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Despite a century of warming, increased snowfall has buffered the ice phenology of North America's largest high-elevation lake against climate change

Running head: Yellowstone Lake ice phenology

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Author contributions: LMT, GG, KC, AH, and PF organized the data set and performed exploratory analyses. IAO led the modeling with input from LMT, DLP, and SH. IAO, GG, and SH made the figures with input from LMT and DLP. IAO, DLP, and SH wrote the manuscript with input from LMT and all authors. All authors read and approved the article for submission.

Scientific significance statement:

Climate change is dramatically altering aquatic ecosystems. For lakes in cold climates, one of the most significant climate impacts is altered ice phenology–the timing and duration of ice cover during winter. Under climate change, most lakes are freezing later, melting out earlier, and experiencing a shorter duration of ice cover. Exceptions to this rule are particularly interesting as they shed light on the factors that promote lake resiliency against change. Using a 96-year record, we show that the ice phenology of Yellowstone Lake, North America's largest high-elevation lake, has not changed despite considerable warming in the region due to the buffering effect of increased snowfall. Yet, climate projections suggest that this buffering may soon fade with far-reaching implications for ecosystem function and biodiversity.

Data availability statement: All data sets and code used for this study are available on GitHub: https://github.com/bellaoleksy/NC_YSL_Ice_Phenology

Abstract:

Lakes are sentinels of environmental change. In cold climates, lake ice phenology–the timing and duration of ice cover during winter–is a key control on ecosystem function. Ice phenology is driven by a complex interplay between physical characteristics and climatic conditions. Under climate change, lakes are generally freezing later, melting out earlier, and experiencing a shorter duration of ice cover; however, few long-term records exist for large, high-elevation lakes which may be particularly susceptible to climate impacts. Here, we quantified ice phenology over the last century (1927-2022) for North America's largest high-elevation lake—Yellowstone Lake. We linked ice phenology to precipitation and temperature, and show that while air temperatures have risen, no change in the timing nor duration of ice cover has occurred due to buffering by increased snowfall. Our findings paired with climate projections suggest that Yellowstone Lake may be on the precipice of change with far-reaching implications.

Keywords: Yellowstone Lake, climate change, Greater Yellowstone Ecosystem, winter limnology

Introduction:

Lakes are sentinels of environmental change as they accumulate and reflect changes to local and regional watersheds through time (Adrian et al. 2009; Moser et al. 2019). Most lakes are located at temperate to arctic latitudes in the Northern Hemisphere (Verpoorter et al. 2014) and experience strong seasonal phenology as they annually transition from open water to a frozen surface. Ice phenology has been recorded on a wide range of lakes around the world and shifts in ice duration have become a hallmark of climate change impacts on lakes (Magnusson et al. 2000; Sharma et al. 2019). Generally, warming temperatures are leading to later ice-on and earlier ice-off dates, expanding ice-free periods (Lopez et al. 2019), and in some cases eliminating ice cover intermittently or entirely (Sharma et al. 2019). For instance, across spatially and morphologically distinct lakes in the Northern Hemisphere, ice-on is occurring on average 11.6 days later per century with ice-off shifting ahead by 8.1 days (Magnuson et al. 2000; Woolway et al. 2020). The duration of ice cover influences the timing and duration of stratification, which controls nutrient mixing and oxygenation in lakes, making it one of the most critical drivers of biological activity (Woolway et al. 2021). Thus, changes in ice phenology can have cascading implications extending from physical characteristics to food webs, and from microfauna to higher trophic levels.

Although ice duration is declining for most lakes due to climate change, substantial variation exists in ice phenology trends over space and time (Weyhenmeyer et al. 2011). Predicting changes in phenology remains challenging, particularly for lakes with unique characteristics (e.g., at exceptionally high elevation or extremely large in size). For instance, deeper lakes take longer to cool in fall and thus are more susceptible to intermittent ice cover (Woolway et al. 2020). Surface area also matters; larger fetch yields more wave action which can inhibit or delay ice formation (Magee and Wu 2017). High elevations, which show large gradients in weather over small distances (Mountain Research Initiative EDW Working Group 2015), are expected to be particularly susceptible to warming, although few long-term records of high elevation lake ice phenology exist. This complex interplay between environmental factors is further complicated by the importance of both temperature and precipitation to ice formation and persistence. While most regions of the globe are experiencing warming, changes in precipitation are more heterogeneous over small spatial scales with higher uncertainty in future projections (Lopez-Cantu et al. 2020).

In this study, we evaluated links between climate and ice phenology at Yellowstone Lake, North America’s largest lake above 2000 m. Yellowstone Lake is located in Yellowstone National Park, the centerpiece of the ~8-million hectare Greater Yellowstone Ecosystem (GYE). Since

1950, the GYE has experienced steady warming with temperatures rising by 1°C in the watershed that includes Yellowstone Lake (Upper Yellowstone; Hostetler et al. 2021). Elevations above 2100 m in the GYE are warming even faster with a rise of 1.4°C from 1980-2018 (Hostetler et al. 2021). Given the high-elevation of Yellowstone Lake paired with rapid contemporary warming, we expected strong shifts in ice phenology, with later ice formation and earlier break-up over time. To test this prediction, we addressed two questions: (1) Has ice phenology changed in Yellowstone Lake over the last century (1927-2022)? And, (2) how are climate factors linked to interannual variability and long-term trends in ice phenology? Surprisingly, we found no change in timing nor duration of ice cover at Yellowstone Lake over a 96-year record. For now, an increase in snowfall is buffering the lake's ice phenology against change. However, projections of how future temperature and precipitation regimes will shift above 2100 m in the Upper Yellowstone River watershed (i.e., Hostetler et al. 2021) suggest we are approaching an abrupt shift where snowfall will no longer buffer Yellowstone Lake against significant change to its seasonal ice cover. Collectively, our study highlights the power of long-term data for tracking environmental change and the value of such a long record for a high-elevation, montane lake.

Methods:

Study area

Yellowstone Lake is located at a moderate latitude (~44.5°N) in Yellowstone National Park in northwestern Wyoming, USA. With a surface area of 341 km^2, a maximum depth of 120 m, a volume of 14.9 km^3, and an elevation of 2,357 m, Yellowstone Lake is the largest high-elevation lake in western North America (Kaplinksi 1991). Yellowstone Lake mixes twice a year and has been typically ice-covered from late December through May (Gresswell & Varley 1988). Water chemistry of Yellowstone Lake is influenced by underlying geothermal activity, including hydrothermal vents in the northern regions of the lake (Anderson & Harmon 2002; Morgan et al.

2007). Surface water temperatures are 9-18°C during the ice-free season (Koel et al. 2019, 2020).

