Science Bulletin 70 (2025) 804–807

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

News & Views

Chinese ice-lake line shifts under climate change

Weijia Wang [a,b,c], Kun Shi [a,b,*], R. Iestyn Woolway [d], Yunlin Zhang [a,b,c]

[a] Key Laboratory of Lake and Watershed Science for Water Security, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] College of Nanjing, University of Chinese Academy of Sciences, Nanjing 211135, China
[d] School of Ocean Sciences, Bangor University, Gwynedd, LL57 2DG, UK

Climate change is profoundly altering natural environments, with lake ice cover being one of the most affected phenomena [1]. These alterations manifest as a delay in ice formation, an earlier occurrence of complete ice cover, and a shorter duration of the ice cover season [2]. As global warming proceeds, the duration of lake ice cover is significantly shortened, leading to extended ice-free periods. The increased exposure of lake surfaces to the atmosphere not only intensifies heat absorption, resulting in more pronounced water stratification, but also potentially alters water circulation and nutrient distribution, further impacting the lake's ecological dynamics and biogeochemical processes [3]. These alterations may also trigger earlier algal blooms, lead to water quality deterioration, and cause a restructuring of aquatic food webs [4]. The ecological and socioeconomic impacts of these changes are profound, with some potentially irreversible consequences under certain conditions [4]. In China, observations suggest a decrease in the duration of lake ice cover and an increase in the number of lakes that no longer freeze due to climate change [5]. This trend presents significant challenges to lake ecosystems and related human activities, including fishing, transportation, and tourism. In northern regions, where lake ice cover is of substantial cultural and economic importance, its reduction could adversely impact the livelihoods and traditional lifestyles of local communities [6].

