How should we analyze seasons and seasonality in lakes?

**Submitted to:** *Limnology and Oceanography Letters*

**Article type:** Synthesis

**Running head:** Seasons and seasonality in lakes

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## Significance statement

Within-year seasonality plays a fundamental role in shaping lake ecosystem function worldwide. However, definitions of lake seasons vary widely, and phenomena traditionally associated with certain seasons are shifting in time as a result of global (e.g., climate) change. It remains unclear how best to incorporate seasonality into lake analyses across space and time. Here, we reviewed existing literature and used high-frequency data from eight lakes to conceptualize seasonality in lakes. We offer several recommendations for how seasons and seasonality may be leveraged when analyzing ecosystem function in lakes and communicating these changes to broader audiences.

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## Data Availability Statement

All data and code for this paper are published openly online. Data sources include previously published data from Beaverdam Reservoir (Carey et al., 2023; Carey & Breef-Pilz, 2023, 2024), Lake Sunapee (LSPA et al., 2022, 2023), Lake Erken (Jakobsson et al., 2025; Pierson et al., 2011), Mohonk Lake (Mohonk Preserve et al., 2020), Lake Ägeri (Bärenbold et al., 2025), and Arendsee (Jordan & Hupfer, 2018, 2020, 2025), as well as previously unpublished meteorological and in-lake data from Midway Pond and Lake Rerewhakaaitu. Data without existing DOIs were compiled into a combined dataset and published to the Environmental Data Initiative repository (Lewis et al., 2025). Data analysis code sources all data directly from the Environmental Data Initiative repository, and is itself published on Zenodo (Lewis & Richardson, 2025).

## Abstract

Across published literature, a wide range of criteria have been used to delineate seasons in lakes, including fixed dates (e.g., months, solstice/equinox), environmental thresholds (e.g., air temperature and precipitation cutoffs), and lake-specific indicators (e.g., beginning and end of thermal stratification, spring algal bloom). There is a growing need to critically evaluate how seasonality is represented in lake ecosystem research, particularly as climate change is altering the environmental drivers of seasonality worldwide. Here, we reviewed existing literature and used high-frequency data from eight lakes (38 ºS to 60 ºN) to conceptualize seasonality in lake ecosystems. We found that using different criteria to define a given season often resulted in significantly different interpretations of lake ecosystem conditions within that season. Based upon our literature review and analysis, we offer recommendations for how to incorporate seasonality into lake ecosystem analyses and communications amidst global change.

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## Keywords

Seasons, seasonality, environmental thresholds, lake-specific indicators, global change, high-frequency data

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# INTRODUCTION

Across lakes worldwide, annual environmental variability is often categorized into discrete seasons (e.g., rainy season, winter, stratified period, growing season, and clearwater phase; Box 1). Seasons provide useful means of conceptualizing annual cycles in part because they represent multiple simultaneous changes in environmental variables within a year (White & Hastings, 2020; Box 1). However, the way seasons have been defined varies widely across lakes, regions of the world, studies, disciplines, cultures, and individuals (Tuller, 1990). Consequently, it can be challenging to make comparisons across lakes on a global scale or over long timescales that encompass changing environmental conditions (Bremer & Wardekker, 2024; Ferrato et al., 2025; Kutta & Hubbart, 2016; Wang et al., 2021). Moreover, the methods commonly used to define seasons in aquatic environments are often adapted from those developed for terrestrial systems, despite the fact that aquatic ecosystems can display divergent dynamics. For example, thermal inertia of water causes seasonal change in water temperature to lag changes in air temperature (Srifa et al., 2016; Winslow et al., 2017). These differences in definition may become increasingly impactful as global change is altering drivers of seasonality in divergent ways. For example, seasons defined by astronomical cycles (e.g., solstice/equinox dates) may be increasingly incongruent with seasons defined by air temperature, due to an increasing temperature departure from day length patterns under global warming (Kutta & Hubbart, 2016). As a result, there is a growing need to assess how seasons and seasonality are defined and applied in studies of lake ecosystem functions across regions and time periods (Box 1).

In this paper, we analyze how definitions of seasons (i.e. discrete times of year) and seasonality (i.e. intra-annual variability; Box 1) may shape our understanding of environmental change in lakes worldwide. In *Section 1*, we synthesize the multi-scale drivers of seasonality in lakes and create a taxonomy of season definitions that are commonly used across published literature. In *Section 2*, we combine continuous sensor data from eight lakes across the United States, Europe, and Aotearoa New Zealand to quantify whether these definitions describe fundamentally similar periods of time within or across lakes. Finally, in *Section 3*, we offer recommendations for how future analyses of lake ecosystem function might consider addressing seasons and seasonality amidst global change.

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| --- |
| Box 1: What is a season? Here, we define a *season* as a discrete period of time that repeats each year (following Körner et al., 2023; Trenberth, 1983). Seasons are often characterized by expected changes in biological, environmental, astronomical, or social variables. We define *seasonality* as the timing, magnitude and predictability of intra-annual variability in any of these variables (Fretwell, 1972; Hernández-Carrasco et al., 2025; Lisovski et al., 2017; Post, 2019; Fig. B1).  We further distinguish between seasons that are *dynamic* in response to changing climate (e.g., ice-covered season) and seasons that are *static* (e.g., seasons constrained by solar calendars; Fig. B1). In the context of global change, static definitions are used to communicate changes in average values (e.g., “summer is getting warmer”), while dynamic seasons are useful for communicating changes in timing and phenology (e.g., “the summer stratified period is getting longer”).  Both seasons and seasonality occur cyclically within a year (Fig. B1). Some variables have clearly discretized states (e.g., ice season) while others exhibit more continuous seasonality (e.g., daylength; Fig. B1). Both static seasons (astronomical seasons) and dynamic seasons (ice cover) affect ecosystem function and lake accessibility within a single year for different lakes (Fig. B1).  **A diagram of different seasons  AI-generated content may be incorrect.**  **Fig. B1:** Demonstration of seasons as cyclical variables in two temperate lakes: (a) a dimictic lake from the northern hemisphere and (b) a polymictic lake from the southern hemisphere. Astronomical seasons (discrete, static) are indicated in the center ring, divided by solstices and equinoxes. Day length seasonality (continuous, static) is shown by the orange color gradient in the second ring. The magnitude of lake stratification (continuous, dynamic) is shown in the outer ring. Stratification was determined by the density difference from surface to bottom waters; a threshold of 0.1 kg m-3 is illustrated in white, blue is mixed, and the shades of red corresponding to the magnitude of the density difference. Ice cover (discrete, dynamic) is indicated within the outer ring when present in (a). |