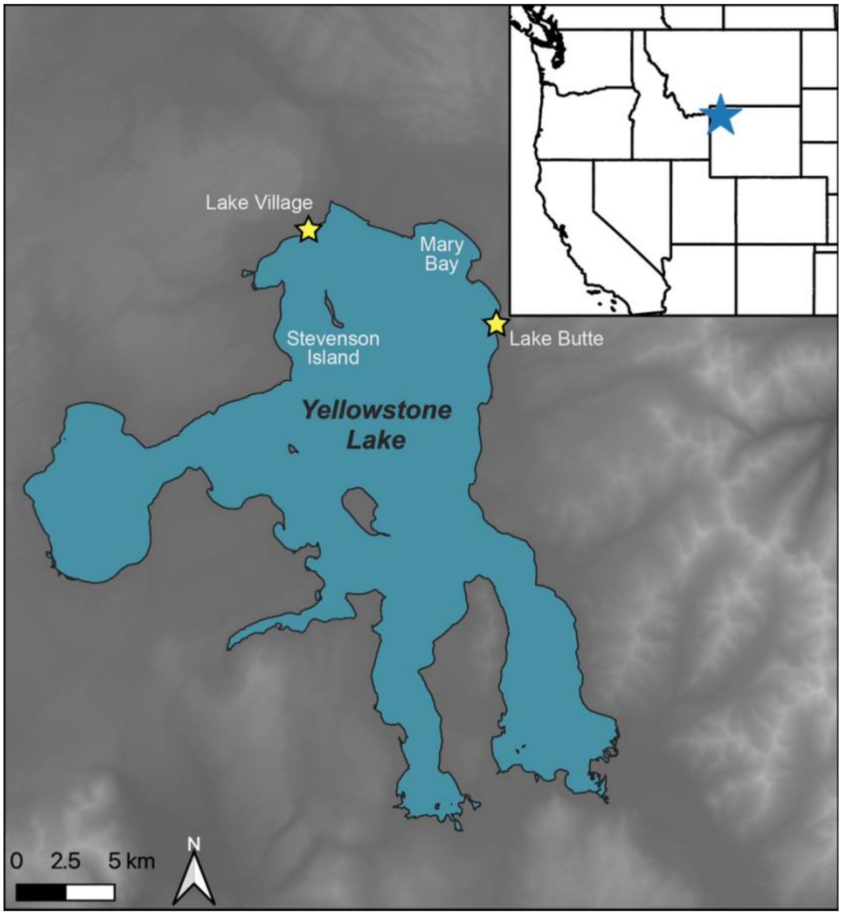

Figure 1. Map of Yellowstone Lake in northwestern Wyoming, USA, with yellow stars and labels indicating key landmarks where ice phenology was assessed. Inset map: Blue star indicating the location of Yellowstone Lake in the western United States.

Long-term data acquisition

The ice-off date for Yellowstone Lake has been recorded each year by Lake Village Ranger Station staff since 1927. The ice-on date has also been recorded since 1931. For this record, ice-on is defined as the date when ice cover is continuous across the northern section of the lake (i.e., from Mary Bay to Stevenson Island) when viewed from the Lake Butte overlook

(Figure 1). For ice-off, the opposite is true; it is the date each year when ice was no longer continuous from the same overlook. We compiled these records from a combination of sources including the Yellowstone National Park archives, Yellowstone National Park Resource Management, and staff records from ranger stations. We obtained corresponding climatic data for the same time period (1927-2022). Daily air temperatures (maximum and minimum) and precipitation were retrieved from the Water Resources Data Systems which is maintained by the State Climate Office at the University of Wyoming (http://www.wrds.uwyo.edu/) for the Yellowstone Lake weather station (#485345) at the Lake Village Ranger Station (Figure 1). From these data, we calculated annual and seasonal air temperatures. Daily precipitation amounts were converted into rainfall and snowfall based on an empirically derived snow probability function (Dai et al. 2008; see Supporting Information for details).

Data analysis

All statistical analyses and data visualizations were conducted in R version 4.2.1 (R Core Team 2022). We constructed time series models to test whether the timing of ice formation and breakup changed over a century and to investigate potential climatic drivers. We tested how weather conditions of the preceding months impacted ice phenology (ice-on, ice-off), such that only data prior to the mean date of ice-on or ice-off were included in models. For ice-on models, we considered summer (June-August) and fall (September-November) minimum, maximum, and cumulative mean daily air temperatures and precipitation totals (as rain or snow). For ice-off models, we considered spring (April-June) and winter (January-March) minimum, maximum, and cumulative air temperature and precipitation totals as well as the maximum observed snowpack depth of the preceding winter.

We modeled the drivers of ice-on and ice-off using generalized additive models (GAMs; Hastie & Tibshirani 1990; Wood et al. 2017) using a gamma family with a logistic link function via the mgcv package (version 1.8-40; Wood 2019). Model diagnostic checks indicated that we did not need to account for temporal autocorrelation in our models. For both ice-on and ice-off, we began with a “full” model that included all predictors and only used uncorrelated variables in models ($|r| < 0.7$; Table S1). We ultimately report the models that balance parsimony and deviance explained; many models performed similarly and are listed in Table S1 for comparison. Similarly, for all climatic variables, we analyzed the time series using GAMs to test for changes over time. For each time series, we additionally calculated the first derivatives in the GAMs time series to test for an acceleration or deceleration in the trend; a period was significant if the confidence intervals around the first derivative did not overlap with zero.

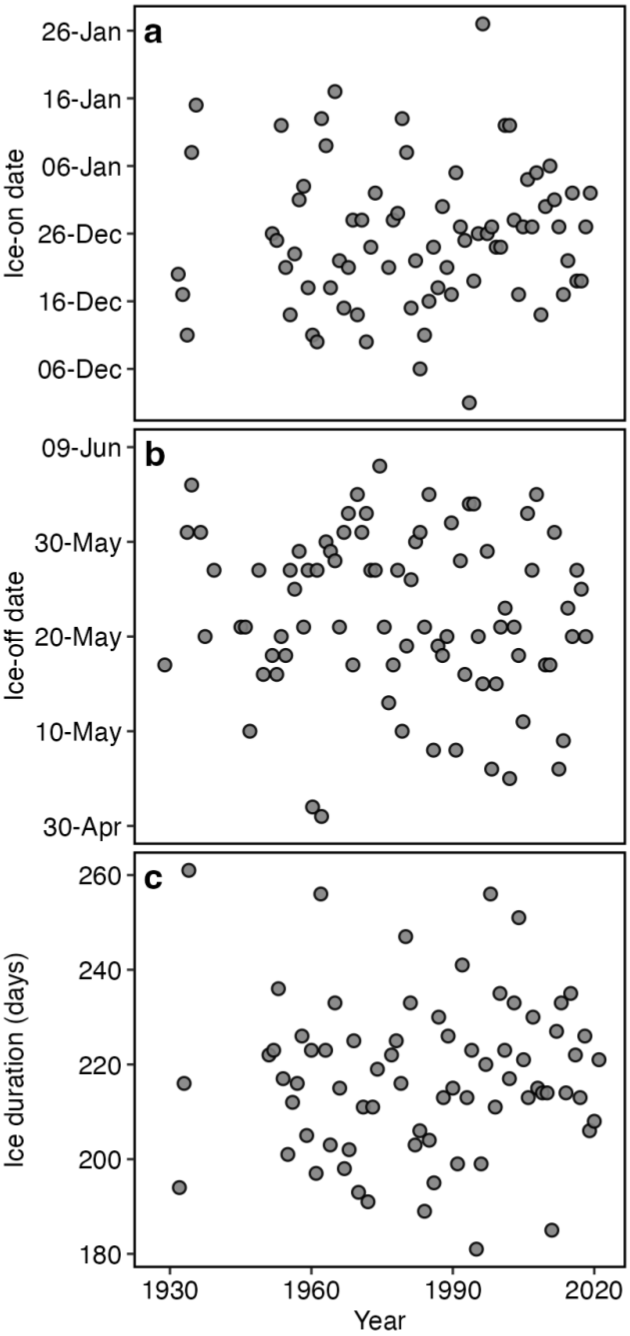

Figure 2. Raw annual data for the timing of (a) ice-on, (b) ice-off, and (c) ice duration at Yellowstone Lake from 1927-2022. Lack of trend lines indicate a lack of statistical significance at $P < 0.05$.

