions of previous assessments (14, 18): winter warming advances the timing of ice-off and extends the length of the annual ice-free period. What is noteworthy about Zhou et al.'s analysis, however, is what it reveals about the consequences of warming for two components of phenological asymmetry in lake ice phenology, the spatial and the temporal components. In the spatial realm, Zhou et al. identified a strong latitudinal gradient in the responsiveness of lake ice melt to warming. Lake ice phenology showed greater temperature sensitivity in mid-latitudinal zones than at higher latitudes. Consequently, more southern lakes in this sample appear poised to transition into dramatically altered states of seasonal ice dynamics with future warming than do northern lakes, raising the possibility of ice-free conditions on such lakes by the end of this century. Such a shift would, apparently, owe primarily to the temporal asymmetry of lake ice phenological responses to warming. The analysis by Zhou et al. demonstrates that the timing of annual melt onset and ice-free conditions were markedly more sensitive to warming than were the timing of the onset of ice formation and complete ice-over. This temporal component of the asymmetry of lake ice phenology points to increasingly early seasonal melt and ice-off as the primary drivers of extended annual ice-free periods with future warming. Even more noteworthy, however, were the threshold dependencies in these relationships. Warming beyond a mean winter temperature threshold of approximately −10 °C (± approximately 2 °C) resulted in dramatic increases in the sensitivities of the annual timing of initial ice melt and completely ice-free conditions, and of the annual duration of ice cover. Once this threshold is crossed, their analysis suggests, we can expect even stronger impacts of incremental warming on melt timing and ice-off compared to ice formation and freeze-over. Earlier and prolonged annual ice-free periods on Northern Hemisphere lakes can, in turn, be expected to exacerbate contributions of diminished albedo to atmospheric warming.

In ecological systems, thresholds in nonlinear phenomena such as, in Zhou et al., phenological dynamics, identify tipping points at which the relationship between a response variable, say timing of annual ice melt onset, and its driver, in this case mean winter temperature, abruptly changes (19). Thresholds in such dynamics may be easier to identify retrospectively, such as through the analyses presented by Zhou et al., than to forecast through simulation modeling, which must account for uncertainty about future conditions such as the rate and magnitude of expected warming and how these might vary with latitude in the Northern Hemisphere. Nonetheless, forecasting in nonlinear systems can be informative, especially in crisis disciplines that require timely and informed action (13). The Millennium Ecosystem Assessment Report forewarned two decades ago of the increasing likelihood of nonlinear and irreversible changes to natural systems resulting from anthropogenic stressors such as climate change (20). And the more recent Intergovernmental Platform on Biodiversity and Ecosystem Services Report noted that trends in nature, for systems including the cryosphere and inland surface waters and water bodies, reported by Indigenous Peoples and Local Communities were more strongly negative than positive (21). Meanwhile, the even more recent Sixth Assessment Report (6AR) of the Intergovernmental Panel on Climate Change highlights that, among impacts of climate change on physical, biological, and human and managed systems, those affecting lakes, rivers, and floods or drought were among the most widespread (22). Notably, the 6AR also cautions that the window of opportunity for implementing the widest array of climate resilient options is narrowing rapidly. The study by Zhou et al. is a powerfully demonstrative and compelling empirical integration of these forewarnings, observations, and projections in the context of lake ice phenology. It offers us yet another opportunity and, indeed, impetus, for meaningful climate action.

1. S. E. Hampton *et al.*, Environmental and societal consequences of winter ice loss from lakes. *Science* **386**, eadl3211 (2024).
2. L. B. Knoll *et al.*, Consequences of lake and river ice loss on cultural ecosystem services. *Limnol. Oceanogr. Lett.* **4**, 119–131 (2019).
3. R. Slats *et al.*, *An Indigenous Perspective for the 2019 Arctic Report Card*, M. L. Druckenmiller, R. Daniel, M. Johnson, Eds. (NOAA, Washington, DC, 2019).
4. A. W. F. Banfield, The role of ice in the distribution of mammals. *J. Mammal.* **35**, 104–107 (1954).
5. J. Culpepper *et al.*, Lake ice quality in a warming world. *Nat. Rev. Earth Environ.* **5**, 671–685 (2024).
6. G. A. Hood, D. L. Patriquin, Beavers on ice: Factors influencing emergence phenology in Boreal Canada. *Glob. Change Biol.* **32**, e70833 (2026).
7. U. S. Bhatt *et al.*, Implications of Arctic sea ice decline for the Earth system. *Annu. Rev. Environ. Resour.* **39**, 12.11–12.33 (2014).
8. S. E. Hampton *et al.*, Ecology under lake ice. *Ecol. Lett.* **20**, 98–111 (2017).
9. L. C. Brown, C. R. Duguay, The response and role of ice cover in lake-climate interactions. *Prog. Phys. Geogr. Earth Environ.* **34**, 671–704 (2010).
10. E. Post, Implications of earlier sea ice melt for phenological cascades in arctic marine food webs. *Food Webs* **13**, 60–66 (2017).
11. E. Cameron, M. Oliva, D. Antoniades, High Arctic lakes reveal accelerating ecological shifts linked to twenty-first century warming. *Sci. Rep.* **15**, 77 (2025).

12. H. Li, A. Fedorov, Persistent freshening of the Arctic Ocean and changes in the North Atlantic salinity caused by Arctic sea ice decline. *Clim. Dyn.* **57**, 2995–3013 (2021).
13. M. Macias-Fauria, E. Post, Effects of sea ice on Arctic biota: An emerging crisis discipline. *Biol. Lett.* **14**, 20170702 (2018).
14. L. Huang *et al.*, Emerging unprecedented lake ice loss in climate change projections. *Nat. Commun.* **13**, 5798 (2022).
15. H. Kashiwase, K. I. Ohshima, S. Nihashi, H. Eicken, Evidence for ice-ocean albedo feedback in the Arctic Ocean shifting to a seasonal ice zone. *Sci. Rep.* **7**, 8170 (2017).
16. F. Marcianesi, G. Aulicino, P. Wadhams, Arctic sea ice and snow cover albedo variability and trends during the last three decades. *Polar Sci.* **28**, 100617 (2021).
17. J. Zhou *et al.*, Rapid acceleration of ice-cover loss from Northern Hemisphere lakes above critical air temperature thresholds. *Proc. Natl. Acad. Sci. U.S.A.* **123**, e2610752123 (2026).
18. M. A. Imrit, S. Sharma, Climate change is contributing to faster rates of lake ice loss in lakes around the Northern Hemisphere. *J. Geophys. Res.-Biogeosci.* **126**, e2020JG006134 (2021).
19. H. Tong, *Threshold Models in Non-Linear Time Series Analysis* (Springer, New York, NY, 1983).
20. R. Hassan, R. Scholes, N. Ash, Eds., *Millennium Ecosystem Assessment: Ecosystems and Human Well-Being: Current State and Trends* (Island Press, Washington, DC, 2005).
21. IPBES, *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, E. S. Brondizio, J. Settele, S. Díaz, H. T. Ngo, Eds. (IPBES Secretariat, Bonn, Germany, 2019).
22. IPCC, "Climate change 2022: Impacts, adaptation, and vulnerability" in *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, UK, 2022).