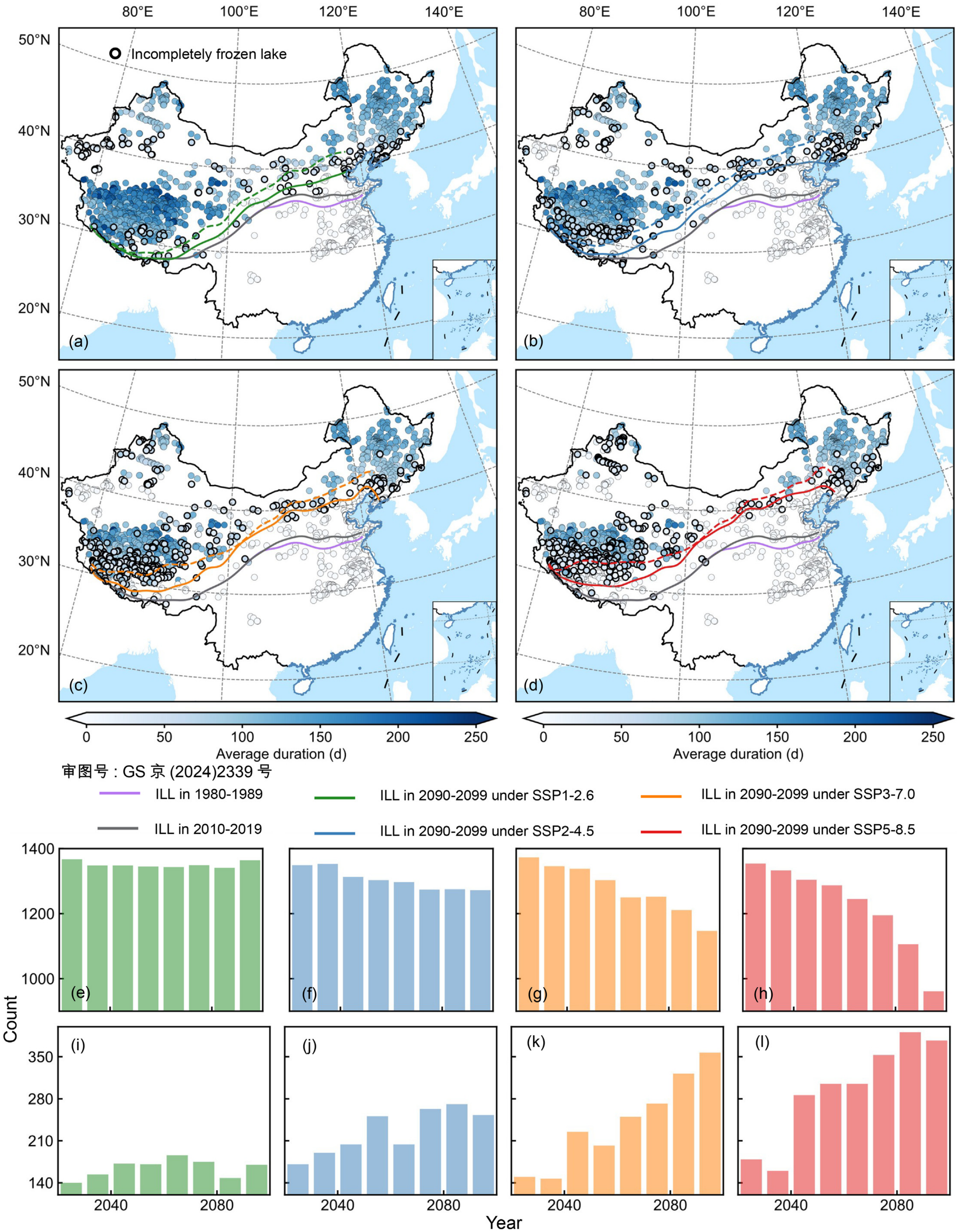
While the phenology of ice cover in large lakes has received considerable attention, the intuitive spatial distribution of China's ice lakes and their status over time remains unclear since we currently lack the ability to model ice phenology for all lakes [2]. Here we propose the concept of an 'ice-lake line' (ILL) to delineate the distribution of frozen lakes, marking the latitude below which lakes cease to freeze. The ILL is defined as the lowest latitudinal connection of frozen lakes in each longitude group. As an indicator and recorder of rapid climate warming, the ILL stands as a succinct and intuitive representation for discerning the icing status of lakes. In addition to providing a scientific basis for decision-making by lake management authorities, it can also offer easily accessible information for non-specialists [6]. It serves not only as a demarcation line of natural geography but also of human geography, unveiling disparities in winter temperatures, transportation, culture, and recreation between the two sides of the ice line in China [6]. Therefore, accurately revealing the changes in the structure and pattern of ILL is of great significance in scientifically assessing the response of lake systems to climate change. Nevertheless, there remains an ambiguity regarding the historical changes in the ILL, and their prospective evolution under climate change [2]. Considering the heightened vulnerability of lake ecosystems and the invaluable ecosystem services they provide, this knowledge gap presents a notable concern [6].

In this study, we quantified the historical variations in ILL, as well as ice phenology, across China's lakes and projected future variations in both. We applied the methodology proposed by Layden et al. [7] to define the ice-cover period for lakes as consisting of over 10 consecutive days with lake surface water temperature (LSWT) below 1 °C. The 'ice-on date' indicates the beginning of this period after July 1st, while the 'ice-off date' marks its conclusion. The threshold of 1 °C rather than 0 °C was adopted to take into account when the lake is partially frozen, in which case the average LSWT will be slightly higher than 0 °C. Lakes that met the criteria for ice formation, with LSWT down to 0 °C, were classified as completely frozen lakes for the year (Fig. S1 online). We analyzed 1705 lakes with at least one year of ice cover between 1980 and 2021, defining those with at least 7 years of ice cover per decade as frozen for that decade.

The ILL of normally frozen lakes has experienced a noticeable shift between 1980 and 2021. Specifically, the average latitude of the Chinese ILL of normally frozen lakes shifted northward from 32.10°N in 1980–1989 to 32.42°N in 2010–2019, i.e., it shifted northward by an average of 0.32° (approximately 35.58 km) over the past 40 years (Fig. 1, Table S1 online). Our analysis demonstrates that the ILL of normally frozen lakes tends to manifest at lower latitudes in the west and at higher latitudes in the east, and delineates different patterns of spatial variability across China. This is largely due to the effect of altitude, with the western part of China situated on the Tibetan Plateau, also known as the "Roof of the World", while the eastern part is dominated by vast plains. Lake ice persists for a long time at high altitudes and is unlikely to transform from a frozen state in winter to an ice-free state during historical climate change.