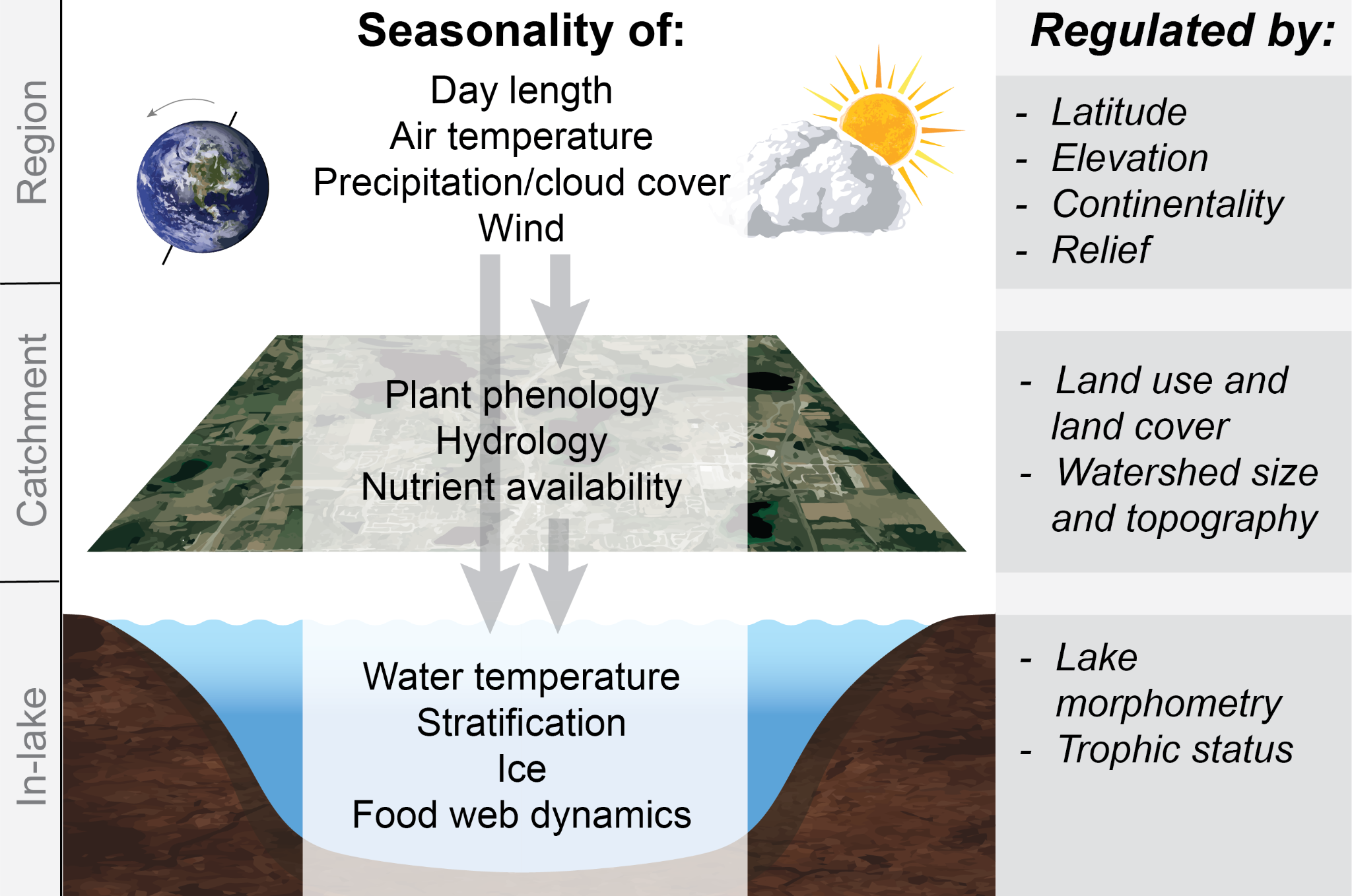
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# SECTION 1: DEFINITIONS OF SEASONS

## Drivers of seasonality in lakes operate across multiple scales

As topographic low points in the landscape, lakes integrate seasonality across multiple spatial and temporal scales, from vegetation, edaphic, and hydrological dynamics in the catchment to regional variation in weather and climate (Fig. 1). Consequently, analyzing seasonality in lakes likely requires considering multiple spatial scales of drivers.

On the highest level, seasonality is driven by Earth’s tilt and orbit around the sun (Copernicus, 1543; Jenkins, 2013). However, local differences at regional, catchment, and in-lake scales (Fig. 1) can regulate global drivers, leading to diverse patterns of lake seasonality within and across geographic regions. For example, seasonality in solar radiation is a key driver of seasonality in regional air temperature and precipitation patterns, which are further regulated by the lake’s elevation and climate teleconnections, among other factors (Lewis, Jr., 1996). Similarly, catchment-scale seasonality in land cover regulates whether there will be seasonal pulses of organic matter deposition (e.g., due to deciduous leaf-off) and stream discharge (e.g., due to snowmelt) to a given lake. Ultimately, the changes in conditions observed within a given lake (i.e., due to the seasonality of environmental factors at regional- and catchment-scale) will depend on lake-specific characteristics including lake morphometry and trophic status, in addition to global, regional, and catchment-level drivers (Fig. 1). Seasonality of environmental variables occurring across multiple scales has the potential to change over time as a result of changes in climate, land use, water management, and other factors, necessitating a thoughtful consideration of cross-scale interactions when analyzing seasonality in lake ecosystems (Heffernan et al., 2014).



**Fig. 1:** Seasonality in lakes is determined by factors occurring across multiple scales, with examples shown here. Lake characteristics including lake morphometry and trophic status can filter the effects of seasonality from regional and catchment variables to shape in-lake responses. The conditions and drivers indicated on this figure are not comprehensive, and many other factors contribute to seasonality, as described throughout the manuscript.

