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Lake Temperature Monitoring in Southwest Alaska Parks

A Synthesis of Year-Round, Multi-Depth Data from 2006 through 2018

Natural Resource Report NPS/SWAN/NRR—2020/2191

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ON THE COVER
Readying the temperature array at Lake Clark for downloading
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Lake Temperature Monitoring in Southwest Alaska Parks

A Synthesis of Year-Round, Multi-Depth Data from 2006 through 2018

Natural Resource Report NPS/SWAN/NRR—2020/2191

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Executive Summary

Water temperature mediates numerous ecosystem processes in lakes, including stratification, decomposition, evaporation, production, and upwelling. The Southwest Alaska Network (SWAN) monitors water temperature hourly year-round at six mid-lake sites in Katmai and Lake Clark national parks and preserves. This monitoring relies on the use of programmable data loggers attached at various depths to moored vertical lines called temperature arrays. Here, we use the data generated via temperature arrays from 2006 through 2018 to assess the status and trend of lake temperature and the pattern of stratification in four lakes of interest to park managers. Our findings indicate that:

- status metrics for the most recent water year on record (2017) fell within the range of previous years' temperatures at most sites;
- monthly mean surface water temperatures have warmed during the period of record at all sites, with some sites exhibiting strong warming trends in deeper waters; and
- stratification patterns have vacillated during the period of record at all sites, with shifts driven by inconsistencies in winter water temperatures.

Although the temperature array dataset is relatively limited in both space (6 sites) and time (7–12 years per site), it encompasses more than 4 million records in a region where continuous water temperature data are generally lacking, and where temperature-sensitive Pacific salmon species are culturally, economically, and ecologically important. All lakes equipped with temperature arrays support spawning, rearing, and migration of Pacific salmon. Moreover, protecting the habitat necessary to support salmon runs is part of the enabling legislation for these parks. Therefore, we examine how these results might affect salmon at various life stages, in the context of a changing climate. For example:

- daily mean temperatures at the 5 m depth exceeded the State water quality threshold (15 °C) at some point during the periods of record at all arrays, as did weekly mean temperatures for most arrays;
- daily mean temperatures at depths below 20 m did not exceed the 15 °C threshold at any array;
- collectively, these findings indicate that deeper waters may still offer refuge to older rearing juveniles and migrating adults, even when temperatures higher in the water column are suboptimal.

We finish by comparing these results to other studies of temperature trends and stratification patterns, and by offering ideas for future analyses of this dataset.

Acknowledgments

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List of Terms

Dimictic: a lake stratification pattern characterized by two periods of mixing per year, typically in spring and fall.

Meromictic: a lake stratification pattern characterized by a lack of mixing between layers.

Mixing: top-to-bottom circulation or turnover of lake water, in the absence of stratification.

Monomictic: a lake stratification pattern characterized by one period of mixing per year, typically in winter.

Monotonic trend: a trend that always goes in one direction (e.g., increasing or decreasing).

Non-parametric: the characteristic of a statistical test that makes no assumptions regarding the underlying probability distributions of the variables being assessed.

Polymictic: a lake stratification pattern characterized by more than two periods of mixing per year. Some polymictic lakes are too shallow to develop multiple layers; others are deep enough to develop multiple layers, but the layers are interrupted occasionally by strong winds.

Seasonal Kendall test: a non-parametric test that analyzes seasonal data for monotonic trends.

Sen slope: a non-parametric alternative to the parametric slope of a regression line, estimated by calculating the median of all pairwise slopes in a given dataset.

Water year: the 12-month period from October 1 of a given year through September 30 of the following year. A water year is named for the calendar year in which it ends (e.g., water year 2017 spans October 1, 2016 through September 30, 2017).

Acronyms and Abbreviations

ALAG	Alagnak National Wild River
ANIA	Aniakchak National Monument and Preserve
C	Celsius
cm	centimeter(s)
I&M	Inventory and Monitoring
KATM	Katmai National Park and Preserve
KEFJ	Kenai Fjords National Park
km	kilometer(s)
LACL	Lake Clark National Park and Preserve
m	meter(s)
NPS	National Park Service
SWAN	Southwest Alaska Network
yr	year

Introduction

In 1998, the National Park Service (NPS) initiated a natural resource Inventory and Monitoring (I&M) Program. The purpose of the program was to develop a baseline inventory of significant natural resources in national parks, and to monitor key ecological indicators — known as Vital Signs — over time. Now the program includes more than 270 park units organized into 32 regional networks.

The Southwest Alaska Network (SWAN) is one of four networks established within Alaska under the Inventory and Monitoring Program. It consists of five park units: Lake Clark National Park and Preserve (LACL), Katmai National Park and Preserve (KATM), Kenai Fjords National Park (KEFJ), Alagnak National Wild River (ALAG), and Aniakchak National Monument and Preserve (ANIA). Collectively, these park units comprise 3.8 million ha, extending across 650 km of the Alaska and Kenai Peninsulas (Figure 1).

