Supplemental information:

How should we analyze seasons and seasonality in lakes?

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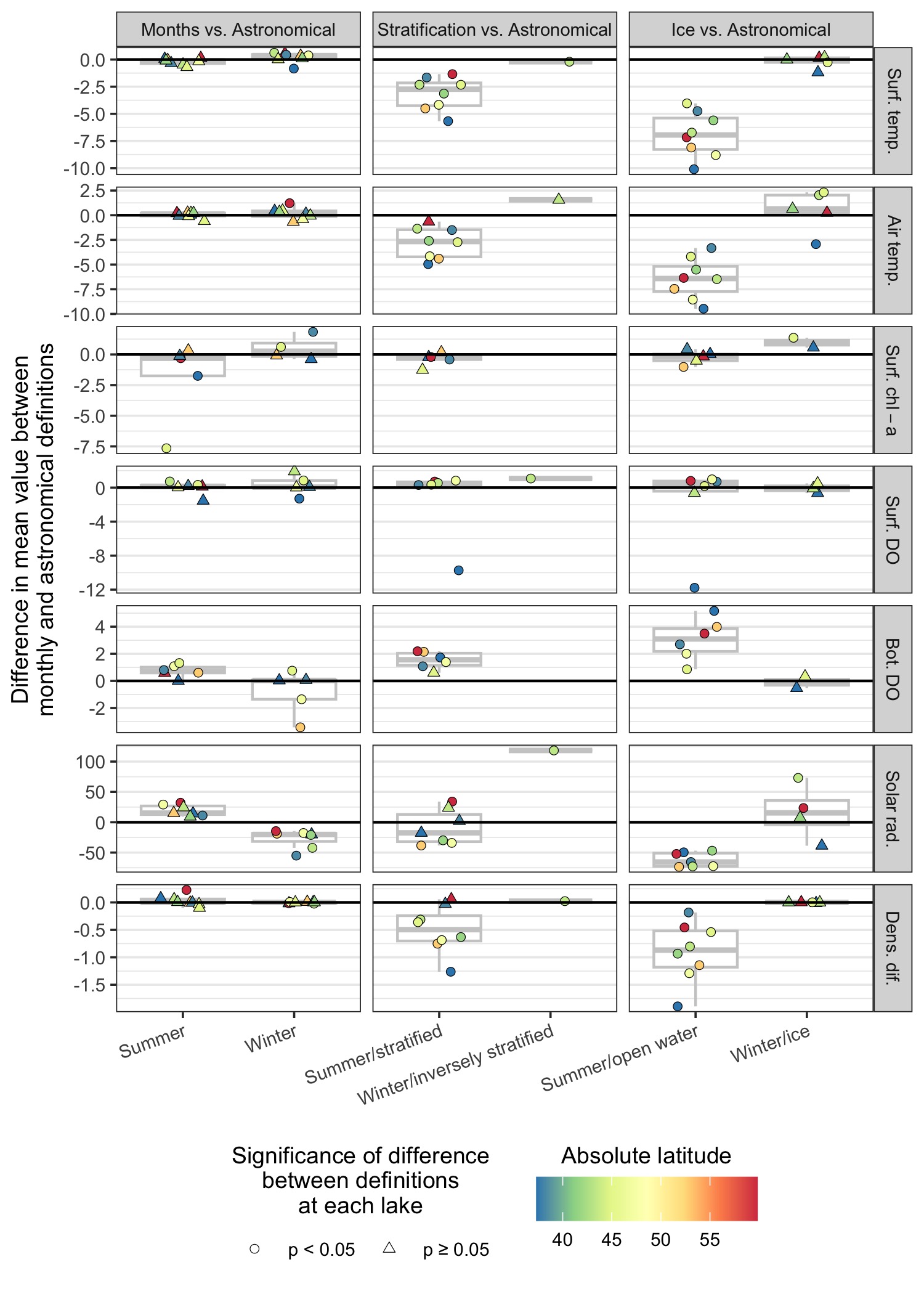
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Contains a supplemental figure (Figure S1) to support the analysis in Figure 3 of the main manuscript and a supplemental table (Table S1) with additional definitions of seasons compared to Table 1 of the main manuscript. Text S1 contains data collection methods from each lake.