As a result of the heterogeneous controls over in-lake seasonality (Fig. 1), the definitions used for different seasons in lakes have varied across studies. Identifying which definition to use for a given analysis, or whether to define discrete seasons at all, can be challenging. Here, we synthesize definitions of seasons from published literature to highlight the variation in definitions used to date and help inform this decision-making process for future research. We summarize common definitions in Table 1 and include an extended list of 39 definitions in Table S1.

**Table 1**: Summary of common definitions of seasons relevant to lakes (see Table S1 for an extended list of 39 definitions, including relevant references). “Scale” referenced here corresponds to Fig. 1. Type indicates whether the dates defining each season are “dynamic” in response to changing climate or “static” (e.g., constrained by solar calendars); definitions that have been used in both static and dynamic ways are listed as “varies” (Box 1).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scale** | **Definition** | **Description** | **Type** | **Reference** |
| Global | *Astronomical* | Four discrete seasons defined by solstice and equinox dates. | Static | (Trenberth, 1983) |
| Regional | *Months (spring/*  *summer/*  *autumn/*  *winter), also known as meteorological seasons* | Four discrete seasons defined by three-month periods. Most often, summer is classified as June, July, and August in the northern hemisphere, and December, January, and February in the southern hemisphere. | Static | (Huschke, 1959; Trenberth, 1983) |
|  | In lakes, some studies have instead classified summer as July, August, and September. |  | (Winslow et al., 2017) |
|  | *Months (wet/dry)* | In tropical regions, months are often used to define wet and dry seasons, though the specific months used differ between studies (e.g., any months exceeding a certain threshold of precipitation across a geographic region). | Varies | (Maidment et al., 2015; Seregina et al., 2019; Zhang & Wang, 2008) |
| Regional/  catchment | *Lake management and recreation* | There are many recreation- and management-based definitions of seasons. These are often defined on regional or catchment scales by local government and regulating organizations. Examples include water level drawdown seasons, seasonal water quality intervention, fishing seasons, swimming and boating seasons, and ice activities (e.g., ice fishing, skating). | Varies | (e.g., Damyanov et al., 2012; Hori et al., 2017; Xu et al., 2024) |
| Catchment | *Plant phenology* | Terrestrial growing seasons mediate in-lake seasonality through water use, shading, and leaf senescence. The definition of the growing season differs substantially among studies and regions for terrestrial plants. | Typically dynamic | (Körner et al., 2023) |
|  | *Hydrology* | Hydrologic seasons are variably defined across locations, including snowmelt seasons, summer drought, and other discrete location-specific periods. | Varies | (Soares et al., 2024; Tomalski et al., 2021) |
| In-lake | *Thermal stratification* | Dimictic lakes are expected to exhibit four distinct stratification seasons: inverse stratification under ice, a water column mixing period following ice out, a stratified period during the warmest time of the year, and another period of water column mixing before the onset of inverse winter stratification. Note that this definition may be complicated by varying definitions of stratification (Gray et al., 2020). | Dynamic | (Boehrer & Schultze, 2008) |
|  | *Ice* | Two seasons: ice-covered and open water. The definition of the open-water season and transition between seasons differs among studies. | Dynamic | (Block et al., 2019; Powers & Hampton, 2016) |
|  | Plankton succession | Plankton are expected to exhibit semi-predictable seasonality, including a “spring” phytoplankton bloom and a following clearwater phase. | Dynamic | (Sommer et al., 1986, 2012; Winder & Cloern, 2010) |
|  | *Fish* | Fish spawning seasons typically occur in spring or autumn, and the duration of the spawning window may be narrow or protracted depending on the species. Seasonal fish in-migration or out-migration depends on the species. Maximum fish biomass growth is typically tied to water temperature for temperate and colder lakes. | Dynamic | (Håkanson & Boulion, 2001) |

## Regional- to global-scale definitions

As seasons are fundamentally constrained by the Earth’s tilt and orbit (Fig. 1), attempts to define discrete seasons often logically begin with astronomical cycles (Table 1). Astronomical seasons mark significant mathematical points on the predictable sinusoidal curve of day length: summer starts when the day length is at its apex; winter starts when the day length is at its nadir (solstices). Spring and autumn both start when hours of light match hours of dark (equinoxes). Latitude plays a key role in regulating the magnitude of difference among seasons, with locations closer to the equator having smaller annual sinusoidal curves in day length. Consequently, astronomical spring, summer, autumn, and winter likely have more environmental relevance in temperate and boreal regions than near the equator (Lewis, Jr., 1996).

While astronomical seasons present one relatively objective way of classifying time throughout a year, other methods are also commonly used. In particular, a “monthly” definition of four seasons—where each season is a three-month window—is common in meteorology (Huschke, 1959; Trenberth, 1983), Intergovernmental Panel on Climate Change reports (IPCC, 2023), and other global-scale analyses (e.g., Delwiche et al., 2021). In tropical regions, wet/dry seasons are also sometimes defined by set months, which can be variable across countries or regions (Maidment et al., 2015; Seregina et al., 2019; Zhang & Wang, 2008). Seasons defined through months are fundamentally human constructs, but using definitions based on months may be convenient for some analyses, including when data resolution is on a monthly scale.

To facilitate global analyses, some studies use temperature or precipitation thresholds to identify seasons that vary across space and time. These thresholds can be absolute (e.g., winter begins when air temperatures decrease below 0 ºC) or relative (e.g., summer begins when temperatures exceed the 75th percentile of historical temperatures during a reference period; Christidis et al., 2007; Park et al., 2018; Wang et al., 2021). However, dynamic definitions are generally less common and inconsistently applied (Table 1, Table S1). Part of the reason for this inconsistency is that there are rarely objective temperature or precipitation thresholds (either absolute or relative) that describe distinct periods across both space and time. Furthermore, quantifying the timing of these environmentally-defined seasons often requires high-resolution (e.g., daily) data availability, which may be prohibitive for some times and locations. Establishing clear, ecologically-meaningful thresholds to define the changing of the seasons remains challenging.