* Corresponding author.
E-mail address: kshi@niglas.ac.cn (K. Shi).

https://doi.org/10.1016/j.scib.2024.12.013


80°E
100°E
120°E
140°E
50°N
40°N
30°N
20°N
Incompletely frozen lake
(a)
(b)
(c)
(d)
0 50 100 150 200 250
Average duration (d)
审图号：GS 京 (2024)2339 号
ILL in 1980-1989
ILL in 2010-2019
ILL in 2090-2099 under SSP1-2.6
ILL in 2090-2099 under SSP2-4.5
ILL in 2090-2099 under SSP3-7.0
ILL in 2090-2099 under SSP5-8.5
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
1400
1200
1000
350
280
210
140
Count
2040
2080
Year

Our analysis suggested that lake ice phenology varied considerably from 1980 to 2021 in all studied lakes. Specifically, the date of ice-on has been delayed by 9.7 (2.0, 14.7) d, the date of ice-off has advanced by 12.7 (6.3, 12.3) d, and the ice duration shortened by 20.7 (11.7, 34.7) d (Fig. S2 online). The statistics described here represent the median and interquartile range (25th and 75th percentiles) for all study lakes, rather than the mean and standard deviation, which were chosen to prevent lakes experiencing particularly dramatic phenological changes from skewing the results. Lake ice phenology has undergone rapid changes over the historic period, with rates of −1.1 (0, 1.9) d/(10 a) for the date of ice-on, −1.9 (−2.8, −1.0) d/(10 a) for the date of ice-off, and −3.5 (−4.7, −2.2) d/(10 a) for the duration of ice cover, with approximately 39 studied lakes that froze in 1980–1989 no longer freezing three decades later in 2010–2019. These results demonstrated a remarkable agreement with the lake ice phenology datasets from the Tibetan Plateau and the Northern Hemisphere in previous studies (Fig. S3 online, refer to Supplementary Material online for details). Average humidity is the most crucial factor affecting lake ice thickness and stability by influencing evaporation and condensation processes on the ice surface. In high latitudes, frequent cold air activity, high albedo, and average precipitation significantly impact the formation and melting rates of lake ice (Fig. S4 online).

By the end of this century (i.e., 2090–2099), we predict that the number of lakes that freeze in winter will be approximately 3, 77, 226, and 393 less than in 2020–2029 under emission scenarios SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, respectively (Fig. 1). Correspondingly, the average latitude of the ILL of normally frozen lakes will move to 33.97°N, 34.72°N, 35.30°N, and 35.75°N, respectively. This is a northward shift of 1.86°, 2.61°, 3.20°, and 3.65° (approximately 206.82, 290.22, 355.82, and 405.86 km) compared with the average latitude of the ILL of normally frozen lakes in 1980–1989, respectively. The ILL of completely frozen lakes will shift northward by 2.99°, 3.93°, 4.42°, and 4.86° (approximately 332.47, 437.00, 491.48, and 540.41 km) in 2090–2099 compared with that in 1980–1989 under the four emission scenarios, respectively. The fact that the northward migration of the ILL of completely frozen will be more rapid compared with the ILL of normally frozen lakes suggests that there will be an increasing number of incompletely frozen lakes in the future. Under the highest emission scenario (SSP5-8.5), the ILL of normally frozen lakes and completely frozen lakes, in 2020–2099 will shift about 10.5 and 12.3 times the distance and 2.9 and 3.7 times the speed of the historical period (11.81 km/(10 a) and 13.51 km/(10 a)), respectively.

Future simulations suggest a further reduction in lake ice duration, with decreases of 7.0 (0, 13.7) d under SSP1-2.6, 17.0 (6.3, 31.3) d under SSP2-4.5, 46.0 (22.7, 66.7) d under SSP3-7.0, and 53.3 (23.3, 77.7) d under SSP5-8.5 compared with 2010–2019 (Fig. S5 online). The rate of change in the date of ice-on would be about 2.8 (1.8, 5.2) d/(10 a), −4.1 (−5.9, −1.5) d/(10 a) in the trend of the ice-off date, and −7.6 (−10.4, −3.3) d/(10 a) in the trend of the ice duration under SSP5-8.5, approximately twice that of the historical period.