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**Figure S1:** We compared mean environmental conditions in astronomical summer to means during monthly summer (left), the stratified period (center), and the open-water period (right). Likewise, we compared mean environmental conditions in astronomical winter to means during monthly winter (left), the inversely stratified period (center), and the ice-covered period (right). Across all panels, negative values indicate a greater mean in the astronomically-defined season. Point shape indicates whether the distribution of values was significantly different between the two definitions.

**Text S1: Study sites and data collection methods**

**Beaverdam Reservoir** (37.313 °N, 79.816 °W; Zmax = 13 m; Surface area = 39 ha) is a meso-eutrophic drinking water reservoir located in southwestern Virginia, USA (Hamre et al., 2018). Beaverdam is dimictic and typically experiences hypolimnetic anoxia from May through November; ice cover is intermittent during December–March. Meteorological and in-lake data collection methods are described in published data products (Carey et al., 2023; Carey & Breef-Pilz, 2023, 2024).

**Lake Ägeri** (47.125 °N, 8.609 °E, Zmax = 83 m, Surface Area = 730 ha) is an oligotropic peri-alpine lake located in Central Switzerland at an elevation of 724 m a.s.l. The lake was historically dimictic and developed an ice-cover for a short period in most winters, but is currently transitioning to a monomictic state. A monitoring station with a profiling buoy "Oscar" from Flydogmarine (Estonia) equipped with multiparameter probe OceanSeven316Plus from Idronaut (Italy) was installed close to the deepest point of the lake in November 2022, financed by the Swiss Federal Office for the Environment (FOEN). The frequency of profiling is adapted to the energy supply from the solar panels and ranges between one and eight profiles per day. The data and more detailed information regarding the measurements is available on the Datalakes platform (Bärenbold et al., 2025).

**Lake Arendsee** (52.889 °N, 11.474 °E; Zmax = 49 m; Surface area = 514 ha) is a highly eutrophic lake situated in the Northern German Lowlands. The lake is undergoing a regime shift from dimictic to monomictic with periods of inverse stratification during winter being irregular and typically very short in recent years. The average water residence time is 50-60 years. Since 2012, Lake Arendsee has been equipped with an automatic measurement station at the deepest point of the lake. Meteorological parameters are measured in 10 min intervals with an MeteoMS multisensor and a CMP3 pyranometer (Ecotech, Bonn, Germany). Temperature, dissolved oxygen, conductivity, pH, Turbidity, Chl-a, and Phycocyanin are monitored using an automatic profiler (YSI 6600 V2, YSI, USA) with a frequency of four measurements per day during summer. Due to limitations in the power supply, the frequency is reduced during winter to 1-2 profiles per day. In close proximity to the measurement station, a sensor chain equipped with oxygen optodes at 15 distinct depths is deployed (D-Opto Logger, ZebraTec, New Zealand, until 2023; PME Minidot, Precision Measurement Engineering, USA, since 2023). Measurement intervals were 60 min until 2023 and 30 min afterwards. Data are published in the Freshwater Research and Environmental Database (Jordan & Hupfer, 2018, 2020, 2025).

**Lake Erken** (59.839 °N, 18.632 °E; Zmax = 21 m; Surface area = 2400 ha) is a mesotrophic temperate lake located in east-central Sweden, approximately 70 km north of Stockholm. It is a dimictic lake that typically experiences ~120–150 days of ice cover per year. The average water retention time is approximately 7 years. Lake Erken is one of the few lakes in Northern Europe that has a long history of monitoring (since the 1940s), including both manual and high-frequency automatic measurements of lake and stream stations. The Erken monitoring programme includes measurements of physical and chemical variables as well as plankton composition (Jakobsson et al., 2025; Pierson et al., 2011). The data is openly available through the SITES Data Portal (https://data.fieldsites.se/portal/), including background information, sensor technology, analytical methods and maps.

**Lake Rerewhakaaitu** (38.29 °S, 176.5 °E, Zmax = 15.8 m; Surface Area = 580) is a shallow, mesotrophic lake located in the Bay of Plenty Region of Aotearoa New Zealand. Lake Rerewhakaaitu is a volcanically-formed, polymictic lake. A high-frequency profiling buoy was deployed at Lake Rerewhakaaitu in February 2021, which collects water quality profiles from the surface to ~12 m eight times per day. Water temperature, dissolved oxygen, and chlorophyll-a fluorescence are measured using Aqualabo Ponsel Digisens pHEH, OptoD, and Turner Designs C7F-C, respectively. A Lufft WS700 Smart Weather meteorological station was also deployed on the profiling buoy with measurements taken every five minutes.