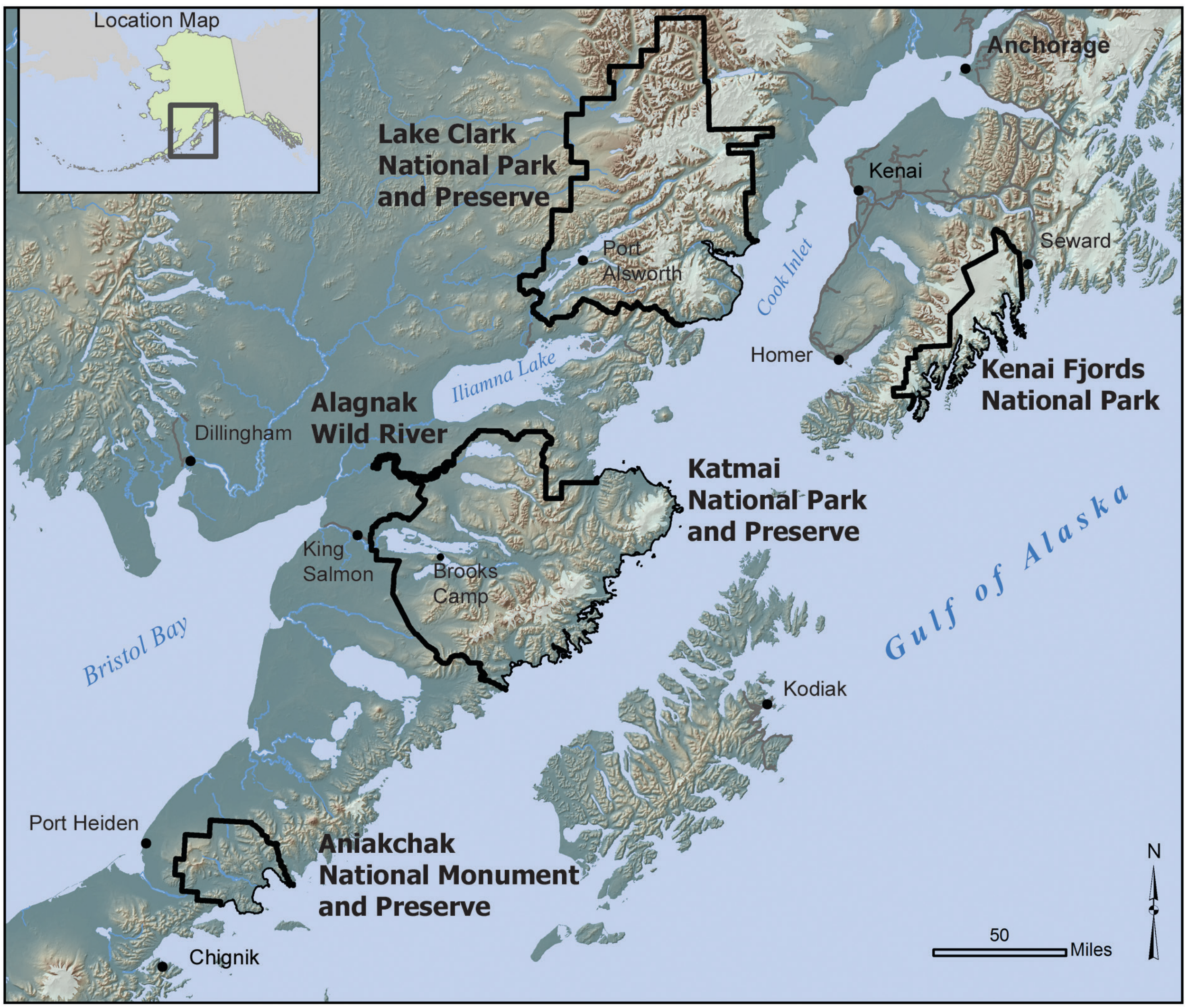

Figure 1. Map of the five park units included in the Southwest Alaska Network.

Freshwater resources in SWAN park units are abundant, featuring thousands of kilometers of rivers and two of the largest lakes in the National Park system: Naknek Lake (58,825 ha) in KATM and Lake Clark (31,116 ha) in LACL. The Naknek Lake and Lake Clark watersheds are so extensive that they cover 41% and 32% of the land area within their respective park units. In establishing these park units, Congress recognized the cultural, ecological, recreational, and economic importance of freshwater resources, with reference to protecting and maintaining lakes in their natural state in the enabling legislation (ANILCA 1980).

Lakes integrate water, energy, nutrients, sediments, and pollutants from the surrounding land and air (Schindler 2009). Therefore, lake water quality can be a useful indicator of broad scale stressors, such as climate change (Williamson et al. 2009). The SWAN monitors several lake water quality parameters, including temperature, pH, conductivity, and dissolved oxygen. Of these parameters, temperature is particularly important, in that values of the other parameters are temperature-dependent (Wilde 2006), as are many physical, chemical, and biological processes in lake ecosystems (Regier et al. 1990, Wrona et al. 2005). Given that lake temperature is a dominant driver which, in turn, is linked to air temperature at broad scales (O'Reilly et al. 2015), and given that air temperature has risen in Alaska and is projected to continue rising throughout this century (Markon et al. 2018), understanding lake temperature change is crucial for managing freshwater resources in Alaskan parklands. It is also crucial for retaining thriving populations of sockeye salmon (*Oncorhynchus nerka*), a temperature-sensitive, lake-dependent keystone species in southwest Alaska (Woll et al. 2014).

Many climate-related studies of lakes have focused on surface water temperature recorded during summer. However, studies that have examined water temperature throughout the water column year-round have observed a variety of interrelated changes. These include earlier onset and later breakdown of thermal stratification in the fall and spring (Niedrist et al. 2018), as well as shortened duration of ice cover in the winter (Magnuson et al. 2000) — all of which may cause shifts in the overall pattern of stratification (Woolway and Merchant 2019).

The SWAN uses several approaches to monitor lake temperature, ranging from year-round measurements at targeted locations to once-a-year measurements at randomly selected sites. These measurements rely on various types of equipment to address specific monitoring objectives listed in the SWAN freshwater monitoring protocol (Shearer et al. 2015a). One of these objectives is the subject of this report — specifically: to assess the status and trend of lake temperature, as well as the pattern of lake stratification within SWAN parklands. To accomplish this objective, the SWAN uses moored installations known as temperature arrays. The arrays record water temperatures in four lakes with relatively easy access, heavy use, and (consequently) focused concern for park managers. Within these lakes, status will be assessed at single depth near the lake surface, using summary statistics for the most recent full water year on record, relative to previous years. Trends will be assessed for all available depths, using non-parametric tests that account for seasonal cycles in water temperature. Finally, stratification will be assessed by defining the type of mixing observed at each array over time (i.e., monomictic, dimictic, polymictic).

Methods

The SWAN monitors lake temperature hourly year-round using programmable data loggers attached at various depths to moored installations called temperature arrays. The SWAN operates six arrays distributed among four lakes previously identified as high priority for monitoring (Table 1, Figure 2; Shearer et al. 2015a). Four of the arrays are located in KATM: three in different basins of Naknek Lake (North, West, and Iliuk) and one in Lake Brooks. The remaining two arrays are located in LACL: one in Lake Clark and another in Kijik Lake.

Table 1. Temperature array site information. Latitude and longitude represent approximate locations of instrument lines. Actual locations change slightly over time as the lines are retrieved, downloaded, and redeployed.

Park	Lake	Basin	Site ID	Year Installed	Latitude (DD) [A]	Longitude (DD) [A]	Depths Monitored (m) [B]	Total Loggers [C]
LACL	Clark	Middle	LCLAR01	2006	60.26433	−154.23468	0, 5, 10. 20, etc., 100	12
LACL	Kijik	[D]	KIJIL01	2010	60.29763	−154.33072	0, 5, 10. 20, etc., 90	11
KATM	Naknek	North	NAKNL01	2008	58.63639	−155.63863	0, 5, 10. 20, etc., 70	9
KATM	Naknek	West	NAKNL02	2008	58.61551	−156.03696	0, 5, 10, 15, 20, 25	6
KATM	Naknek	Iliuk	NAKNL03	2011	58.52188	−155.60320	0, 5, 10. 20, etc., 100	12
KATM	Brooks	[D]	LBROO01	2010	58.53035	−155.85318	0, 5, 10. 20, etc., 50	7

[A] DD = decimal degrees, using WGS84 as the datum.

[B] Etc. = 10-meter increments between 20 m and the deepest depth listed.

[C] The total, across sites, is 57 loggers (or individual time series).

[D] Kijik Lake and Lake Brooks have only one basin each.