Ice cover is an essential component of lake function and interacts with numerous physical, chemical, and biological processes [8]. The loss of ice cover will decrease the reflectivity of the lake surface, allowing greater absorption of solar radiation. This increase in absorbed heat leads to higher LSWT and increased evaporation. As a result, these changes contribute significantly to variations in water storage in lakes [9]. Global annual lake evaporation rates will increase by 27% under Representative Concentration Pathway (RCP) 8.5 [10]. In addition, thermal stratification in lakes that experience one or two mixing events per year may occur earlier and with greater stability [11]. The earlier release of nutrients from sediments into the water column due to stratification can significantly alter the species composition and succession of the phytoplankton community. When coupled with warmer LSWT and increased dissolved oxygen, this shift often favors cyanobacteria as the dominant species. Consequently, advanced cyanobacterial blooms can occur, disrupting the diversity and stability of lake ecosystems [4,8]. For instance, the years without freezing in two Swedish lakes were characterized by higher LSWT and greater primary production [12]. Strong stratification may also lead to hypoxia in deep lakes. Therefore, oxygen-sensitive aquatic organisms in deep and cold lakes may be exposed to a risk of habitat loss and mortality [3]. Completely frozen lakes and partially frozen lakes exhibit markedly different physical, chemical, and biological characteristics during winter. Completely frozen lakes present a more isolated environment, with faster oxygen depletion and significantly reduced biological activity. These differences have important implications for the overall health and structure of the lake ecosystem.

The loss of lake ice cover in China may have a wide-ranging impact on 747 million people in up to 18 provinces. Vulnerable social services include freshwater supply, transportation, tourism and fisheries [6,13] can be impacted by the loss of lake ice. The loss of lake ice cover may also result in reduced freshwater supplies to neighboring cities due to increased evaporation [14]. The frozen lakes often serve as winter transportation routes in frigid regions, facilitating the transport of goods and the movement of people [6]. If lakes no longer freeze, alternative transportation may be needed, which can increase the cost of transportation and affect the stability of the transportation system [6]. For communities that depend on fisheries for subsistence, anglers may be challenged with reduced income if winter fishing is limited due to loss of ice cover, thus affecting their livelihoods and the economic circumstances of their communities [15]. Ice activities like ice fishing and skating are crucial for winter recreation and community culture. The disappearance of ice cover would severely impact tourism, regional economies, and the social and cultural life of local residents [13]. Overall, the northward shift of available lake ice may trigger a range of economic, social, and cultural changes, and the rapid disappearance of lake ice in areas characterized by strong winter cultures underscores the urgency of this threat under climate change [1,4,13].

Future research should focus on the change in ice cover under climate change across a range of lake types and geographic locations, with an emphasis on the impact of topography on ILL movement. This will enhance our understanding of how the reduction of frozen lakes affects regional ecological balance, especially in cold mountainous regions, with implications for biodiversity, water quality, and habitat. Moreover, it will provide insights into the socio-economic impacts on the communities that depend on these

Fig. 1. Shifts of ice line across lakes in China under different scenarios. Spatial patterns of ILL for normally frozen lakes in 1980–1989 (solid purple line), 2010–2019 (solid grey line), and 2090–2099 under SSP1-2.6 (solid green line) (a), SSP2-4.5 (solid blue line) (b), SSP3-7.0 (solid orange line) (c), and SSP5-8.5 (solid red line) (d). The dashed line represents the ILL for completely frozen lakes in 2090–2099 for the corresponding scenarios. The color of dots indicate the average duration of ice in the study lakes in 2090–2099, where the dots with bolded borders indicate lakes that did not freeze completely in 2090-2099. For longer durations, the dots get darker blue. (e–h) and (i–l) denote the change in the number of normally frozen and incompletely frozen lakes per year from 1980 to 2099 under the four scenarios, respectively.

lakes. Policymakers can use these findings to strengthen climate adaptation measures and ensure regional socio-economic stability while protecting lake ecosystems.