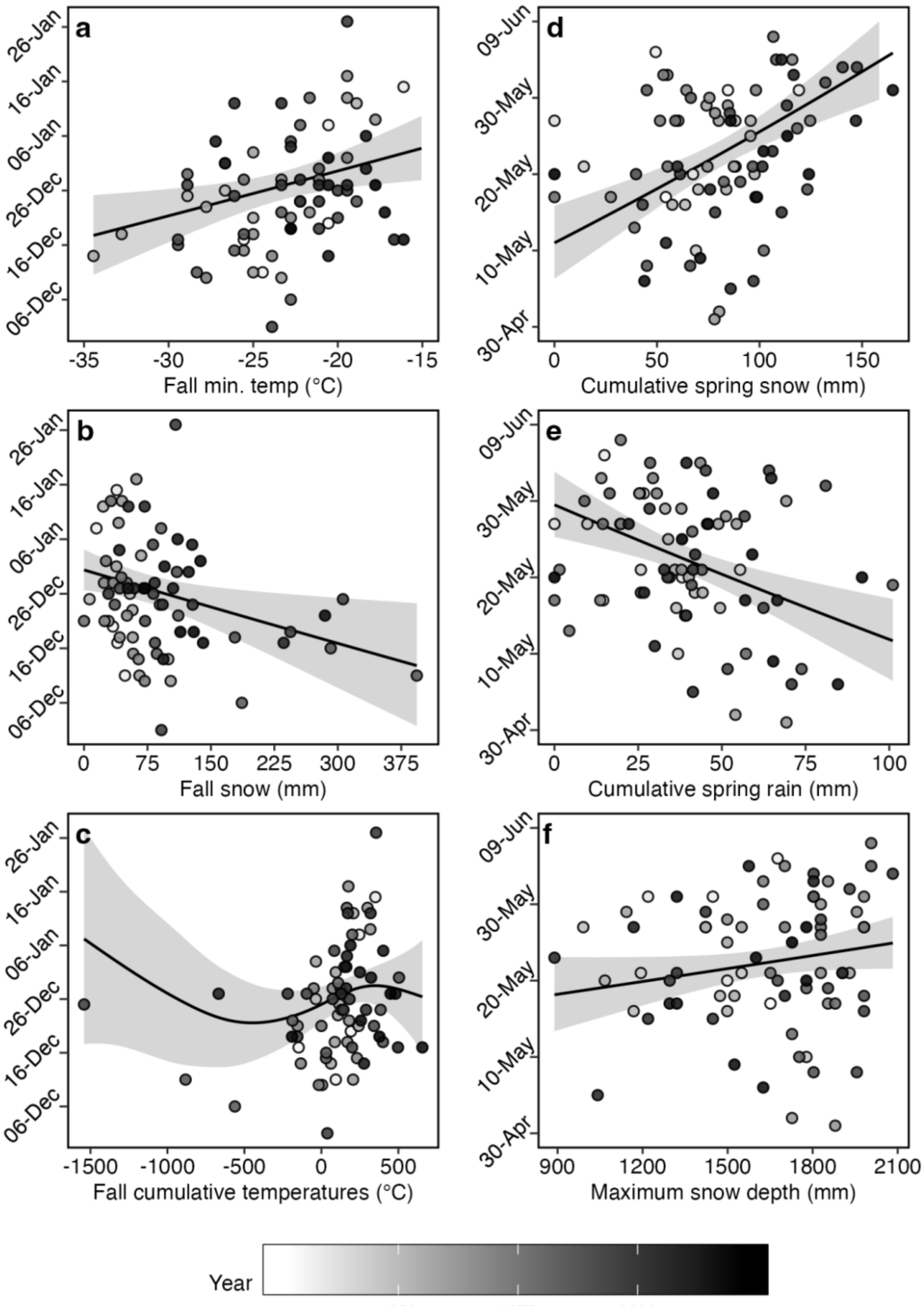

Figure 3. General Additive Model (GAM) results for the date of (a-c) ice-on and (d-f) ice-off. Ice-on date was best explained by (a) minimum fall air temperatures, (b) cumulative fall snow, and (c) cumulative fall air temperatures (deviance explained = 28.9%). Ice-off date was best explained by (d) cumulative spring

snowfall, (e) cumulative spring rain, and (f) maximum snow depth of the previous winter (deviance explained = 37.2%). For all panels, the points represent raw data, and the fitted curves are the predictions when holding all other predictors at their median value.

Results:

Our data set included 75 and 83 years of data for ice-on and ice-off, respectively, which translated to 21% and 13% missing data for each metric. For our study period, the average ice-on date for Yellowstone Lake was 25 December with the earliest ice-on occurring on 30 November and the latest on 26 January. We found no evidence for a shift in the timing of ice-on (edf = 1.001, F = 0.23, *P* = 0.633; Figure 2a). For ice-off, the average ice-off date was 22 May with the earliest break-up occurring on 28 April and the latest on 12 June. We found no evidence for a shift in the timing of ice-off (edf = 1, F = 0.008, *P* = 0.93; Figure 2b). The average ice duration was 217 days with a minimum of 181 and maximum of 261. Similarly, we found no evidence of changing ice duration over the period of record (edf = 1.041, F = 0.032, *P* = 0.987; Figure 2c).

The best-fit model for ice-on included minimum fall air temperatures, cumulative fall snow, and cumulative fall air temperatures (deviance explained = 28.9%; Figure 3a-c). Generally, later ice formation was associated with warmer minimum fall temperatures, early build-up of winter snowpack, and colder cumulative air temperatures. Ice-off date was best explained by cumulative spring snowfall, cumulative spring rain, and maximum snow depth of the previous winter (deviance explained = 37.2%; Figure 3d-f). Ice-off was positively correlated with cumulative spring snow and the maximum observed snow depth of the preceding winter, and negatively correlated with cumulative spring rain.

All of the top predictors of ice phenology show evidence of change over the period of record, although the strength and direction of those trends varied, and not all trends were linear (Figure 4). Indeed, minimum fall air temperatures have increased slightly since the mid-20th century (edf = 2.132, $P = 0.0676$; Figure 4a), with an acceleration in the trend from ~1996-2002. Cumulative fall snowfall has been increasing linearly since the 1930s (edf = 1.001, $P < 0.001$; Figure 4b) and cumulative fall temperatures have also increased more recently with an accelerating trend from ca. 2000-2011 which continues increasing to present day (edf = 2.051, P < 0.001). We observed pronounced changes in spring precipitation, with linear increases over the entire record in both cumulative snow (edf = 1.001, $P < 0.001$; Figure 4d) and rainfall (edf = 1.001, $P = 0.003$; Figure 4e). Finally, maximum winter snow depth displayed highly non-linear patterns (edf = 6.003, $P < 0.001$), with an accelerating trend between ca. 1950-1966, followed by relatively stable conditions, and a decelerating trend between ca. 1990-2003; since the early 2000s, there is evidence that maximum snow depth is again increasing (Figure 4f). For transparency, trends for all predictors that were assessed are included in the Supporting Information and organized by focal period: annual (Figure S1), winter (Figure S2), spring (Figure S3), summer (Figure S4), and fall (Figure S5).