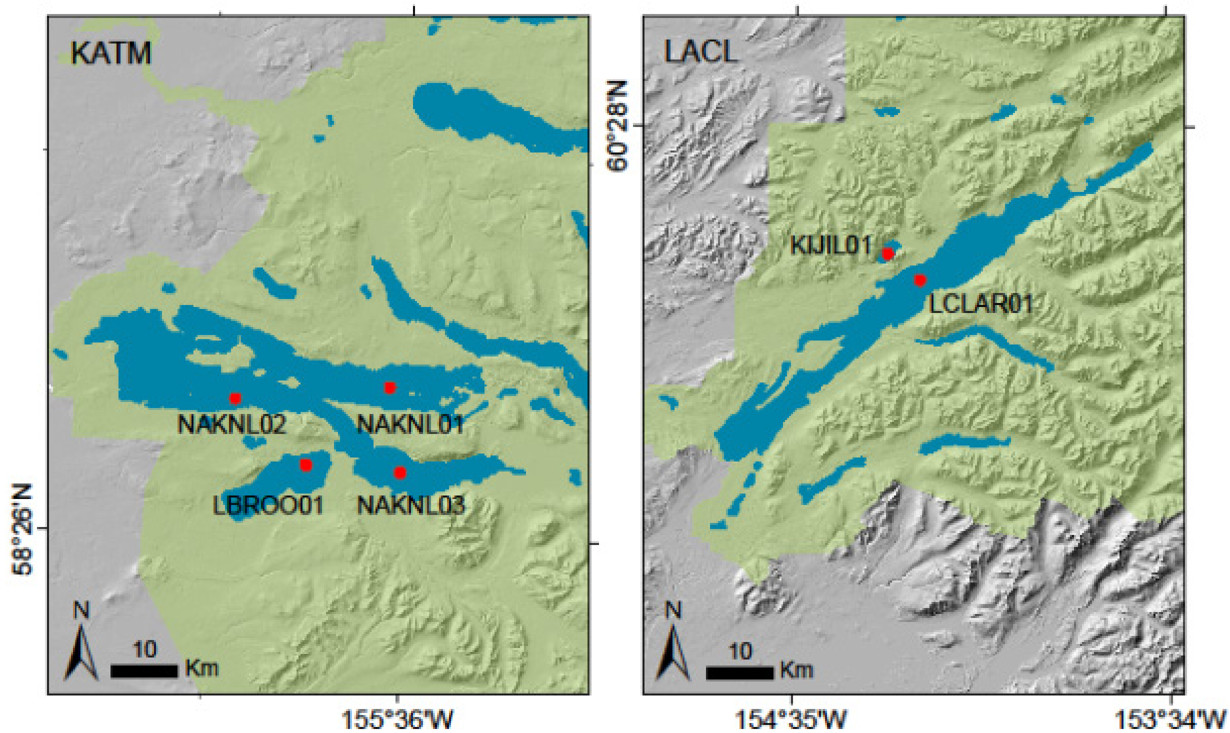

Figure 2. Map of temperature monitoring sites (red points) in Katmai (KATM) and Lake Clark (LACL) national parks and preserves. Parklands are depicted in green; lakes are depicted in blue. Site abbreviations NAKL01, NAKNL02, and NAKNL03 represent Naknek Lake North, West, and Iliuk basins, respectively; LBROO01, LCLAR01, and KIJIL01 represent Lake Brooks, Lake Clark, and Kijik Lake, respectively.

Study Sites

While these lakes vary in size and depth, from 5 to 588 km^2 and from 82 to 266 m, respectively (Table 2), all are oligotrophic, with low biological activity, low nutrient loads, and low to moderate acid buffering capacity. Previous studies have described their stratification patterns as discontinuous cold polymictic (Naknek Lake and Lake Brooks; LaPerriere 1997), weakly stratified during summer and inversely stratified during winter (Lake Clark; Wilkens 2002), and stratified with isothermal waters below 30 m (Kijik Lake; Brabets and Ourso 2006).

Table 2. General characteristics of the four lakes containing SWAN temperature arrays.

Park	Lake	Elevation (m)	Max Depth (m)	Area (km^2)	Volume (km^3)	Glacier Cover (%) [A]	Spawning Salmon Abundance (fish) [B]
LACL	Clark	77.4	265.8	327.1	27.3	5.9	362,400
LACL	Kijik	114.0	108.2	4.5	[C]	0.0	[B]
KATM	Naknek	10.4	175.3	588.2	25.2	2.7	1,883,800
KATM	Brooks	18.9	82.3	75.6	3.4	0.0	64,600

[A] The percentage of glacier cover in each lake's watershed, based on data from the RGI Consortium (2017).

[B] The mean annual abundance of spawning sockeye salmon, for years when various data sources overlapped (2001–2005 and 2007– 2011; Young 2014 and D. Young, unpublished data for Lake Clark; ADFG 2020a and b for Naknek Lake; and ADFG, unpublished data for Lake Brooks). Data were not available for Kijik Lake during this time period.

[C] A volume estimate is not available for this lake.

The lakes also vary in elevation from 10 to 114 m above sea level (Table 2), but all occur within the same overarching hydrologic unit (19040002; Seaber et al. 1987) and climate region (Bristol Bay; Bieniek et al. 2012). Climate in this region is largely influenced by high latitude, complex topography, marine proximity, and the interaction of these features with global atmospheric circulation (Simpson et al. 2002). Long term climate data are available for two nearby monitoring stations: King Salmon and Port Alsworth (Figure 1). Records for the most recent 30-year period (1981–2010) were similar at each station, although King Salmon had a narrower range of monthly mean air temperatures (−8.8 to 13.1 °C) than Port Alsworth (−9.2 to 14.4 °C), and was cooler and wetter, in terms of annual mean temperature (1.7 vs. 2.2 °C) and total precipitation (41.5 vs. 33.6 cm) (Figure 3; NOAA 2020). At both stations, September was the wettest month of the year (Figure 3). During winter months, Lake Clark and Kijik Lake had higher fractions of precipitation falling as snow versus rain than Naknek Lake and Lake Brooks (73.0% and 74.1% vs. 66.7% and 64.6%, respectively, for December through February of 1980–2009), according to estimates by McAfee et al. 2014.