**Lake Sunapee** (43.37 °N, 72.05 °W; Zmax = 33 m; Surface area = 1655 ha) is an oligotrophic, glacially-formed lake, located in central New Hampshire, USA (Woelmer et al., 2024).Lake Sunapee is dimictic with summer stratification occurring from approximately May to October and is inversely-stratified under ice cover typically occurring from December until April (Bruesewitz et al., 2015). A buoy maintained by the Lake Sunapee Protective Association (LSPA) was deployed at a central site in the lake near the deep hole. Details about the sensors on the buoy, their years deployed, and monitoring data are specified in LSPA et al. (2022, 2023).

**Midway Pond** (44.931 °N, 70.541 °W; Zmax = 9 m; Surface area = 3.35 ha) is an oligotrophic, dimictic, glacially-formed lake with no inlets or outlets, located in the northern Appalachian Mountains, Maine, USA (Nelson et al., 2021). Since November 2022, in situ sensors have been deployed on a subsurface buoy line located at the deepest point in the lake. Temperature was recorded every 15 minutes at each 1 meter depth increment, from 0.5 m above the benthos to 1-m below the surface (HOBO Tidbit temperature loggers; Onset Computer Corporation, Bourne, MA). Dissolved oxygen was measured every 30 minutes at two locations: 0.5 m above the benthos and 1 m below the surface (MiniDOT dissolved oxygen meter; Precision Measurement Engineering, Vista, CA). Chlorophyll was measured at 30 minute intervals, located 1 m below the surface (Cyclops-7F CHL sensor, Turner Designs, San Jose, CA). Mean daily air temperature was sourced at the nearest National Weather Service station (Rangely airport), located 10 km from Midway Pond.

**Mohonk Lake** (41.766 °N, 74.158 °W; Zmax = 18.5 m; Surface area = 6.9 ha) is an oligo/mesotrophic glacial lake located in the mid Hudson Valley, NY, USA (Oleksy & Richardson, 2024). Mohonk Lake is dimictic and experiences ~30 days of ice cover per year (Oleksy & Richardson, 2024). From November 2016 to May 2018, high‐frequency (15‐min) temperature data were collected using NexSens T‐Node temperature loggers at 1‐m intervals from the surface to 9 m deep. We matched that data with a high‐frequency (1‐hr) meteorology station <5 km from Mohonk Lake (Brotzge et al., 2020). that were linearly interpolated to 15‐min intervals to match the lake thermal data. Meteorological and in-lake data collection methods are described in the published data product (Mohonk Preserve et al., 2020)**.**