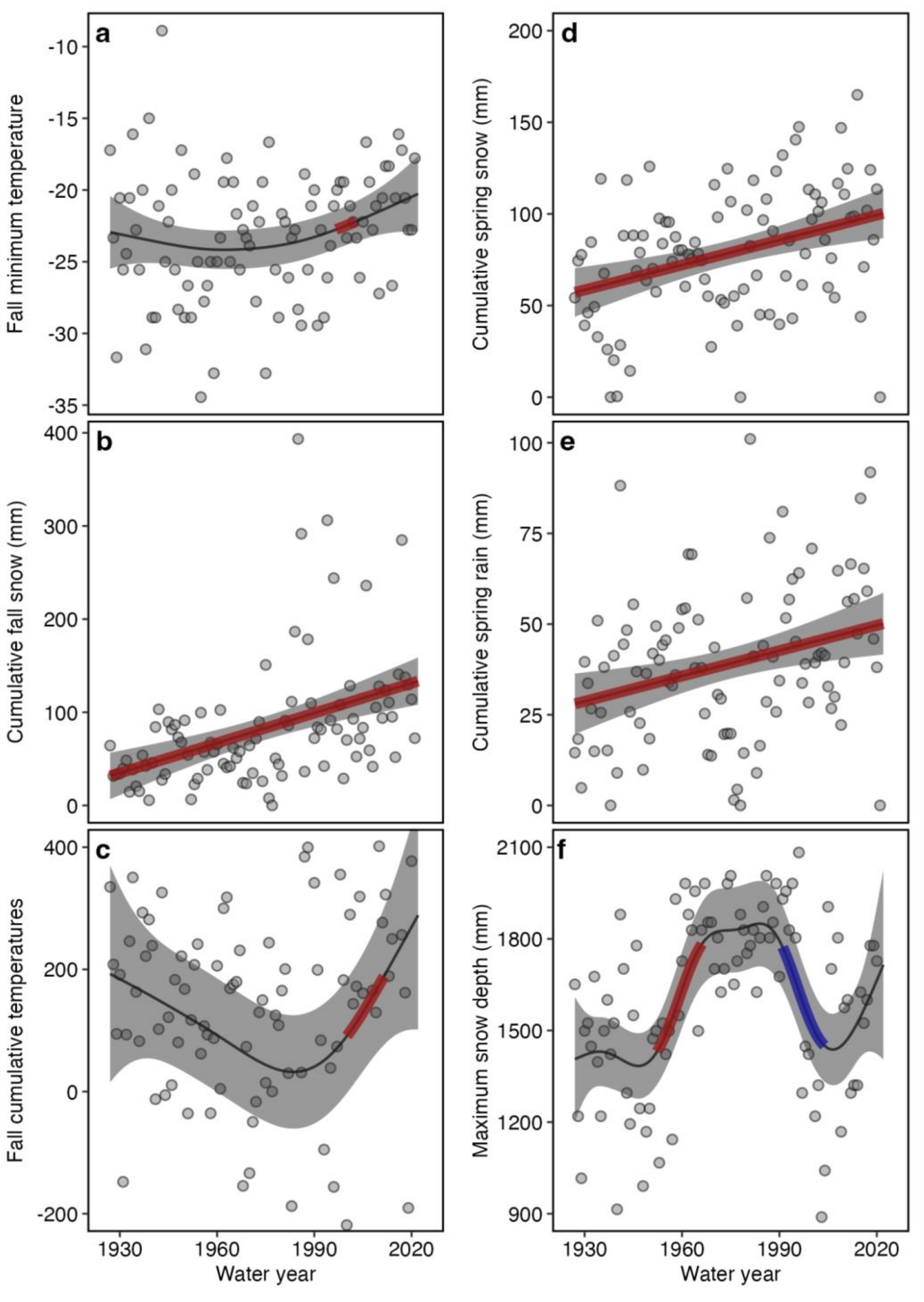

Figure 4. Time series of the top predictors of the date of (a-d) ice-on and (e-g) ice-off. Grey points are raw data and lines are fitted trends from generalized additive models (GAMs). Shading around trend-lines represents 95% confidence intervals. Red or blue lines indicate periods of a significant increase or decrease in the trend, respectively, as indicated by the first derivative of the GAMs.

Discussion:

Globally, most lakes are experiencing shifts in ice phenology due to climate change (Magnusson et al. 2000; Sharma et al. 2019). Exceptions to this trend are interesting as they can reveal factors that promote resilience in lake ecosystems against climate-induced shifts in ecosystem functioning. Here, using a 96-year record, we show that Yellowstone Lake has been remarkably resistant to changes in ice phenology despite long-term warming in the region. Shifts in local precipitation, especially increases in fall and spring snow, appear to be buffering the lake's ice phenological shifts against warming temperatures.

The lack of long-term directional change in ice phenology at Yellowstone Lake was unexpected given regional and local evidence for warming. Since 1950, annual temperatures have increased by 1°C throughout the Greater Yellowstone Ecosystem (Hostetler et al. 2021). These changes are particularly pronounced at the high elevation (above 2000 m) of Yellowstone Lake where air temperatures increased by 1.4°C in less than 40 years (1980-2018; Hostetler et al. 2021). Using local weather data, we found some evidence for increased summer, fall, and spring temperatures, primarily in the last three decades. Given the key role of air temperatures in driving ice formation and break-up (Kirillin et al. 2012), it is noteworthy that we did not find evidence for directional shifts in ice phenology in association with spring and fall temperature increases. One possible explanation is that fall minimum temperatures–which were important in predicting ice formation– are not rising as quickly as overall temperature trends in the region. A more likely explanation, however, likely lies in how precipitation regimes are concurrently changing at Yellowstone Lake.

Snow cover, particularly in spring, can delay ice break-up. Cumulative spring snow, which was strongly correlated with delayed ice-off dates, has nearly doubled over the last century at

Yellowstone Lake (Figure 4d). In general, precipitation has increased in spring and fall in the region. Conversely, snowfall has declined or been relatively stable at high elevations in the Upper Green River basin to the south (Hostetler et al. 2021). Ice-off timing of other high elevation lakes is strongly correlated with spring snowfall (e.g., Caldwell et al. 2021; Preston et al. 2016) and increased snowfall has been suggested as a primary cause in other lakes where ice phenology is not shifting with warming temperatures (e.g., Korhonen 2006; Ñoges & Ñoges 2013; Yao et al 2013). Our results further emphasize the importance of considering interactions between air temperature and precipitation patterns in predicting changes in ice phenology.

Looking ahead, our results paired with recent analyses of climate projections suggest a ‘tipping point’ may be coming soon when ice cover duration abruptly changes for Yellowstone Lake. This tipping point will largely stem from the ongoing shift from snow- to rain-dominated precipitation regimes in the fall and spring. Spring rainfall was strongly correlated with earlier ice-off dates and also showed an increasing temporal trend over the last century (Figure 4e). Increased spring rainfall has not yet caused a detectable long-term trend towards earlier ice break-up, potentially because of the counteracting effects of increased spring snow. As temperatures warm further, and fall and spring snowfall decreases, it is possible that ice phenology will rapidly change on Yellowstone Lake. Future temperature projections under an RCP4.5 scenario across all seasons suggest an increase of around 2.8°C by 2061-2080 for the Greater Yellowstone region (Hostetler et al. 2021). More concerning are projections under the same scenario for the dominant precipitation regime across elevations in the Upper Yellowstone watershed. At present, the elevation band that contains Yellowstone Lake (1800-2400m) sits between “snow-dominant” and “rain-snow mix.” By 2040, this is projected to shift firmly to “rain-snow mix” and trending towards “rain-dominated” (Hostetler et al. 2021).

If Yellowstone Lake experiences an abrupt shift in ice phenology, there may be wide-ranging consequences for nutrient cycling, lake productivity, fisheries, and recreation. Abrupt shifts in lake ecosystem functioning have increased in recent decades (Huang et al. 2022) and often result in significant consequences for cultural values and ecosystem services. Early warning signs of abrupt shifts in ecosystem functioning–e.g., increases in the variance of ecosystem properties–will be useful to monitor moving forward (Ratajczak et al. 2018). Yellowstone Lake, although relatively isolated, has a history of nonnative species introductions (e.g., lake trout) and may experience future change due to atmospheric nitrogen deposition (Nanus et al. 2017; Koel et al. 2019). Understanding ways in which multiple drivers interact will be critical in predicting future shifts in lake functioning and provisioning of ecosystem services for Yellowstone Lake and other large lakes globally.

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References:

Adrian, R., C.M. O'Reilly, H. Zagarese, S.B. Baines, D.O Hessen, W. Keller, D.M. Livingstone, R. Sommaruga, D. Straile, E. Van Donk, G.A. Weyhenmeyer and M. Winder. 2009. Lakes as sentinels of climate change. Limnol. Oceanogr. 54: 2283-2297, doi:10.4319/lo.2009.54.6_part_2.2283

Anderson, R. J., and D. Harmon. 2002. Yellowstone Lake: hotbed of chaos or reservoir of resilience. Proceedings of the 6th Biennial Scientific Conference on the Greater Yellowstone Ecosystem, 8-10.

Caldwell, T. J., S. Chandra, T.P. Albright, A.A. Harpold, T.E. Dilts, J.A. Greenberg, S. Sadro, and M.D. Dettinger. 2021. Drivers and projections of ice phenology in mountain lakes in the western United States. Limnol. Oceanogr. 66: 995–1008. doi:10.1002/lno.11656

Dai, A. 2008. Temperature and pressure dependence of the rain-snow phase transition over land and ocean. Geophys. Res. Lett. 35: L12802, doi:10.1029/2008GL033295

Gresswell, R. E., and J. D. Varley. 1988. Effects of a Century of Human Influence on the Cutthroat Trout of Yellowstone Lake, p. 45-51. In R.E. Gresswell [ed.], Status and Management of Interior Stocks of Cutthroat Trout.

Hastie, T., and R. Tibshirani. 1987. Generalized Additive Models, Cubic Splines and Personalized Likelihood. University of Toronto.