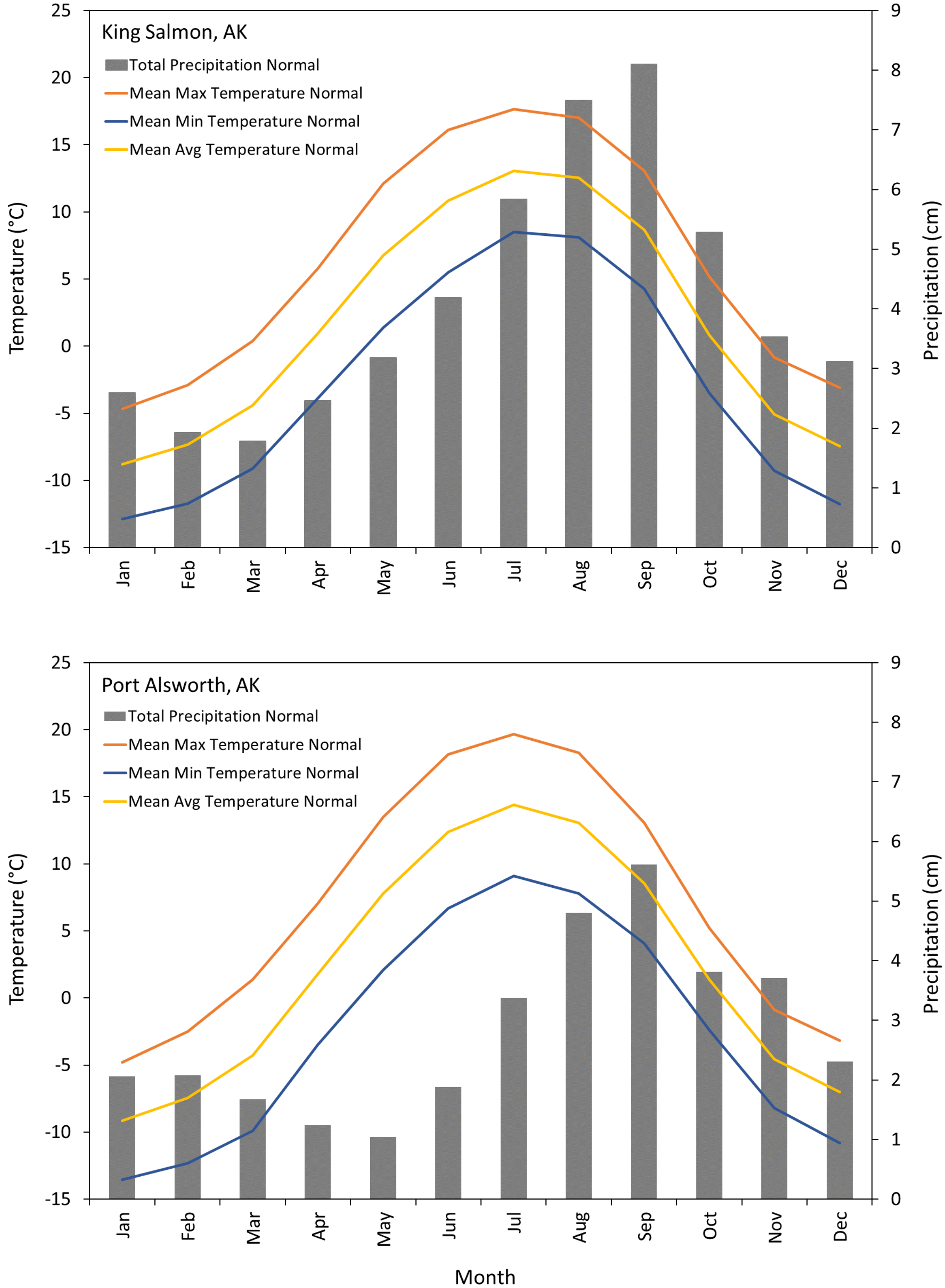

Figure 3. Monthly climate normals for the 30-year time period from 1981 to 2010, measured at the King Salmon and Port Alsworth airports near the SWAN temperature array sites (NOAA 2020).

Field Methods

Each array was built from three lines (Figure 4): an instrument line (vertical rope with the data loggers attached), an anchor line (identical to the instrument line, minus the data loggers), and a bridle line (horizontal rope linking the two other lines). Data loggers were attached year-round to the instrument line, typically at depths approximating 5 m, 10 m, 20 m, 30 m, etc., down to 100 m unless the lake bottom intervened (Table 1). However, data loggers on the shallowest array (Naknek Lake — West basin) were attached at 5-m intervals, from 5 m to 25 m, to increase resolution. For the ice-free portion of the year (approximately June through September), a data logger was also attached at the surface between 0 m and 1 m depth (hereafter called the 0 m logger). Note that the instrument and anchor lines were moored to the lake bottom, so the actual logger depths fluctuated somewhat with lake level. All data loggers were Onset HOBO® Pro v2 U22-001 devices (accuracy: ±0.21 °C from 0 to 50 °C) and were downloaded once or twice per year. For additional details, see Shearer et al. 2015b.

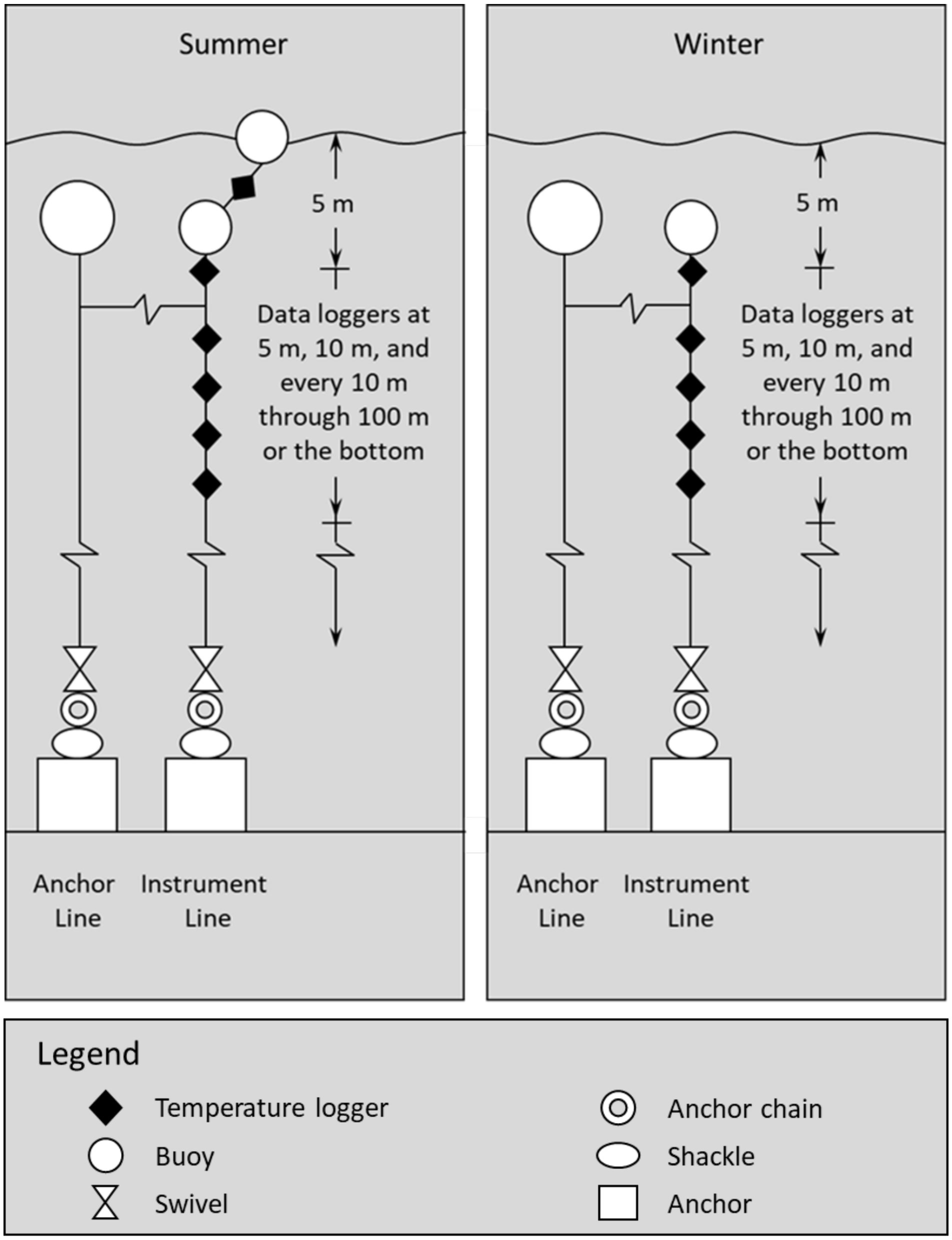

Figure 4. Generic temperature array design during summer and winter months.