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## Catchment-scale definitions

On a catchment or watershed scale, lake seasons are often affected by hydrological processes and biological phenology occurring throughout the surrounding landscape (Table 1). For example, terrestrial or emergent plant growing seasons can be defined in multiple ways, including when plants are photosynthetically active, when plants are producing new tissue, when vegetation is experiencing net carbon gain, or when plants could grow based on meteorological conditions (Körner et al., 2023; Treat et al., 2018). Terrestrial or wetland plant growing seasons could affect lakes by affecting hydrologic cycles (Bosch & Hewlett, 1982; Gerten et al., 2004), by affecting carbon fluxes into surface and groundwater inflows (Marx et al., 2017; Strohmeier et al., 2013), or through direct allochthonous contributions (Cole et al., 2007; Cole & Caraco, 2001; Tank et al., 2018; Weyhenmeyer & Karlsson, 2009).

Catchment hydrology can also follow annual cycles including during snowmelt seasons, monsoons, or soil freeze/thaw cycles, with seasonal downstream effects on lentic waterbodies. Hydrological seasons may be defined based on various properties of streamflow including water quantity and stochasticity (Tomalski et al., 2021). For example, the United States Geological Survey (USGS) water-year starts October 1 and ends September 30 of the following year, revolving around the hydrologic regime for much of the U.S. (Hirsch & Fisher, 2014). “Local water years” expand on this definition by setting the start of the water year to the month with the lowest or highest average monthly streamflow (Sun & Cheruvelil, 2025). Overall, catchment-scale definitions are more frequently defined based upon dynamic environmental states compared to regional and global definitions, which are often defined based upon astronomy or calendar years (Table 1).

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## In-lake definitions

Within lakes, seasons are often defined by an intra-annual temperature-driven cycle of physical processes, including thermal stratification, ice-cover duration, and water level changes. For example, dimictic lakes are expected to exhibit four distinct seasons that can be defined by thermal stratification: inverse stratification under ice, a water column mixing period following ice out, a stratified period during the warmest time of the year, and another period of water column mixing before the onset of inverse winter stratification (Boehrer & Schultze, 2008). Similarly, in lakes that experience seasonal ice cover, lake seasons could be bifurcated into an open-water and an ice-covered season (e.g., Weyhenmeyer et al., 2013; Weyhenmeyer & Karlsson, 2009). However, there is often some intermittency to ice cover and stratification in spring and autumn, even in dimictic lakes, making it difficult to draw clear boundaries (Howard et al., 2024; Sharma et al., 2021). Methodologically, stratification-based definitions are complicated by the fact that the definition of thermal stratification varies among studies, including definitions based on the difference in water temperature or density between surface and bottom waters, among other factors (Gray et al., 2020). More broadly, these seasons are not applicable in lakes that are permanently stratified (amictic), lakes that experience frequent mixing events year-round (polymictic), and lakes that are permanently or never ice covered (e.g., Holgerson et al., 2022; Mziray et al., 2018).

Seasons in lakes have also been commonly defined according to the phenology of plankton communities. For example, the Plankton Ecology Group (PEG) model identifies a clear seasonal succession of plankton communities occurring throughout the year in temperate lakes (Sommer et al., 1986, 2012). Phytoplankton have distinct waxing and waning periods depending on bottom-up and top-down controls. “Spring blooms” follow ice-off and are driven by a combination of internal and external nutrient loading as well as the onset of thermal stratification. Herbivorous zooplankton subsequently graze down the phytoplankton, resulting in a “clearwater phase” characterized by high water transparency (Gronchi et al., 2023; Sommer et al., 1986, 2012). As temperatures rise, phytoplankton populations often increase again, leading to another peak in summer that is typically dominated by less edible taxa (Sommer et al., 1986, 2012). Monitoring the timing of phytoplankton bloom initiation, peak, and decline is crucial for understanding lake food web dynamics (Rolinski et al., 2007), and the PEG model describing these seasonal successions has been widely supported across many lakes (e.g., Carey et al., 2016; Wentzky et al., 2020). However, the magnitude and predictability of seasonal change in phytoplankton populations can vary from lake-to-lake (e.g. depending on lake depth, Winder & Cloern, 2010) and inter-annually within a single lake (e.g. depending on weather conditions; Rolinski et al., 2007).

Seasons in lakes have also been defined in numerous other biological and chemical ways, which tend to be highly specific to the research question of interest and tend to integrate various drivers across temporal and spatial scales. Microbial phenology can follow seasonal patterns with communities exhibiting strong temporal coherence at finer timescales than lake physics. For example, three different microbial community seasons were identified within the typical summer stratified period—clear-water, early summer, and late summer—across a 20 year time series of data in Lake Mendota (Wisconsin, USA; Rohwer et al., 2023). However, this pattern is not consistent among other lakes (Linz et al., 2017; Shade et al., 2010). Fish exhibit seasonal patterns of movement within lakes, e.g., between littoral and pelagic zones, as well as movement between lotic and lentic systems for spawning, seeking resources, thermal regulation, hypoxic survival strategies, and predator avoidance (Hall & and Werner, 1977; Offem et al., 2011; Skov et al., 2008). The seasonal phenology of fish integrates various biological, physical, and chemical variables but is also dependent on species-level functional traits. For example, the freshwater eel (genus *Anguilla*) migrates as adults from freshwater ecosystems to spawning grounds in oceans, and their migration phenology is influenced by life-history stage and water quality conditions (Cresci, 2020). Seasonal insect emergence is driven by changes in water temperature and taxa specific phenology (Phillips et al., 2019; Salvarina et al., 2017), and can occur over short time spans (days to weeks) to ensure predator satiation or increase evolutionary fitness (Sweeney & Vannote, 1982). Water chemistry also exhibits seasonality, with annual patterns in dissolved gases (e.g., oxygen, carbon dioxide, methane) and nutrient concentrations that incorporate limnological drivers across varying temporal scales (Finlay et al., 2019; Ray et al., 2023). Synthesizing multiple in-lake variables, Srifa et al. (2016) quantitatively assessed the most appropriate “seasons” for Lake George, a sub-tropical lake in Florida, USA. They combined 18 years of data for water chemical, biological, and physical parameters, and found data clustered into three states—a cold season, a warm season, and a flushing (i.e., high discharge) season. These seasons are optimized directly to the lake, and are therefore highly predictive, but not highly transferable across other lakes.