Hostetler, S., C. Whitlock, B. Shuman, D. Liefert, C.W. Drimal, and S. Bischke. 2021. Greater Yellowstone climate assessment: past, present, and future climate change in greater Yellowstone watersheds. Montana State University, Institute on Ecosystems.

Huang, S., K. Zhang, Q. Lin, J. Liu, and J. Shen. 2022. Abrupt ecological shifts of lakes during the Anthropocene. Earth. Sci. Rev. 227: 103981. doi:10.1016/j.earscirev.2022.103981

Kaplinksi, M. A. 1991. Geomorphology and Geology of Yellowstone Lake, Yellowstone National Park, Wyoming. Northern Arizona University.

Kirillin, G., M. Leppäranta, A. Terzhevik, N. Granin, J. Bernhardt, C. Engelhardt, T. Efremova, S. Golosov, N. Palshin, P. Sherstyankin, G. Zdorovennova, and R. Zdorovennov. 2012. Physics of seasonally ice-covered lakes: a review. Aquatic Sci. 74: 659-682. doi:10.1007/s00027-012-0279-y

Koel, T.M., L.M. Tronstad, J.L. Arnold, K.A. Gunther, D.W. Smith, J.M. Syslo, and P.J. White. 2019. Predatory Fish Invasion Induces within and across Ecosystem Effects in Yellowstone National Park. Sci. Adv. 5: 1–12. doi:10.1126/sciadv.aav1139.

Koel, T. M., J. L. Arnold, P. E. Bigelow, T. O. Brenden, J. D. Davis, C. R. Detjens, P. D. Doepke, B. D. Ertel, H. C. Glassic, R. E. Gresswell, C. S. Guy, D. J. MacDonald, M. E. Ruhl, T. J. Stuth, D. P. Sweet, J. M. Syslo, N. A. Thomas, L. M. Tronstad, P. J. White, and A. V. Zale. 2020. Yellowstone Lake ecosystem restoration: A case study for invasive fish management. Fishes. 5:18. doi:10.3390/fishes5020018

Korhonen, J. 2006. Long-Term Changes in like Ice Cover in Finland. Nordic Hydrology. 37: 347–63. doi:10.2166/nh.2006.019

Lopez, L.S., B.A. Hewitt, and S. Sharma. 2019. Reaching a Breaking Point: How Is Climate Change Influencing the Timing of Ice Breakup in Lakes across the Northern Hemisphere? Limnol. Oceanogr. 6: 2621–31. doi:10.1002/lno.11239

Lopez-Cantu, T., A.F. Prein, and C. Samaras. 2020. Uncertainties in future US extreme precipitation from downscaled climate projections. Geophys. Res. Let. 47: e2019GL086797. doi:10.1029/2019GL086797

Magee, M.R., and C.H. Wu. 2017. Effects of Changing Climate on Ice Cover in Three Morphometrically Different Lakes. Hydrol. Proc. 31: 308–23. doi:10.1002/hyp.10996

Magnuson, J.J., D.M. Robertson, B.J. Benson, R.H. Wynne, D.M. Livingstone, T.Arai, R.A. Assel, et al. 2000. Historical Trends in Lake and River Ice Cover in the Northern Hemisphere. Science. 289: 1743–46. doi:10.1126/science.289.5485.1743

Morgan, L. A., W.C. Shanks III, K.L. Pierce, D.A. Lovalvo, G.K. Lee, M.W. Webring, W.J. Stephenson, S.Y. Johnson, S.S. Harlan, B. Schulze, and C.A. Finn. 2007. The floor of Yellowstone Lake is anything but quiet—New discoveries from high-resolution sonar imaging, seismic-reflection profiling, and submersible studies, p. 95-123. In L.A. Morgan

[Ed.] Integrated Geoscience Studies in the Greater Yellowstone Area—Volcanic, Tectonic, and Hydrothermal Processes in the Yellowstone Geoecosystem.

Moser, K. A., J.S. Baron, J. Brahney, I.A. Oleksy, J.E. Saros, E.J Hundey, S. Sadro, J. Kopáček, R. Sommaruga, M.J. Kainz, A.L. Strecker, S. Chandra, D.M. Walters, D.L. Preston, N. Michelutti, F. Lepori, S.A. Spaulding, K.R. Christianson, J.M. Melack, and J.P. Smol. 2019. Mountain lakes: Eyes on global environmental change. Global. Planet. Change. 178: 77-95. doi:10.1016/j.gloplacha.2019.04.001

Nanus, L., J.A. McMurray, D.W. Clow, J.E. Saros, T. Blett and J.J. Gurdak. 2017. Spatial variation of atmospheric nitrogen deposition and critical loads for aquatic ecosystems in the Greater Yellowstone Area. Environ. Pollut. 223: 644-656. doi:10.1016/j.envpol.2017.01.077

Nõges, P. and T. Nõges. 2014. Weak Trends in Ice Phenology of Estonian Large Lakes despite Significant Warming Trends. Hydrobiol. 731: 5–18. doi:10.1007/s10750-013-1572-z.

Mountain Research Initiative EDW Working Group. 2015. Elevation-dependent warming in mountain regions of the world. Nature Clim. Change. 5: 424-430. doi:10.1038/nclimate2563

Preston, D.L., N. Caine, D.M. McKnight, M.W. Williams, K. Hell, M.P. Miller, S.J. Hart, and P. Johnson. 2016. Climate Regulates Alpine Lake Ice Cover Phenology and Aquatic Ecosystem Structure. Geophys. Res. Lett. 43: 5353–60. doi:10.1002/2016GL069036.

R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ratajczak, Z., S.R. Carpenter, A.R. Ives, C.J. Kucharik, T. Ramiadantsoa, M.A. Stegner, J.W. Williams, J. Zhang, and M.G. Turner. 2018. Abrupt change in ecological systems: inference and diagnosis. Trends Ecol. Evol. 33, 513-526. doi:10.1016/j.tree.2018.04.013

Sharma, S., K. Blagrave, J.J. Magnuson, C.M. O'Reilly, S. Oliver, R.D. Batt, M.R. Magee, et al. 2019. Widespread Loss of Lake Ice around the Northern Hemisphere in a Warming World. *Nature Clim. Change* 9: 227–31. doi:10.1038/s41558-018-0393-5

Verpoorter, C., T. Kutser, D.A. Seekell, and L.J. Tranvik, 2014. A global inventory of lakes based on high-resolution satellite imagery. Geophys. Res. Lett. 41: 6396-6402. doi:10.1002/2014GL060641

Weyhenmeyer, G. A., D.M. Livingstone, M. Meili, O. Jensen, B. Benson, and J.J. Magnuson. 2011. Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes. Glob. Change Biol. 17: 268-275. doi:10.1111/j.1365-2486.2010.02249.x

Wood, S.N. 2017. Generalized Additive Models, 2nd ed. New York: Chapman and Hall.

Wood, S.N. 2019. *mgcv: Mixed GAM Computation Vehicle with Automatic Smoothness Estimation* (1.8-31).

Woolway, R. Iestyn, B.M. Kraemer, J.D. Lenters, C.J. Merchant, C.M. O'Reilly, and S. Sharma. 2020. Global Lake Responses to Climate Change. Nat. Rev. Earth Environ. 1: 388–403. doi:10.1038/s43017-020-0067-5

Woolway, R. I., S. Sharma, G.A. Weyhenmeyer, A. Debolskiy, M. Golub, D. Mercado-Bettín, M Perroud, V. Stepanenko, Z. Tan, L. Grant, R. Ladwig, J. Mesman, T.N. Moore, T. Shatwell, I. Vanderkelen, J.A. Austin, C.L. DeGasperi, M. Dokulil, S.L. Fuente, E.B. Mackay, S.G. Schladow, S. Watanabe, R. Marcé, D.C. Pierson, W. Thiery, and E. Jennings. 2021. Phenological shifts in lake stratification under climate change. Nat. Commun. 12: 2318. doi:10.1038/s41467-021-22657-4

Supporting Information:

Despite a century of warming, increased snowfall has buffered ice phenology of North America's largest high-elevation lake against climate change

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Methods:

Estimating Daily Rainfall and Snowfall

We converted the daily precipitation values into snowfall and/or rainfall amounts using a function that generates proportions of snow and rain based on air temperature (Dai *et al*., 2008). The daily mean temperature was calculated as the mean of the maximum and minimum temperatures on each day. When the mean daily temperature is near the threshold at which precipitation changes from snow to rain, it is likely that both types of precipitation fell within the same 24 hr period for which daily precipitation was measured. Following Dai *et al.,* (2008), we used the function:

$$\text{Snow Probability} = -50 * [\tanh(0.4 *(\text{ Mean Temp} - 1.75))] - 1$$

We parameterized the function to have a threshold temperature of 1.75°C (when precipitation is 50% rain and 50% snow) and a slope of 0.4, which is consistent with empirically observed values at high altitudes (Dai *et al*., 2008). We applied the function over all of the daily temperature and precipitation values. We then multiplied the resulting daily snow probabilities by the total daily precipitation to calculate daily snowfall, and used 1 minus the snow probability to calculate daily rainfall.