Data Management

Data downloaded from temperature arrays were stored in a proprietary, centralized database called AQUARIUS Time-Series™ (Aquatic Informatics, Inc.). Each array-by-depth combination was stored as a separate time series — 57 time series in total. Once imported into AQUARIUS, data were assigned grades and approval ratings (Table 3). Erroneous data, such as air temperatures logged during array maintenance, were graded as unusable and omitted from further analysis (Appendix A). All other downgraded data were incorporated into the analysis. At the time of analysis, graded and approved data were available through August, 2018 for all 57 time series. These data are accessible via the public portal of AQUARIUS at https://irma.nps.gov/aqwebportal/.

Table 3. Grades and approvals assigned to temperature array data in AQUARIUS.

Grade	Approval	Explanation
Good	Approved	No issues noted
Fair	Approved	Minor issues noted (e.g., time stamps not on the hour)
Poor	Approved	Major issues noted (e.g., temperature sensor drifted over time)
Undefined	Approved	Gap in data noted (e.g., maintenance prevented data logging)
Unusable	Rejected	Erroneous data noted (e.g., air temperature recorded)

Prior to analysis, hourly data were examined to determine whether data gaps occurred randomly or with a recurring pattern that could affect analysis results. We found that, while some large data gaps lasted several months and occurred randomly, the majority lasted four hours or less and tended to occur in the late afternoon, during the warmest hours of the day when the arrays were typically serviced (Appendix A). To address these data gaps, we used a rule-of-thumb called the “3/5 rule,” which is commonly applied to missing climate data. According to the rule, any month missing more than three consecutive daily values, or more than five daily values in total, is omitted from the calculation of monthly means (Anderson and Gough 2018). Here, we applied the rule twice: first to filter out days with missing hours (when calculating daily metrics), and then to filter out months with missing days (when calculating monthly metrics). Days and months that met the 3/5 rule criteria were included without interpolation of missing values.

Status Summary

Various metrics were calculated to provide an annual snapshot of temperature in lakes with arrays. We focused primarily on metrics listed in the SWAN freshwater monitoring protocol (Shearer et al. 2015a and b), such as the warmest and coldest daily mean temperatures for each month, the standard deviation of those means for each month, and the warmest day and week of each year. To this list, we added the total number of daily means per year above 15 °C, the State of Alaska’s temperature threshold for waters supporting fish migration and rearing (ADEC 2018). These metrics were selected to highlight monthly and yearly — rather than hourly — patterns (Shearer et al. 2015a). Collectively, they summarize the current status of water temperature as well as the status earlier in the time series, because the calculations cover each year on record. The metrics were computed for every depth of each array using base commands in R software (R Core Team 2017). Data that did not meet the 3/5 rule requirements (described above) were omitted.

Trend Analysis

Seasonal Kendall analysis was used to examine whether lake temperature has changed since the beginning of monitoring at each array. This is a non-parametric, rank-based test that accounts for seasonal cycles in water quality variables like temperature, first by comparing values within user-defined seasons (e.g., months, quarters, etc.) and then by aggregating the results for each season into an overall test for trend (Helsel and Hirsch 2002). For example, if months are selected as seasons, the test analyzes trends in each month separately, then combines the 12 monthly results into a single monotonic trend (i.e., a trend in only one direction, either increasing or decreasing). The test returns a

final p-value and test statistic, Kendall's tau (τ). The value of τ ranges from -1 to 1, signifying the direction of the trend. A negative τ represents cooling and a positive τ represents warming, if the associated p-value is at or below the threshold for statistical significance ($p = 0.05$, for this analysis). For each value of τ, a non-parametric Sen slope may be calculated, estimating the median annual change for a given time series (Hirsch et al. 1982).

Seasonal Kendall tests were applied to both the mean and standard deviation of water temperature to examine changes over time in central tendency and variation in the dataset. Changes in variation were included because lake temperature is expected to become increasingly variable (Niedrist et al. 2018), as extreme weather events become increasingly frequent (Schär et al. 2004, Coumou and Rahmstorf 2012). Monthly means and standard deviations were calculated in R from raw hourly data for each time series. Months that did not meet the requirements of the 3/5 rule (described above) were omitted from the calculation of monthly means and standard deviations. The 0 m data were also excluded due to the limited ability to detect trends in datasets with small samples sizes (i.e., <20 observations; Schertz et al. 1991). All seasonal Kendall tests and Sen slopes were computed in R using Version 2.3.1 of the 'EnvStats' package (Millard 2013).

Stratification Patterns

Stratification is the process whereby lakes develop discrete layers of water with contrasting temperatures and, therefore, densities. Various stratification patterns occur among lakes, depending on their chemistry, morphometry, location, and surrounding climate (Wetzel 2001). Here, these patterns are named via the classification system devised by Lewis (1983) and simplified by Boehrer and Schultze (2008). See the List of Terms above for details.

We assessed stratification patterns at each array by first defining stratified waters as having a daily mean temperature difference of $>|1|$ °C between the shallowest (5 m) and deepest loggers (Woolway and Merchant 2019). We then quantified the duration of stratification by water year (October 1–September 30) and season (summer, winter) at each array. Summer stratification included dates when the temperature difference between layers (i.e., top minus bottom) was >1 °C, typically June–October. Winter (or inverse) stratification included dates when the temperature difference between these layers was < -1 °C, typically December–April. Duration was measured as the longest continuous period of stratification, with one exception. Specifically, if a period of stratification was interrupted midway by a one- to three-day period of mixing, then it was considered continuous for the purpose of this report. Finally, the first and last years in each array's time series were excluded from calculations of summer stratification, because we did not capture the beginning or ending of stratification in these years.

Results

Water temperature has been monitored continuously via temperature array for varying time periods, ranging from 7 years in the Iliuk basin of Naknek Lake to 12 years in Lake Clark. The resulting dataset includes 6 sites, with 6–12 depths per site, totaling 57 time series containing more than 4 million data points (Table 3). For an overview of key features and data gaps in the time series at each site, see Appendix B.

Status Summary

For this report, our summary of current status describes the 2017 water year relative to previous years on record. Water year 2017 was selected because it was the most recent complete year on record at the time of analysis. Here, for the sake of brevity, we highlighted the 5 m depth, as in past annual reports (e.g., Shearer and Moore 2010, Moore and Shearer 2011). Comparable summaries for other depths are available upon request.

Lake Clark

The warmest day (i.e., highest daily mean temperature) in 2017 at the 5 m depth (14.89 °C) occurred on August 3 and was within the range recorded in previous years, both for temperature (11.50–15.91 °C) and for date (July 18–September 19) (Figures 5 and 6). The warmest week (i.e., highest weekly mean temperature) in 2017 at the 5 m depth (14.33 °C, beginning July 29) was also within the range recorded in previous years (11.25–14.72 °C, beginning July 14–September 13). Both metrics (i.e., warmest day and week) were at the high and early end of the range. The coolest day (i.e., lowest daily mean temperature) in 2017 at the 5 m depth (0.55 °C) occurred on January 19, and was similar to the median value for previous coolest days in January (0.51 °C; Figures 5 and 6). Daily mean temperature at the 5 m depth did not exceed 15 °C in 2017, similar to the range recorded in previous years (0–1 day >15 °C). For details, see Appendix C.