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## Social and cultural definitions

Social, economic, and cultural applications often motivate the definition of seasons. Discrete seasons have been constructed in varying ways across cultures worldwide often informing the social, cultural, economic, and political ways that people engage with the environment. For example, Japan’s traditional calendar divides the year into 24 *sekki*, which are further divided into 72 *kō* (Kondo, 2014). These static seasons are named for subtle changes in the natural world and agricultural practices, such as the awakening of insects (*Keichitsu*) and the timing of planting rice (Kokuu; Kondo, 2014). Conversely, in ancient Sanskrit calendars, the year was divided into six seasons (*ritu*), describing both air temperature and monsoon dynamics (Mughal, 2014; Selby, 2003). Gwich'in First Nation land users recognize five seasons—*sreendyit*, *daii*, *shin*, *khaiints’an’*, and *khaii*—that correspond to changes in environmental conditions and harvest, including lake-related changes in ice dynamics, fishing, and waterfowl (Proverbs et al., 2021). In Germanic languages, the word for autumn (e.g. old english *hærfest*, old high german *herbist*) appeared relatively late compared to the words for summer and winter, as a concept of two (or three) seasons was gradually replaced by four distinct seasons (Anderson, 1997). The four temperate seasons commonly referenced in contemporary global analyses (IPCC, 2023) are far from universal across space and time.

Socially- and culturally-defined seasons have implications for how we monitor and understand lake ecosystem function (Shogren et al., 2020), as well as for the seasonality of human impacts on lakes (Table 1). For example, the primary and secondary education and university calendars control when students are available for summer employment like scientific research or lifeguarding, graduate students can turn to research full-time, and professors leave their classrooms and conference rooms for the lab and field. These calendars are region- and university-specific depending on semester schedule (e.g., semesters vs. trimesters), government and religious holidays, and other factors. Conversely, lake ecosystem function can also impact the definition of social and cultural seasons; many public swim seasons will only open when water temperature is high enough for safe swimming, water quality is adequate (e.g., after early season phytoplankton blooms), or when seasonal employees (e.g., lifeguards) are available (Skowron, 2018; Szalkai & Ács, 2025).

Social and cultural seasons often revolve around hunting and fishing, and these practices in turn can affect seasonal lake ecosystem functions. For example, maramataka is the Māori calendar that is used for determining appropriate times for hunting, fishing, planting, and cultural seasons (Hikuroa, 2017). The maramataka follows lunar cycles in conjunction with *tohu* (signals) like bird migrations or plant phenology, creating a seasonal calendar that changes dynamically with environmental conditions (Matthews, 2023; Warbrick et al., 2023). The traditional Palauan calendar divides the year into 12 lunar months that are all named based upon dominant wind patterns and used, in combination with precipitation signals, to time fishing seasons (Klee, 1976). In the United States, the hunting season for migratory game birds cannot exceed 107 days with the earliest start to the season on September 1 and the latest end to the season on March 10 (U.S. Fish & Wildlife Service, 2023).

The use of lakes for transportation for economic, cultural, or every day needs also revolves around a seasonal calendar. Ice roads around the northern hemisphere are critical routes for residents and regional economies during the ice covered period, often connecting isolated or remote communities with resources or tourists (Hori et al., 2017; Sharma et al., 2024). Likewise, lakes are often central figures in religious pilgrimages. St. Patrick allegedly visited an island on Lough Derg in Ireland and remained in a cave for 40 days, fasting and praying before learning that pain from sin would be expiated in purgatory. Consequently, pilgrims have journeyed to Lough Derg for prayer and reflection since as early as the 5th century (Shalvey, 2003). The pilgrimage season continues today and is open from June through mid-August (https://www.loughderg.org/). People of the Western Province of Zambia celebrate the Kuomboka Ceremony where royalty moves from a summer palace to a winter palace indicating the end of the rainy season. Kuomboka means “To get out of water” and involves a royal procession and celebration marking the end of the seasons (Flint, 2006).

Ultimately, seasons are widely used in both scientific and societal contexts due to their strong influence on environmental systems around the world. However, the specific environmental patterns associated with seasons vary significantly across space and time, leading to diverse definitions of seasons (Fig. 1; Table 1). To facilitate more thoughtful consideration of seasons and seasonality in lake analyses, we aim to clarify where and when conclusions are most sensitive to the specific seasonal definition used in a given study.

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# SECTION 2: CROSS-LAKE DATA COMPARISON