References:

Dai, A. 2008. Temperature and pressure dependence of the rain-snow phase transition over land and ocean. Geophys. Res. Lett. 35: L12802, doi:10.1029/2008GL033295

Tables:

Table S1. Summary of all GAMs built in the analysis (four models for ice-on and five for ice-off). In the main text, we focus our model interpretation on the model that minimized AIC, maximized deviance explained (% Dev.), and was the most parsimonious.

rank	y	term	edf	ref.df	F statistic	p	% Dev.	logLik	AIC
Ice-on									
1	iceOn	s(FallMin)	1	1	6.87	0.011	0.289	-262	540
		s(FallSnow)	1	1	6.39	0.014			
		s(FallTempSum)	2.89	3.62	1.19	0.235			
2	iceOn	s(FallMin)	1	1	10.2	0.002	0.207	-266	540
		s(FallSnow)	1	1	7.24	0.009			
3	iceOn	s(FallMin)	1	1	6.84	0.011	0.287	-262	542
		s(FallMax)	1	1	0.371	0.545			
		s(FallSnow)	1.13	1.24	4.75	0.019			
		s(FallTempSum)	2.63	3.31	0.975	0.339			
4	iceOn	s(FallMin)	1	1	7.28	0.009	0.284	-263	544
		s(FallMax)	1	1	0.681	0.412			
		s(FallRain)	1	1	0.492	0.486			
		s(FallSnow)	1.18	1.33	2.33	0.087			
		s(FallTempSum)	2.36	2.97	0.864	0.409			
Ice-off									
1	iceOff	s(SnowDepth)	1	1	3.29	0.074	0.372	-266	546
		s(SpringRain)	1	1	15.4	0			
		s(SpringSnow)	1	1	26.3	0			
		s(WinterMin)	1	1	2.37	0.128			
		s(SpringMax)	1	1	1.04	0.312			
2	iceOff	s(WinterSnow)	1.58	1.97	1.6	0.242	0.416	-263	547
		s(SnowDepth)	1	1	4.03	0.049			
		s(SpringSnow)	1	1	24.9	0			
		s(SpringRain)	1	1	17.5	0			
		s(WinterMin)	1	1	4.43	0.039			
		s(SpringMin)	1	1	2.03	0.159			
		s(SpringMax)	1	1	0.999	0.321			
3	iceOff	s(WinterSnow)	1.71	2.17	1.34	0.307	0.402	-264	547
		s(SnowDepth)	1	1	3.29	0.074			
		s(SpringRain)	1	1	15.2	0			
		s(SpringSnow)	1	1	23.8	0			
		s(WinterMin)	1	1	2.73	0.103			
		s(SpringMax)	1	1	1.1	0.297			
4	iceOff	s(SnowDepth)	1	1	3.11	0.082	0.346	-274	560
		s(SpringRain)	1	1	16.8	0			
		s(SpringSnow)	1.06	1.12	24.1	0			
		s(WinterMin)	1	1	2.57	0.113			
5	iceOff	s(SnowDepth)	1	1	4.12	0.046	0.323	-275	560
		s(SpringRain)	1	1	19.8	0			
		s(SpringSnow)	1	1	26.9	0			

Figures:

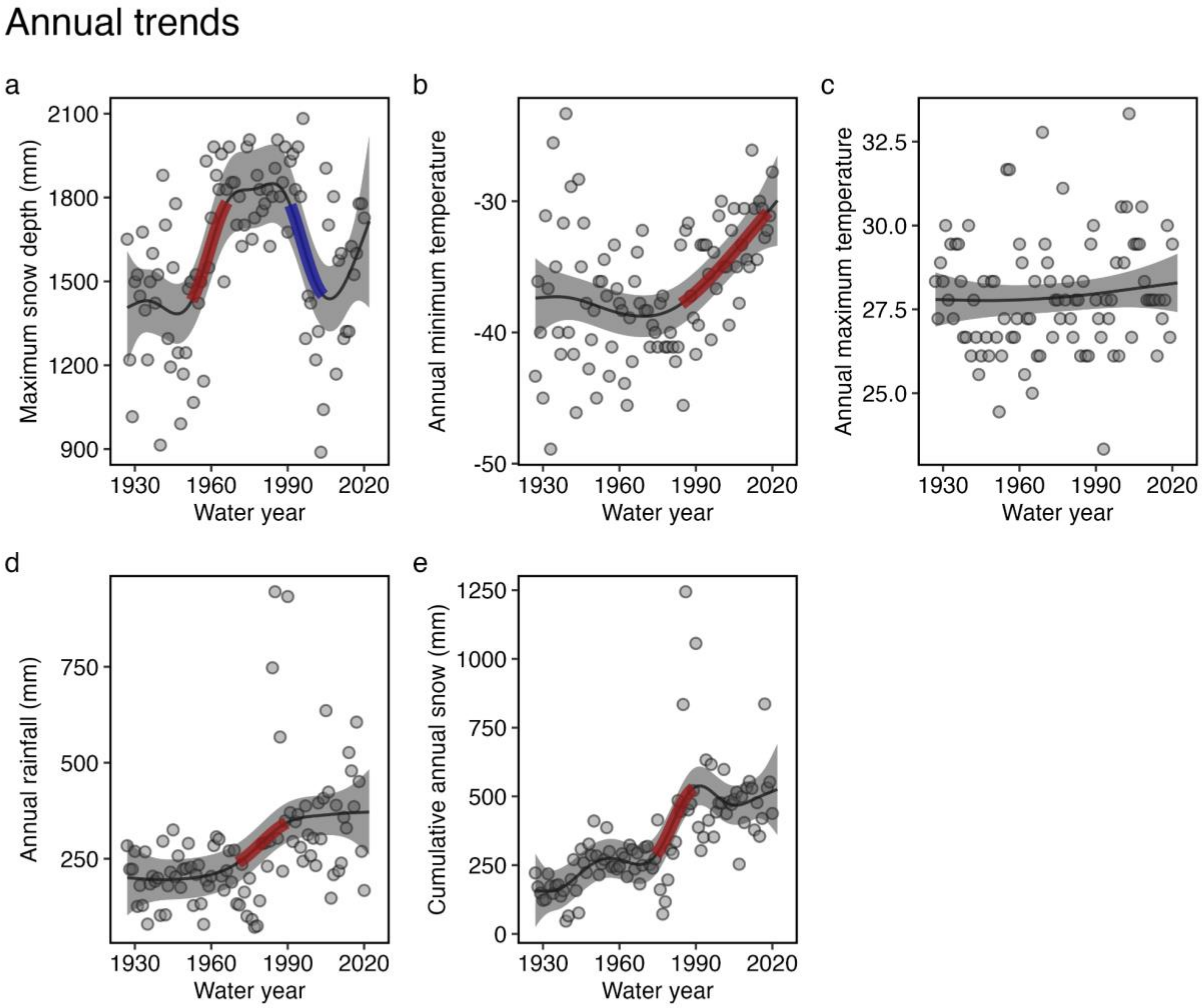

Figure S1. GAMs timeseries for annual climatic trends. Red or blue lines indicate periods of a significant increase or decrease in the trend as indicated by the first derivative of the GAMs.