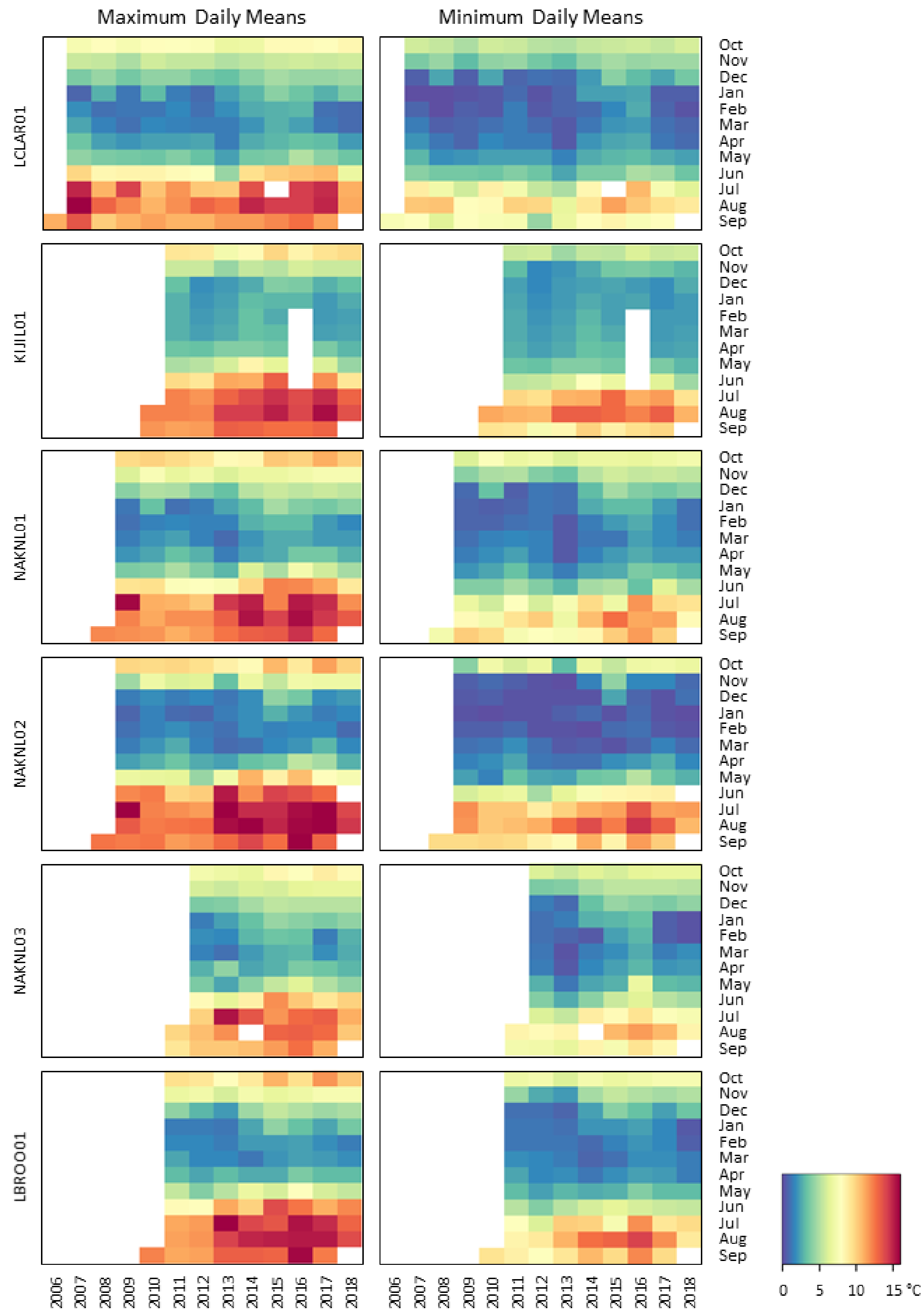

Figure 5. Heatmaps depicting maximum and minimum daily mean temperatures at the 5 m depth, organized by array and water year. Site abbreviations are as follows: LCLAR01 = Lake Clark; KIJIL01 = Kijik Lake; NAKNL01, NAKNL02, and NAKNL03 = Naknek Lake North, West, and Iliuk basins, respectively; and LBROO01 = Lake Brooks.

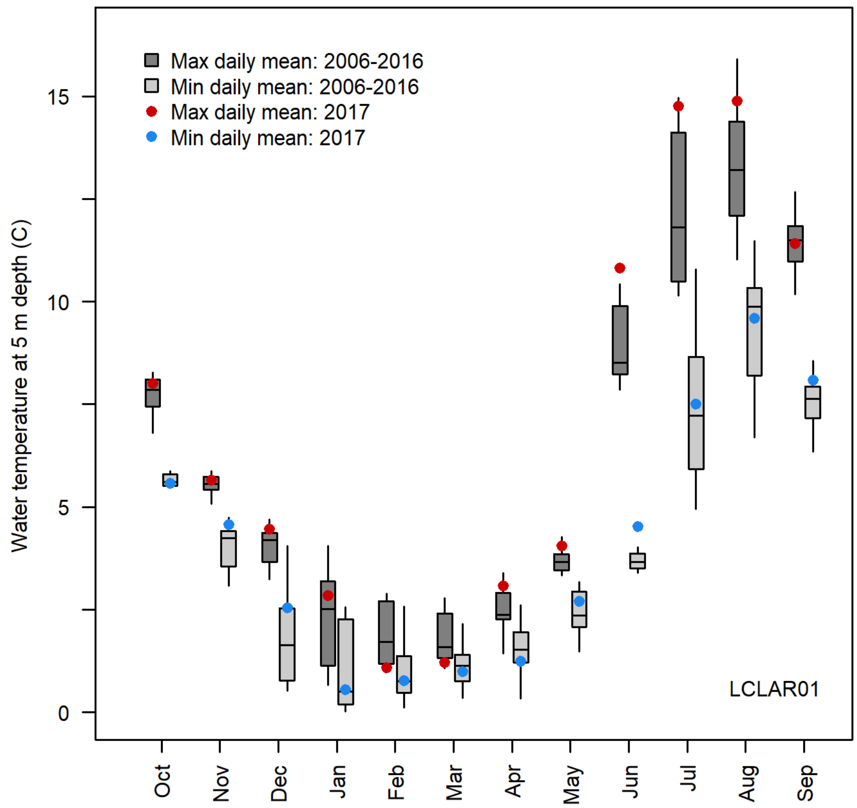

Figure 6. Boxplots of maximum and minimum daily mean temperatures at the 5 m depth in Lake Clark (LCLAR01), organized by month for water years on record before 2017 (2006–2016). Maximum and minimum daily means for 2017 (red and blue dots, respectively) are superimposed for comparison. In each box, the midline is the median, the lower and upper box edges are the 25th and 75th percentiles, and the whiskers extend up to 1.5 times the interquartile range from the edge to the furthest datum within that distance.

Kijik Lake

The warmest day in 2017 at the 5 m depth (15.58 °C) occurred on August 5 and exceeded the range from previous years (12.04–15.10 °C), which occurred within a narrow period (July 31–August 23) (Figures 5 and 7). The warmest week in 2017 (15.34 °C, beginning August 4) also exceeded the range from previous years (11.88–14.92 °C, beginning July 30–August 18). The coolest day in 2017 at the 5 m depth (1.79 °C) occurred on December 8. Overall, the warmest and coolest days at the 5 m depth in 2017 were warmer than the median values during summer months and cooler than the median values during winter months, for previous years on record (2010–2016) (Figure 7). Lastly, daily mean temperature at the 5 m depth exceeded 15 °C for 9 consecutive days in 2017. This number of exceedances surpassed the range recorded in previous years (0–2 days >15 °C). See Appendix D for additional information.