**Table S1**: Extended list of definitions of seasons that are relevant to lakes. Scale referenced here corresponds to Figure 1. Type indicates whether the dates defining each season change (“dynamic”) or remain consistent (“static”) in response to environmental (e.g., climate) change. The in-lake definitions list some of the most frequently used terms for phases of the annual cycle in lake ecosystems that vary seasonally.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scale** | **Definition** | **Description** | **Type** | **Reference** |
| Global |  | |  |  |
|  | *Astronomical* | Four discrete seasons defined by solstice and equinox dates. Based on the Heliocentric model of our solar system; i.e. the triple motion comprising the earth’s tilt, daily revolution and elliptical orbit around the sun. | Static | (Copernicus, 1543) |
|  | *Volcanic* | Volcanic eruptions can dramatically affect seasonal patterns depending on the season when and location where the eruption occurs. For example, the Mount Tambora (Indonesia) eruption made 1816 the “year without a summer” with one of the coldest and driest years in centuries and seasonal disruptions as far away as Europe and North America. | Dynamic | (Kravitz & Robock, 2011; Wilson et al., 2023) |
| Regional |  |  |  |  |
|  | *Months (spring/*  *summer/*  *autumn/*  *winter)* | 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. In lakes, some studies have instead classified summer as July, August, and September. | Static | (Huschke, 1959; 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; Ren et al., 2019; Seregina et al., 2019; Zhang & Wang, 2008; Zinabu, 2002) |
|  | *Monsoon* | In areas where the heavy rainfall is associated with a wind shift, the wet season is known as the monsoon season, and can have significant effects on lake ecosystems. | Dynamic | (Robert et al., 2021) |
| Regional: Management and recreation | | | | |
|  | *Ice shelter* | Ice shelters are common on ice-covered lakes in the US, for use by fishers.. Annual licences are required, and specify the dates by which shelters have to come off the ice. | Static | https://www.dnr.state.mn.us/fishing/shelter.html |
|  | *Cold water season* | This is a safer-related definition, defined as the times for the year when lake users must wear a personal floatation device to mitigate cold-water shock. |  | https://www.pa.gov/agencies/fishandboat/boating/regulations/cold-weather-life-jacket.html |
|  | *Ice roads - opening and closing dates* | Many lakes are used as ice roads when frozen. For example, the James Bay Winter road in Canada operates typically January and March each year. The Lake Ladoga “Road of life” was used in WWII to carry supplies to the Leningrad pocket, and evacuate non-combatants, wounded, and industrial equipment. | Dynamic | (Glantz, 2001; Hori et al., 2017) |
|  | *Shipping seasons - winter opening and closing dates* | The opening and closing of shipping routes when lakes are frozen for the winter are important economic delineations. For example, between 35 to 40 million tonnes of cargo is transported along the Great Lakes St. Lawrence Seaway every year, but winter ice necessitates a break for up to two months. | Dynamic | (St. Lawrence Seaway Management Corporation & Great Lakes St. Lawrence Seaway Development Corporation, 2022) |
|  | *Shipping season - low level conditions* | While decreasing lake ice may extend shipping season, low water levels curtail boating activities, which are also a common seasonal activity. | Dynamic | (Marchand et al., 1988) |
|  | *Sports seasons* | Swimming, ice hockey, recreational fishing all have distinctive times of the year when activity peaks. Whilst the determining factors are dynamic and variable (ice cover, temperature etc), legislation or guidance around these activities may be static. | Dynamic | (Knoll et al., 2019; Sharma et al., 2020) |
|  | *Fishing seasons - migratory fish* | The arrival of spring salmon (large Atlantic salmon *Salmo salar* that have spent more than one winter at sea) is often linked to the presence of deep lakes that provide a holding habitat with cool water. Fishing season will be determined by the arrival of these fish (often inflexible dates for licensing purposes). | Dynamic | (Reed et al., 2017) |
|  | *Fishing seasons - resident fish* | Fishing seasons are often related to the timing of insect emergence such as Ephemeroptera. For example, Lough Mask in the west of Ireland is a famous trout fishing destination, and the Mayfly season (and hence probability of catching trout) is normally best from May 20th to June 12th. | Dynamic | (Jacobus et al., 2019) |
|  | *Fishing seasons (licensed)* | Licensed fishing, either for recreation or commercial operations are often restricted by licence to particular dates. Unless real-time monitoring of catch is implemented, these dates are often fixed, with resulting implications on fishery-dependent data. | Static | (NYS DEC, 2025) |
| Regional: Social or cultural | | | | |
|  | *Kuomboka* | Ceremony of the Lozi/BuLozi/MuLozi people of the Western Province of Zambia, whereby the Litunga King of the Lozi travels across the Zambezi Floodplain system. The occasion marks the journey away from the Barotse Floodplain of the Zambezi River (a RAMSAR site) to Limulunga on higher ground. | Dynamic | (Kalaluka, 1979) |