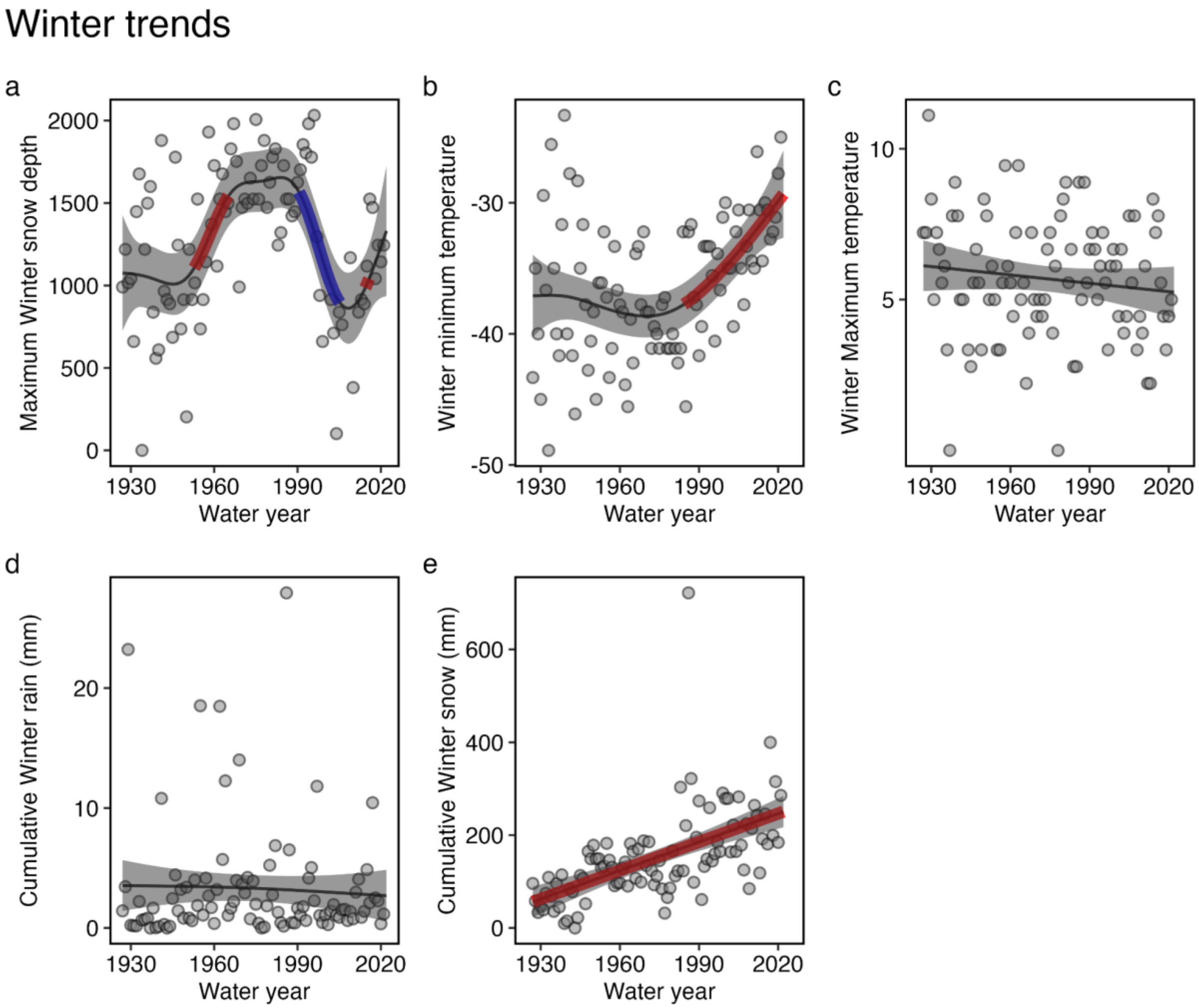

Figure S2. GAMs timeseries for winter climatic trends. Red or blue lines indicate periods of a significant increase or decrease in the trend as indicated by the first derivative of the GAMs.

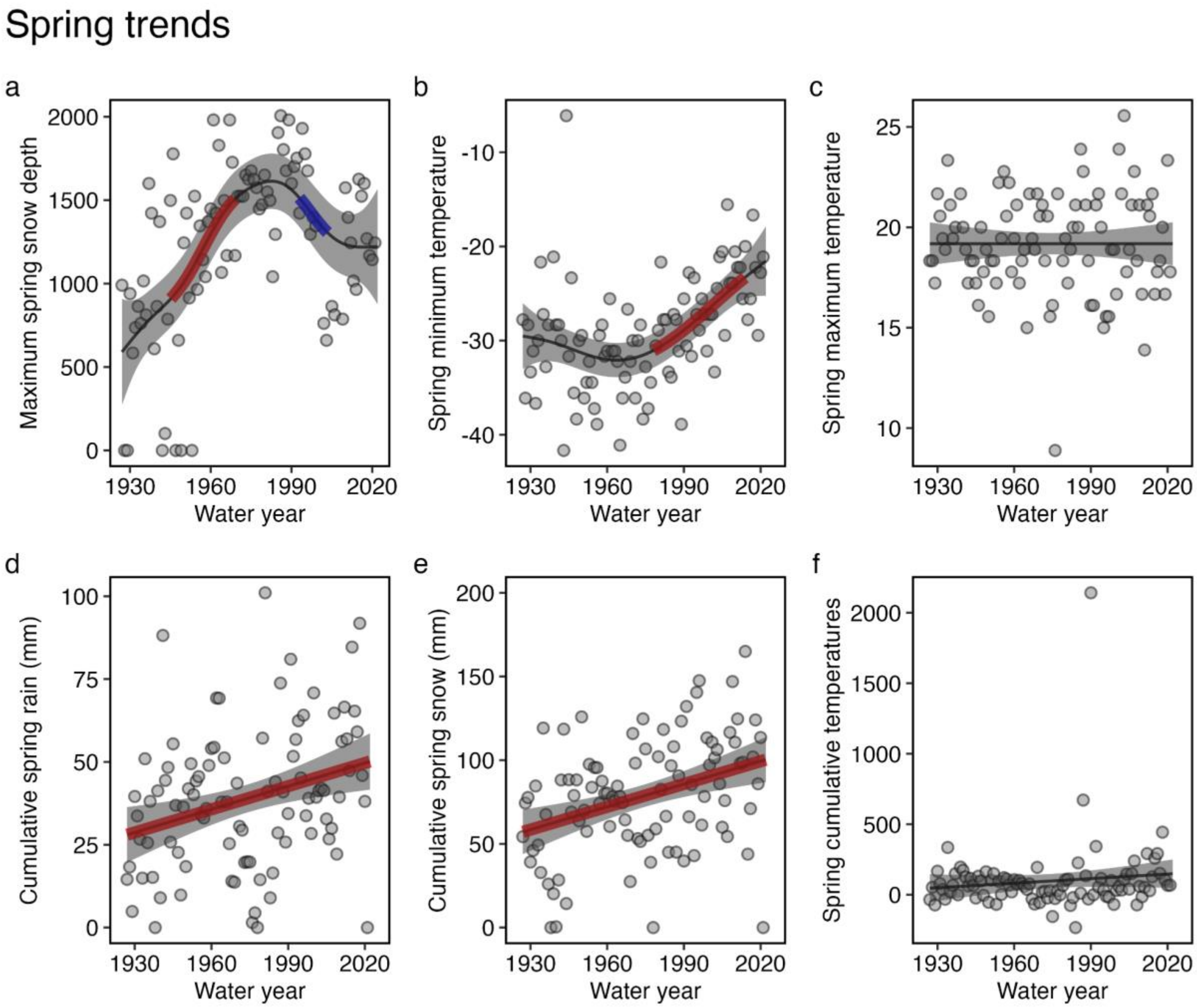

Figure S3. GAMs timeseries for spring climatic trends. Red or blue lines indicate periods of a significant increase or decrease in the trend as indicated by the first derivative of the GAMs.