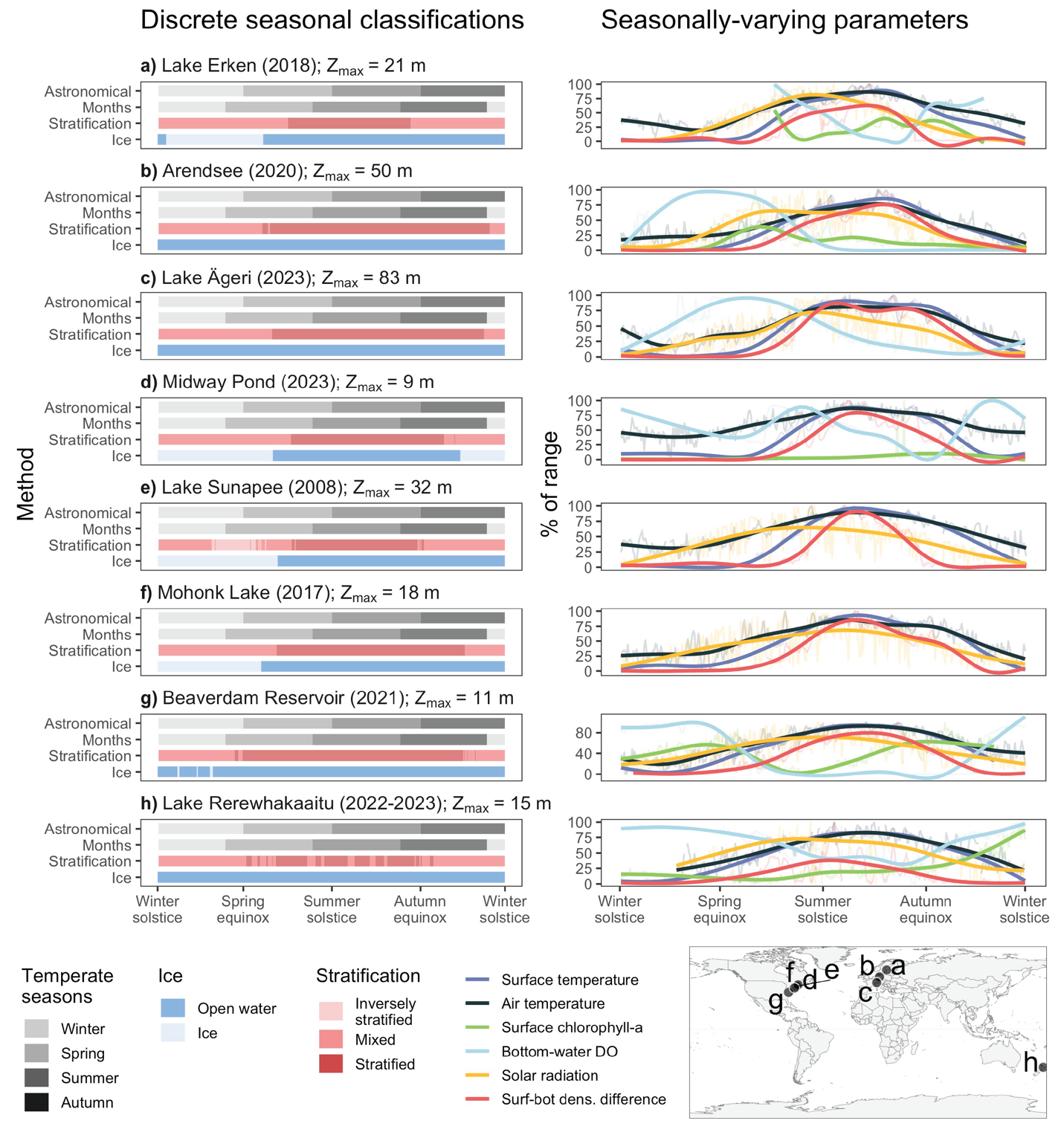
Because definitions of seasons vary widely (e.g., Table 1), a given season—such as “spring” or “summer”—may refer to different periods of the year across studies, lakes, or regions. Even when seasonal labels align temporally, the underlying physical, chemical, or biological dynamics they capture can differ substantially. As a result, the way seasons are defined can significantly influence both the scientific interpretation and the social or policy relevance of limnological analyses.

To begin assessing the correspondence between varying definitions of seasons, we compiled one year of high-frequency meteorological and in-lake data from eight geographically and morphometrically diverse lakes: Lake Erken (Sweden), Arendsee (Germany), Lake Ägeri (Switzerland), Midway Pond (Maine, USA), Lake Sunapee (New Hampshire, USA), Mohonk Lake (New York, USA), Beaverdam Reservoir (Virginia, USA), and Lake Rerewhakaaitu (Aotearoa New Zealand; Fig. 2). These lakes span a morphometric gradient with maximum depth ranging from 9 m to 83 m (Fig. 2), and they provide examples of potential patterns of seasonality. However, they are biased to temperate systems given data availability (absolute latitudes from 37º to 60º) and are not meant to be representative of all lakes worldwide. Detailed methods at each lake are presented in the Text S1. We analyzed these data both quantitatively and qualitatively to understand the correspondence between seasons and seasonality within and across lakes.

## 

## Discrete seasons provide a coarse representation of intra-annual environmental variability

At each lake, we identified four types of discrete seasons (astronomy, months, thermal stratification, and ice cover), then compared these discrete seasons to continuous sensor data recording in-lake conditions (Table 1; Fig. 2). We observed substantial variation in the durations of each season among lakes. In general, the seasonality of physical variables (air temperature, solar radiation, surface temperature, and the difference in water density between surface and bottom waters) followed congruent intra-annual patterns among lakes, as expected for temperate ecosystems. Conversely, the seasonality of chemical and biological variables (bottom-water dissolved oxygen and surface-water chlorophyll-a concentrations) were much less consistent among lakes. Most of the study lakes are northern dimictic lakes which are traditionally thought to have clear and distinct stratified and ice-covered periods. However, both thermal stratification and ice cover had high degrees of intermittency across the lakes, creating discontinuous stratified and ice covered seasons during transitional periods.



**Fig. 2:** Seasonality of lake metrics differs both among metrics within a single lake and among lakes for the same metric. Left: Discrete seasons. Stratification classes are calculated using a density threshold of 0.1 kg/m3 difference between surface and bottom waters. Right: Selected seasonally-varying variables during one example year for eight temperate lakes (2008–2023). Surf-bot dens. difference refers to the strength of thermal stratification, assessed by the density difference between the surface and bottom of the lake. Variables are standardized to a percentage of their total range. Smooth lines show fitted General Additive Model predictions based upon the daily data. Inset map (bottom right) illustrates the location of lakes in this analysis (basemap from Massicotte et al., 2023).

## 

## Mean environmental states differ depending on how a season is defined

We quantitatively assessed the environmental relevance of seasonal definitions by comparing the mean value of continuous environmental conditions (e.g. chlorophyll-*a*, water temperature, solar radiation) between definitions of seasons. We focused on monthly and astronomical seasons (Table 1) for this analysis because these seasons have the same names between both definitions and both definitions are commonly used in scientific research. We also compared mean conditions in astronomical summer to the stratified period and open-water period, and we compared astronomical winter to the inversely stratified period and the ice-covered period (Fig. S1). For each comparison, we visualized the difference in means across seasons, lakes, and variables.

Lakes commonly exhibited significant differences in mean lake ecosystem conditions between monthly and astronomical definitions of the same season (Fig. 3). In particular, the magnitude of difference in mean state between definitions tended to be higher in spring and autumn than winter and summer. Across the lakes in this analysis, spring and autumn represent dynamic periods of the year, with rapid changes in environmental conditions (Fig. 2). Consequently, shifting the period of analysis by only ~20 days when using a different definition (e.g., starting spring on March 1 vs. March 21) produces a substantial difference in environmental conditions. More broadly, it may be expected that the choice of seasonal definition used for a given analysis will be most impactful for variables and periods with rapid environmental change.