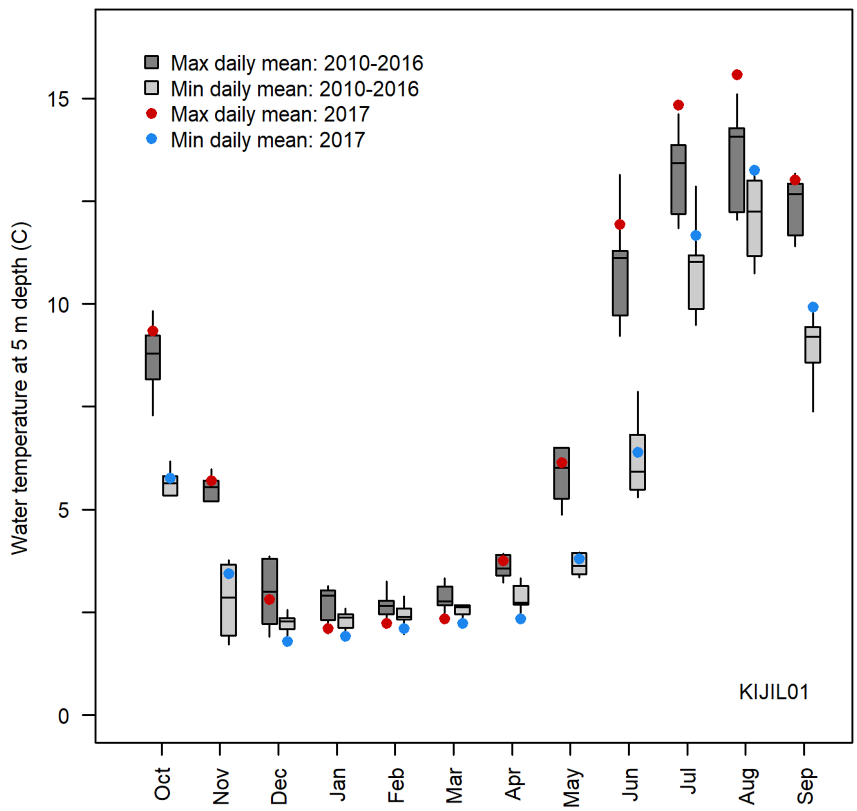

Figure 7. Boxplots of maximum and minimum daily mean temperatures at the 5 m depth in Kijik Lake (KIJIL01), organized by month for water years on record before 2017 (2010–2016). Maximum and minimum daily means for 2017 (red and blue dots, respectively) are superimposed for comparison. In each box, the midline is the median, the lower and upper box edges are the 25th and 75th percentiles, and the whiskers extend up to 1.5 times the interquartile range from the edge to the furthest datum within that distance.

Naknek Lake

North Basin (NAKNL01)

The warmest day in 2017 at the 5 m depth (14.83 °C) occurred on July 30 and was within the range recorded in previous years, both for temperature (11.77–15.83 °C) and for date (July 15–September 20) (Figures 5 and 8). The warmest week in 2017 (14.45 °C, beginning July 26) was also within the range recorded in previous years (11.47–15.48 °C, beginning July 14–September 14). By comparison, the coolest day in 2017 (1.77 °C) occurred on February 20. Overall, the warmest and coolest days at the 5 m depth in 2017 were warmer than the median values for previous years on record (2008–2016) (Figure 8). Finally, daily mean temperature at the 5 m depth remained below the 15 °C threshold in 2017, matching the low end of the range recorded in previous years (0–20 days >15 °C). For details, see Appendix E.

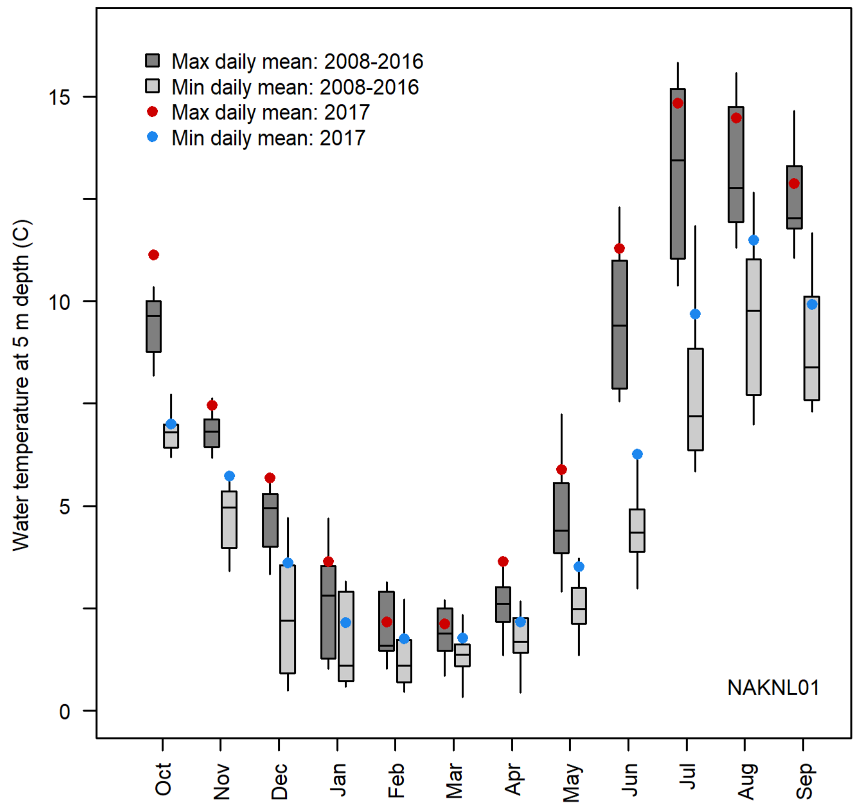

Figure 8. Boxplots of maximum and minimum daily mean temperatures at the 5 m depth in the North basin of Naknek Lake (NAKNL01), organized by month for water years on record before 2017 (2008–2016). Maximum and minimum daily means for 2017 (red and blue dots, respectively) are superimposed for comparison. In each box, the midline is the median, the lower and upper box edges are the 25th and 75th percentiles, and the whiskers extend up to 1.5 times the interquartile range from the edge to the furthest datum within that distance.

West Basin (NAKNL02)

The warmest day in 2017 at the 5 m depth (16.23 °C) occurred on July 31 and was within the range recorded in previous years, both for temperature (12.51–16.30 °C) and for date (July 15–September 19) (Figures 5 and 9). The warmest week in 2017 (15.93 °C, beginning July 29) was warmer than previous weeks on record (11.98–15.88 °C, beginning July 14–August 31). The coolest day in 2017 (0.17 °C) occurred on January 18. Overall, the warmest and coolest days at the 5 m depth in 2017 tended to be warmer than the median values for previous years on record (2008–2016), except during winter months, when 2017 temperatures were at or below the median (Figure 9). Daily mean temperature at the 5 m depth exceeded 15 °C for 24 days in 2017. This number of exceedances was within the range recorded in previous years (0–37 days >15 °C). See Appendix F for details.