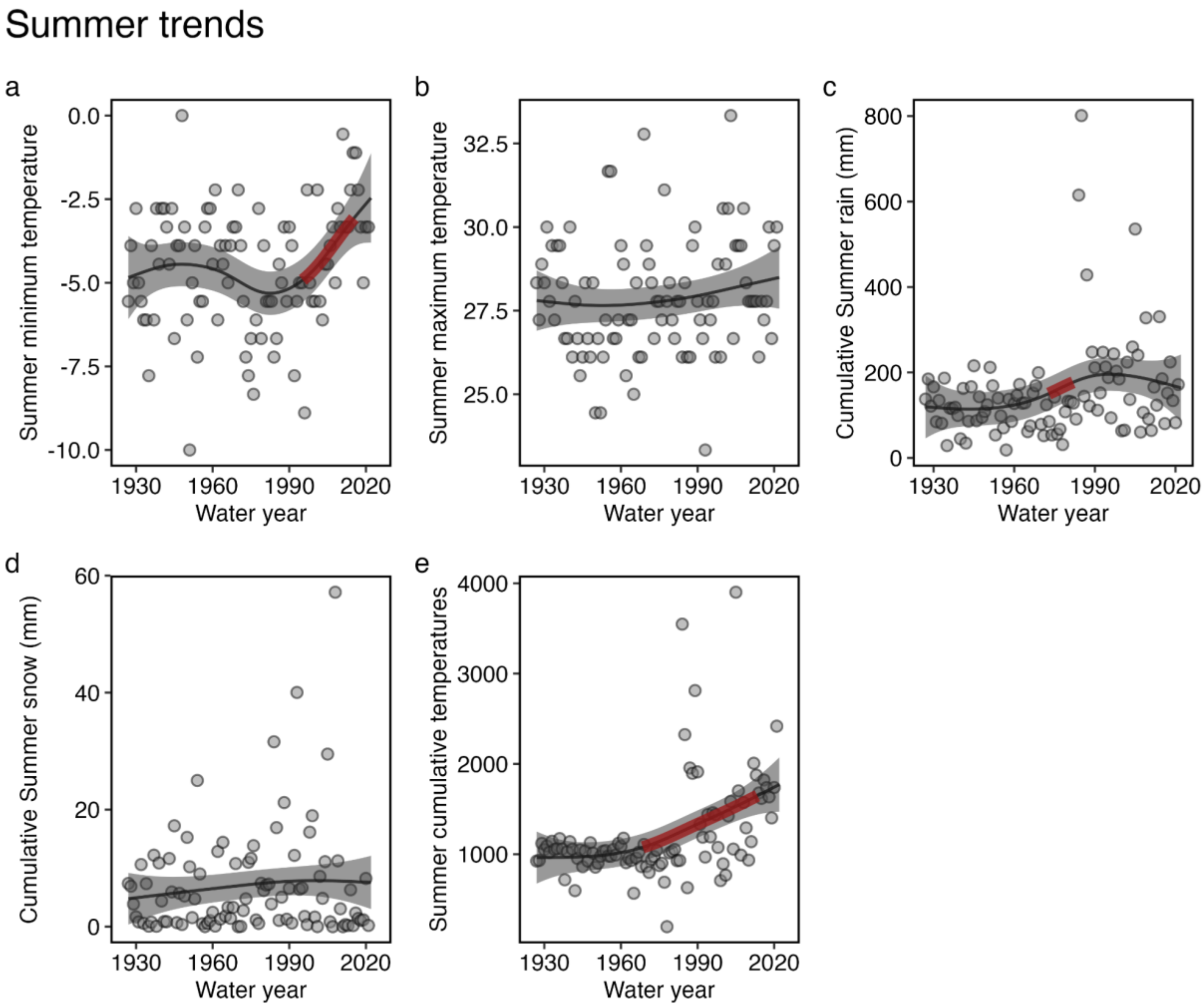

Figure S4. GAMs timeseries for summer climatic trends. Red or blue lines indicate periods of a significant increase or decrease in the trend as indicated by the first derivative of the GAMs.

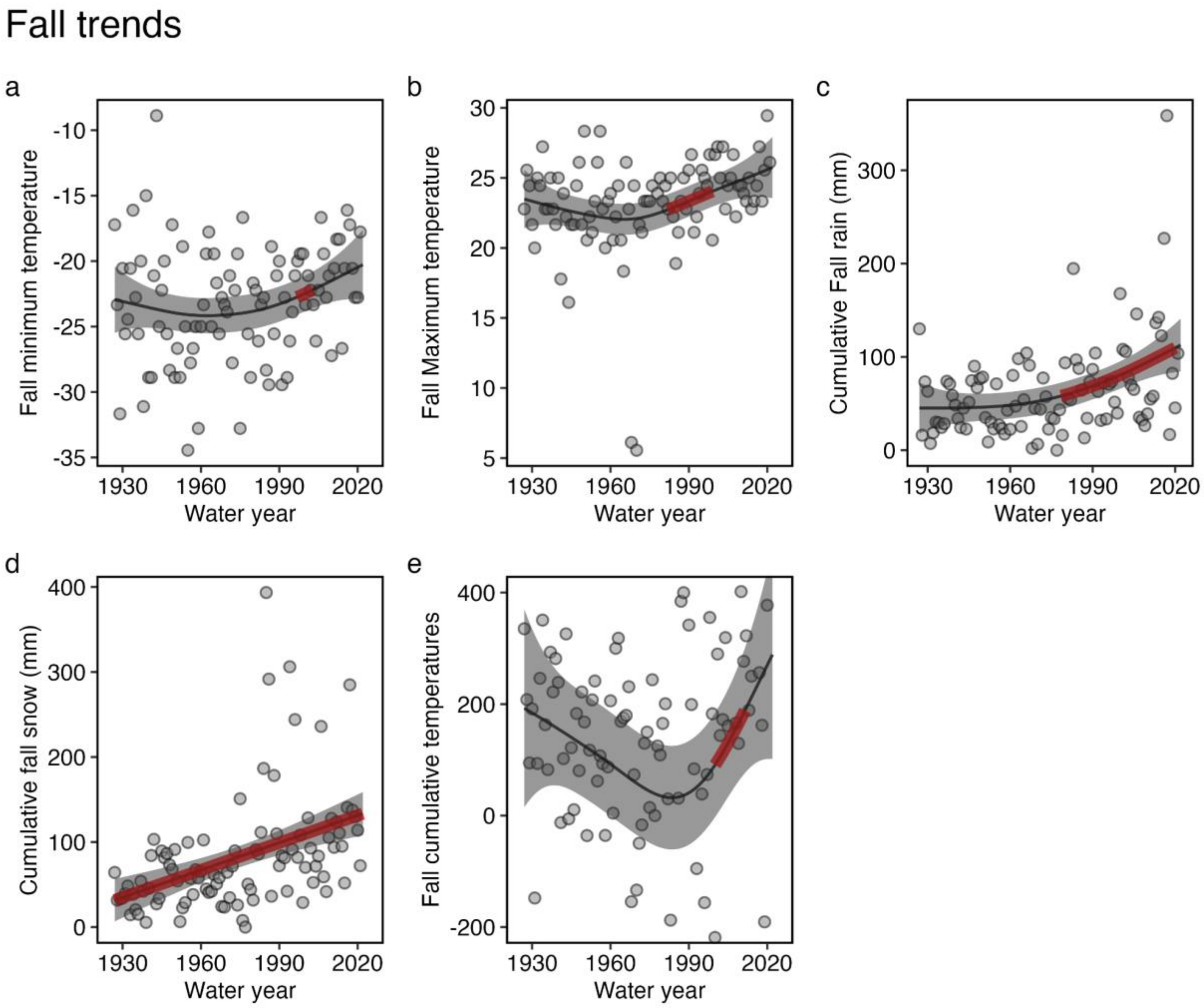

Figure S5. GAMs timeseries for fall climatic trends. Red or blue lines indicate periods of a significant increase or decrease in the trend as indicated by the first derivative of the GAMs.