Differences in mean conditions were typically even more pronounced when comparing astronomical summer/winter to seasons defined by stratification and ice cover (Fig. S1). Whereas monthly and astronomical definitions have similar durations, offset by ~20 days, seasons defined by stratification and ice cover varied substantially in duration within and among lakes, and encompassed widely different environmental states (Fig. S1).

A graph of different types of temperature

AI-generated content may be incorrect.

**Fig. 3:** The difference between monthly and astronomical definitions of seasons varied among lakes, variables, and seasons. Here, positive values indicate a greater mean in the month-defined season and negative values indicate a greater mean in the astronomically-defined season. For example, spring surface temperatures were typically warmer when using astronomically defined seasons than month-defined seasons (March, April, May in the northern hemisphere). Point shape indicates whether the distribution of values within the month-defined season is significantly different from the distribution of values within the astronomically-defined season at that lake.

# SECTION 3: RECOMMENDATIONS

While discrete seasonal frameworks have historically provided valuable approaches for sampling, communication, and management, the growing availability of high-resolution data and modeling tools makes it increasingly feasible—and often preferable—to analyze seasonality as a continuous phenomenon. We advocate that limnologists critically evaluate when and why they use discrete seasons and consider continuous alternatives where feasible (Kraemer, 2020). In scientific research, a disproportionate emphasis on seasons versus seasonality may lead to study designs that focus on understanding “typical” summer or winter conditions rather than analyzing more dynamic transition periods (Ferrato et al., 2025). Similarly, fixed seasons can obscure changes in the timing of environmental events from year to year, and discussion of seasons can conflate multiple distinct axes of environmental variation, including time of year, stratification, air temperature, and ice. Outside of scientific research, seasons are broadly recognized and defined by many cultures worldwide (see *Social and cultural definitions*, above), and these locally-defined seasons create a powerful foundation for communicating the effects of climate change (Chambers et al., 2021). However, effectively leveraging seasons for science communication requires being conscious of how seasons are socially and culturally conceptualized and clearly targeting communication to engage with these definitions. Below, we offer recommendations for ways to thoughtfully consider seasons and seasonality in scientific research and communications.

### 

## Recommendation 1: Intentionally consider seasons and seasonality

In the absence of a one-size-fits-all solution, we advocate for explicit definitions and intentional discussion of seasonality and seasons. In many cases, it may be appropriate to conduct analyses using continuous environmental drivers directly, rather than discrete seasons (examples in *Recommendation 3*). For analyses that must include discrete seasons, we recommend considering multiple definitions (e.g., Table 1) and exploring the extent to which results depend upon the specific definition using sensitivity analyses. As a general guideline, time series with strong seasonality and rapidly varying conditions may be most sensitive to the choice of definition (e.g., spring and autumn in northern dimictic lakes, Fig. 3). Regardless of the approach used, clear and precise terminology will facilitate appropriate interpretation and allow for cross-study syntheses. For example, it may be more precise to analyze trends in the duration of the “ice covered period” or the “period with air temperatures below 0 ºC” than analyzing trends in the duration of “winter.” These precisely-defined periods are also more comparable across lakes.

### 

## Recommendation 2: Quantify seasonality with higher resolution data

When possible, we encourage sampling at multiple times of year to quantify intra-annual variation in environmental conditions. In particular, periods with rapid environmental change are important for understanding seasonality and are under-represented in limnological sampling programs. These transitional windows often exhibit the most dynamic and informative ecological processes—yet they are undersampled due to logistical challenges, including harsh weather, ice hazards, and/or institutional calendar constraints. In particular, field sampling is often difficult in the dynamic periods surrounding the onset and break up of ice cover (Block et al., 2019). Permanently deployed *in situ* high-frequency sensors are useful for increasing data resolution, enabling daily or sub-daily collection from lakes worldwide (Marcé et al., 2016). However, challenges remain in deploying continuous sensors under ice (Block et al., 2019). Furthermore, in many cases and locations these sensors continue to be prohibitively expensive to purchase, deploy, and maintain (Marcé et al., 2016).

## 

## Recommendation 3: Use statistical methods that account for seasonality

As high-resolution data become more available in many lakes, analysis methods may need to evolve to better capture and account for seasonality. While analyses with limited data have historically defaulted to comparing within or among discrete seasons, continuous data offer an opportunity to explicitly incorporate seasonality in more complex model structures and use non-linear trends to understand environmental patterns (White & Hastings, 2020). Many potential options exist for continuous data analysis of seasonality, and explicitly comparing multiple metrics will often yield more robust insight into changing environmental phenomena (Thackeray et al., 2012). An initial approach to continuous analysis of seasonality may involve quantifying relationships between a response variable and air temperature, day of year, or other covariates that are mechanistically expected to be important (Bansal et. al. 2023), recognizing some of these covariates are static (day of year) and others are dynamic (air temperature) in response to global change. Importantly, non-linear analyses will often be helpful for quantifying patterns of seasonality. For example, when day of the year is used to describe seasonality, circular statistics help account for the fact that day one is only one day removed from day 365 of the previous year (Box 1; Landler et al., 2018; Lee, 2010; Morellato et al., 2010). In generalized additive models (GAMs), seasonal predictors can be fitted with a cyclic cubic regression spline (Wood, 2017), which facilitates modeling variables that follow a cyclical annual pattern. The 'cyclic' property ensures that the fitted curve wraps smoothly from December 31 back to January 1, preserving continuity without artificial edge effects at the year boundary. To capture the aggregated environmental change that occurs over the course of a year, it is also important to account for relevant lag effects (e.g., growing degree days, ecological memory). This can be done in empirical models using a variety of approaches (e.g., distributed lag non-linear models, long short term memory neural networks, autoregressive integrated moving average models) or by expressing lag terms explicitly in the governing equations of process-based models. Including these lagged relationships can improve predictions of seasonal phenomena under climate variability and change (Sahoo et al., 2019).