|  | *Maramataka* | The maramataka is a calendar system combining space, time, and observations of natural phenomena with what natural signs are expected during seasonal changes. | Dynamic | (Matthews, 2023) |
|  | *Religious ceremonies* | Many lakes are visited at certain times of the year for specific religious celebrations, e.g. Lough Derg in Ireland, the Shinto ceremony on Lake Suwa, the crossing of Lake Constance with a statue of John the apostle. | Dynamic | (Arai, 2000; Knoll et al., 2019; O’brien, 1991) |
|  | *Other* | Chambers et al. (2021) compiled an extensive list of seasonal calendars throughout the Pacific (see their Table S1). These calendars are often based upon lunar cycles, and include seasons defined by agriculture, fishing, navigation, and harvest, which vary substantially among regions. | Often dynamic | (Chambers et al., 2021) |
| Catchment | | |  |  |
|  | *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) |
|  | *Leaf senescence* | Leaf senescence is controlled by photoperiod and minimum air temperature and depends on species but may not be a reliable indicator of biomass accumulation. | Dynamic | (Körner et al., 2023) |
|  | *Leaf cover* | Can be estimated remotely and over large scales. This is an important component of the allochthonous fueling of lake ecosystems. | Dynamic | (Polgar & Primack, 2011) |
|  | *Growing and runoff season* | Arccosine function of mean air temperature and air temperature amplitude. | Dynamic | (Weyhenmeyer & Karlsson, 2009) |
|  | *Growing season* | Defined based on the “soil biological-zero temperature” concept. For ease of determination this period can be approximated by the number of frost-free days (U.S. Geological Survey 1970) | Dynamic | (Williams & Malone, 2010) |
| 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 cover* | Two seasons: ice-covered and open water. Definitions of ice-cover have differed between studies. Ice-on and Ice-off are a common alternative binary descriptor. | Dynamic | (Block et al., 2019; Powers & Hampton, 2016) |
|  | *Spring bloom* | Plankton communities are expected to exhibit semi-predictable seasonal dynamics, including a “spring” phytoplankton bloom and a following clearwater phase. These in turn have become colloquial terms for predictable patterns in some lakes. | Dynamic | (Adrian et al., 2009; Gronchi et al., 2021; Sommer et al., 2012) |
|  | *Clear water phase* | Characterized by the clearing of the phytoplankton spring bloom by herbivorous zooplankton, this is a characteristic phase of some lake types. | Dynamic | (Dröscher et al., 2009) |
|  | *Plankton Abundance metrics (proxy)* | Proxy abundance metrics are used to define “seasons” of primary productivity, such as remotely sensed chlorophyll a, e.g. seasonal peak or start of seasonal increase | Dynamic | (Ji et al., 2010; Winder & Cloern, 2010) |
|  | *Snow and/or light* | In ice-covered lakes, winter is divided in winter I (snow cover or arctic winter = no light) and winter II  (no snow - light can penetrate). | Dynamic | (Kirillin et al., 2012) |
|  | *Light availability* | Water column light availability has been used as a general indicator of the start of spring across lakes as it will be influenced simultaneously by presence of ice, mixing, lake depth, latitude, and browning. | Dynamic | (Gronchi et al., 2023) |
|  | *Methane emissions* | Lakes exhibit characteristic peaks in methane emissions which are not correlated with peak summer temperatures of GPP, but are nonetheless predictable | Dynamic | (Delwiche et al., 2021) |
|  | *Growing season* | Number of days in which epilimnetic temperature exceeds 9°C | Dynamic | (Håkanson & Boulion, 2001) |
|  | *Daphnia maximum* | Coincides with clear-water phase, and is recognized as a characteristic event in many lakes | Dynamic | (Berger et al., 2007; Thackeray et al., 2012) |
|  | *Bacterial succession* | Recent work has indicated that bacterial communities display predictable patterns that are related to “seasonal” drivers | Dynamic | (Park et al., 2023; Shade et al., 2007) |
|  | *Limnological degree day* | The sum of mean daily epilimnion or surface (or other defined region) temperatures. Similar to degree day or growing degree day but specific to certain depth regions in a lake. | Dynamic | (Sterner et al., 2020) |
|  | *Cardinal dates* | Phytoplankton seasonal dynamics may be described using "cardinal dates" i.e. beginning, time of maximum and time of end of an identified peak. Can be determined using a weibull function | Dynamic | (Rolinski et al., 2007) |
|  | *Water level* | Lakes may be defined as being low or high, depending on antecedent weather conditions. | Dynamic | (Li et al., 2016) |
|  | *Macrophyte phases* | Aquatic plants have growth and die-back phases, which are influenced by water temperature, light availability, and nutrient levels throughout the season. | Dynamic | (Villa et al., 2018) |
|  | *Fish presence* | Presence and abundance of migratory fishes at different life stages can influence lake ecology in different seasons. Abundance and composition of fish communities in different seasons also have food web implications, particularly if they are migrating in from the nutrient rich marine environment |  | (Durbin et al., 1979) |

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