Our analysis illustrates the impact of climate change on the ILL and lake ice phenology across large spatial and temporal scales, highlighting the specific challenges that lake ecosystems and the communities reliant on them will face as climate change intensifies. These findings are of significant scientific value and offer crucial insights for practical application. The smaller shifts in lake ice phenology and the ILL under low emission scenario further underscore the effectiveness and necessity of climate mitigation efforts. Immediate action is essential to develop and enforce more stringent climate policies, aimed at protecting lake ice cover and preserving the balance and stability of global ecosystems.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (42425102 and U22A20561), the NIGLAS Foundation (E1SL002), and the UKRI Natural Environment Research Council (NERC) Independent Research Fellowship (NE/T011246/1).

Data availability

The ERA5-Land data used in this study are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.e2161bac?tab=overview;

The NEX-GDDP-CMIP6 data are available at https://doi.org/10.7917/OFSG3345;

Landsat LSWT data are available at https://developers.google.com/earth-engine/datasets/catalog/;

HydroLAKES dataset is available at https://www.hydrosheds.org/pages/hydrolakes;

GSWO are available at https://developers.google.com/earth-engine/datasets/catalog/JRC_GSW1_3_GlobalSurfaceWater.

Air2Water source codes are available at https://github.com/marcotoffolon/air2water.

The source codes used in this study are publicly available at https://github.com/arielwwj/Ice-lake-Line.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2024.12.013.

References

[1] Sharma S, Blagrave K, Magnuson JJ, et al. Widespread loss of lake ice around the northern hemisphere in a warming world. Nat Clim Change 2019;9:227–31.
[2] Li X, Peng S, Xi Y, et al. Earlier ice loss accelerates lake warming in the northern hemisphere. Nat Commun 2022;13:5156.
[3] Huang L, Timmermann A, Lee SS, et al. Emerging unprecedented lake ice loss in climate change projections. Nat Commun 2022;13:5798.
[4] Quinlan R, Douglas MSV, Smol JP. Food web changes in arctic ecosystems related to climate warming. Global Change Biol 2005;11:1381–6.
[5] Lazhu, Yang K, Hou J, et al. A new finding on the prevalence of rapid water warming during lake ice melting on the Tibetan Plateau. Sci Bull 2021;66:2358–61.
[6] Woolway RI, Huang L, Sharma S, et al. Lake ice will be less safe for recreation and transportation under future warming. Earth's Future 2022;10:e2022EF002907.
[7] Layden A, Merchant C, MacCallum S. Global climatology of surface water temperatures of large lakes by remote sensing. Int J Climatol 2015;35:4464–79.
[8] Råman Vinnå L, Medhaug I, Schmid M, et al. The vulnerability of lakes to climate change along an altitudinal gradient. Commun Earth Environ 2021;2:35.
[9] Wang W, Lee X, Xiao W, et al. Global lake evaporation accelerated by changes in surface energy allocation in a warmer climate. Nat Geosci 2018;11:410–4.
[10] La Fuente S, Jennings E, Lenters JD, et al. Ensemble modeling of global lake evaporation under climate change. J Hydrol 2024;631:130647.
[11] Cannon DJ, Troy CD, Liao Q, et al. Ice-free radiative convection drives spring mixing in a large lake. Geophys Res Lett 2019;46:6811–20.
[12] Weyhenmeyer GA, Westöö AK, Willén E. Increasingly ice-free winters and their effects on water quality in Sweden's largest lakes. Hydrobiologia 2008;599:111–8.
[13] Knoll LB, Sharma S, Denfeld BA, et al. Consequences of lake and river ice loss on cultural ecosystem services. Limnol Oceanogr Lett 2019;4:119–31.
[14] Kirillin GB, Shatwell T, Wen LJ. Ice-covered lakes of Tibetan Plateau as solar heat collectors. Geophys Res Lett 2021;48:e2021GL093429.
[15] McGoodwin JR. Effects of climatic variability on three fishing economies in high-latitude regions: implications for fisheries policies. Mar Policy 2007;31:40–55.