### 

## Recommendation 4: Recognize seasonal heterogeneity when conducting and communicating research

Ongoing global disparities have often contributed to inaccurate representation of seasons in scientific research and science communications. In research, disproportionate focus on northern, dimictic temperate lakes (including here in Figs. 2 and 3) has led to the conflation of summer, thermal stratification, and open water periods as seasons, despite the vast heterogeneity of seasonal patterns, particularly in shallow and tropical lakes. These issues also extend outside of academic research. Socially, discussion of “spring” or “fall” conferences can be alienating to researchers across a global community (Hart & Nazarian, 2024). In science communication, educational materials often describe four seasons (spring/summer/autumn/winter), even outside of regions where these temperate seasons have any local environmental relevance (e.g., tropical regions; Selles & Ferreira, 2004).

We recommend that researchers and science communicators actively consider the diversity of seasonal dynamics across lakes and regions, and avoid assuming that temperate, four-season frameworks are universally applicable. When synthesizing across systems, researchers should report the environmental or calendar basis for seasonal definitions and, where possible, use standardized descriptors (e.g., “stratified period,” “high rainfall period,” or “post-mixis window”) that are more universally interpretable. Across fields, recognizing global heterogeneity in seasonality is essential to develop more appropriate, effective, and targeted scientific research and communication. By acknowledging and adapting to the global diversity in seasonality, researchers can improve the accuracy, inclusivity, and cross-regional applicability of lake science and its communication.

### 

## Recommendation 5: Leverage socially- and culturally-defined seasons for science engagement

Localized social and cultural seasons provide a lens through which societies worldwide conceptualize environmental change over the course of a year, and may therefore provide a strong foundation for communicating broader environmental changes. As one example, National Meteorological Services in the Pacific have worked extensively with local communities to co-construct calendars that recognize traditional knowledge systems, such as those based on farming practices, hunting and fishing seasons, and religious or ceremonial events (Chambers et al., 2021). The resulting calendars are typically dynamic between years, as seasonality shifts with environmental variability. These calendars document traditional knowledge while providing an interface for engagement on climate policy (Mondragon, 2013), and they serve as a particularly strong example for how socially- and culturally-defined seasons may provide a foundation for science communication.

Importantly, the perceived stability of discrete, socially defined seasons can itself serve as a powerful contrast to emerging ecological variability. When long-standing seasonal patterns—such as planting times, rainy season onset, or culturally significant migration events—begin to shift, this disruption can clearly illustrate how continuous environmental variation is intensifying and why conventional seasonal frameworks may need to be reconsidered. In Bangladesh, the traditional calendar included six seasons marked by ecological changes, but some have now shifted to recognizing only three seasons—summer, winter, and the monsoon—as climate change has altered seasonal rain dynamics (Bremer & Wardekker, 2024). Ultimately, these socially-recognized changes highlight the communicative power and the evolving nature of seasons in a changing world. Effective science communication will recognize not only how social definitions can foster engagement, but also how their apparent breakdown can signal the urgency of environmental change and the value of transitioning toward more flexible, continuous representations of seasonality in research and policy.

# SEASONS AMID GLOBAL CHANGE

Global changes in seasonality have profound social, ecological, and evolutionary implications (Hernández-Carrasco et al., 2025; Woolway et al., 2022). However, analyzing and discussing these changes can be complicated by the widely varying drivers and definitions of seasons across space and time. For example, consider that winter is often said to be getting both “warmer” and “shorter”—these seemingly congruent trends result from two fundamentally different underlying definitions, as winter is either defined as a static period of time in which higher average temperatures are occurring (IPCC, 2023; Twardosz et al., 2021) or a dynamic environmental process (e.g., ice cover) with changing phenology (Magnuson et al., 2000; Sharma et al., 2021). Subsequently, astronomical winter can get “warmer” and the winter ice season can get “shorter” but these concepts need to be explicitly defined separately. While communicating with scientists and the general public, static definitions (e.g., astronomical summer) are used to communicate changes in average values, while dynamic seasons (e.g., stratification) are useful for communicating changes in timing and phenology. Highlighting specific changes in seasonality may be particularly powerful; for example, the duration of ice cover is decreasing by 17 days per century on average in a survey of lakes worldwide (Sharma et al. 2021).

As climate change is driving changes in air temperatures but not day length, seasons defined dynamically based on climate may be increasingly divergent from seasons defined based on static astronomical cycles. Simultaneously, a wide variety of anthropogenic changes in land use, water regulation, urbanization, and other factors are altering seasonality in divergent ways worldwide. The seasons that were experienced in the past—that is, the specific combinations of daylength, temperature, plant phenology, animal behavior, and other environmental states that were characteristic of a given time of year—may no longer occur (Seidl & McKibben, 2010). Lakes provide a particularly clear example of this change, as some lakes that have historically had a consistent ice covered period have now lost ice cover entirely (Sharma et al. 2019). Many unanswered questions remain regarding how to analyze, communicate, and adapt to these changes in seasonality. Ultimately, this article serves as a framework to foster intentional and precise conversation about changing seasonality in lakes worldwide.

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# ACKNOWLEDGEMENTS

We thank the Virginia Tech Reservoir Group and a Global Lake Ecological Observatory Network working group for their contributions to conceptualizing this paper. We are particularly grateful to Freya Olsson, Alo Laas, Dominique Edwards, and Shajar Rejev for assistance during the early stages of manuscript development. We are also thankful to the many researchers and organizations who have helped to collect data used in this manuscript, including the Bay of Plenty Regional Council. While writing this manuscript, ASLL, DCR, CCC, DWH, and KKH received financial support from the U.S. National Science Foundation (NSF; DGE-1840995, DEB-1753639, DEB- 2306898, BIO/EF-2318861, and 2327030). ASLL received further support from the Institute for Critical Technology and Applied Science (ICTAS), the College of Science Roundtable at Virginia Tech, and the Smithsonian Climate Change Fellowship. CCC, DWH, and KKH recognize support from the Western Virginia Water Authority. SB was funded by the USGS Ecosystems Land Change Science Program and U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research (Grant DE-SC0023084). BMK was supported by an Early Career Fellowship from the Freiburg Institute for Advanced Studies. PZ was supported by the CSF project No.22-33245S. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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