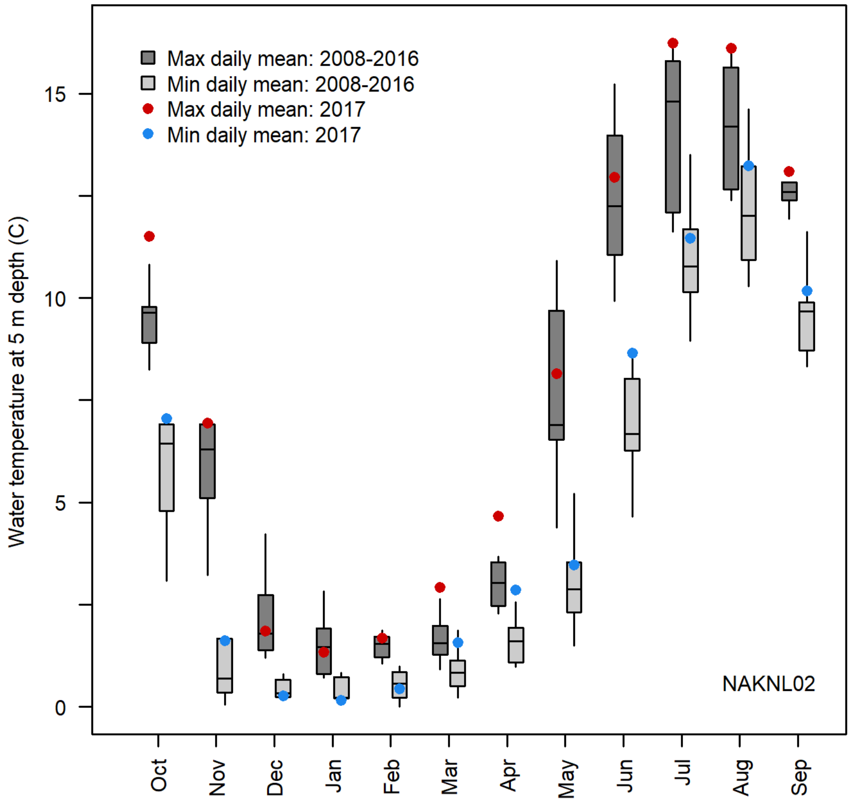

Figure 9. Boxplots of maximum and minimum daily mean temperatures at the 5 m depth in the West basin of Naknek Lake (NAKNL02), organized by month for water years on record before 2017 (2008–2016). Maximum and minimum daily means for 2017 (red and blue dots, respectively) are superimposed for comparison. In each box, the midline is the median, the lower and upper box edges are the 25th and 75th percentiles, and the whiskers extend up to 1.5 times the interquartile range from the edge to the furthest datum within that distance.

<u>Iliuk Basin (NAKNL03)</u>

The warmest day in 2017 at the 5 m depth (13.15 °C) occurred on July 28, which was earlier than in previous years (July 30–August 18), but within the range of recorded high temperatures (9.87–13.33 °C) (Figures 5 and 10). The warmest week in 2017 (12.58 °C, beginning July 28) was also within the range recorded in previous years (9.63–15.48 °C, beginning July 27–August 14). The coolest day in 2017 (0.52 °C) occurred on January 22. Similar to the West basin site, the warmest and coolest days at the 5 m depth in 2017 were warmer than the median values for previous years on record (2011–2016), except during winter months, when 2017 temperatures were typically at or below the median (Figure 10). Daily mean temperature at the 5 m depth did not exceed 15 °C in 2017, which was comparable to previous years on record (0–1 day >15 °C). For details, see Appendix G.

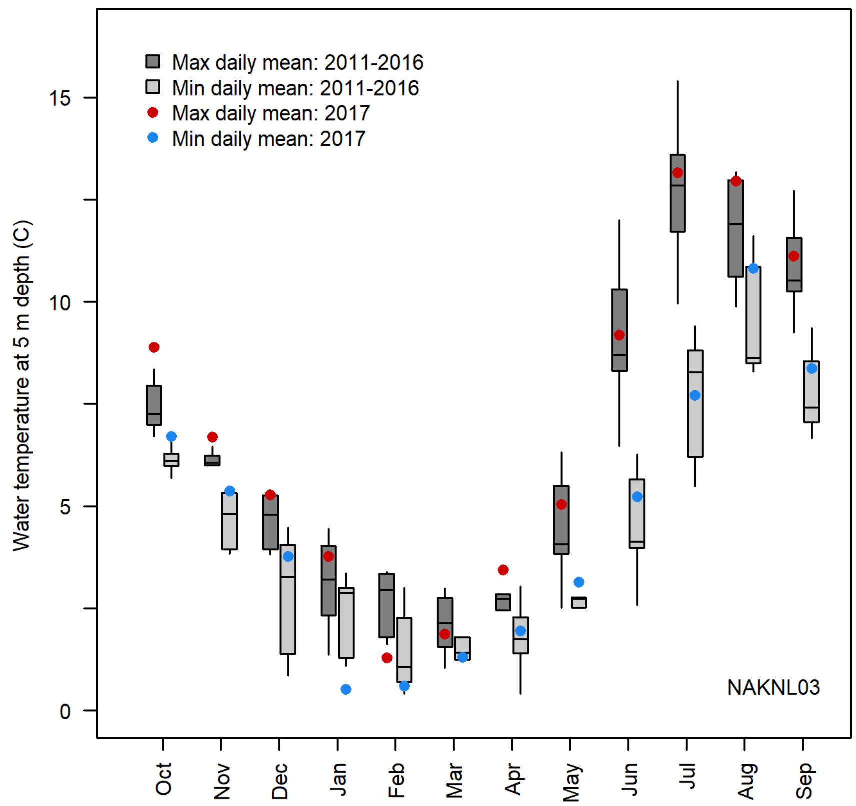

Figure 10. Boxplots of maximum and minimum daily mean temperatures at the 5 m depth in the Iliuk basin of Naknek Lake (NAKNL03), organized by month for water years on record before 2017 (2011–2016). Maximum and minimum daily means for 2017 (red and blue dots, respectively) are superimposed for comparison. In each box, the midline is the median, the lower and upper box edges are the 25th and 75th percentiles, and the whiskers extend up to 1.5 times the interquartile range from the edge to the furthest datum within that distance.

Lake Brooks

The warmest day in 2017 at the 5 m depth (15.33 °C) occurred on August 3 and was within the range recorded in previous years, both for temperature (11.49–15.91 °C) and for date (July 31–September 3) (Figures 5 and 11). The warmest week in 2017 (14.85 °C, beginning July 29) was also within the range recorded in previous years (11.24–15.40 °C, beginning July 25–August 31). The coolest day in 2017 (1.61 °C) occurred on January 12. Overall, the warmest and coolest days at the 5 m depth in 2017 tended to be warmer than the median value for previous years on record (2010–2016), when summarized by month (Figure 11), particularly for October. Lastly, daily mean temperature at the 5 m depth exceeded 15 °C for 2 days in 2017. This number of exceedances was within the range recorded in previous years (0–32 days >15 °C). See Appendix H for additional information.

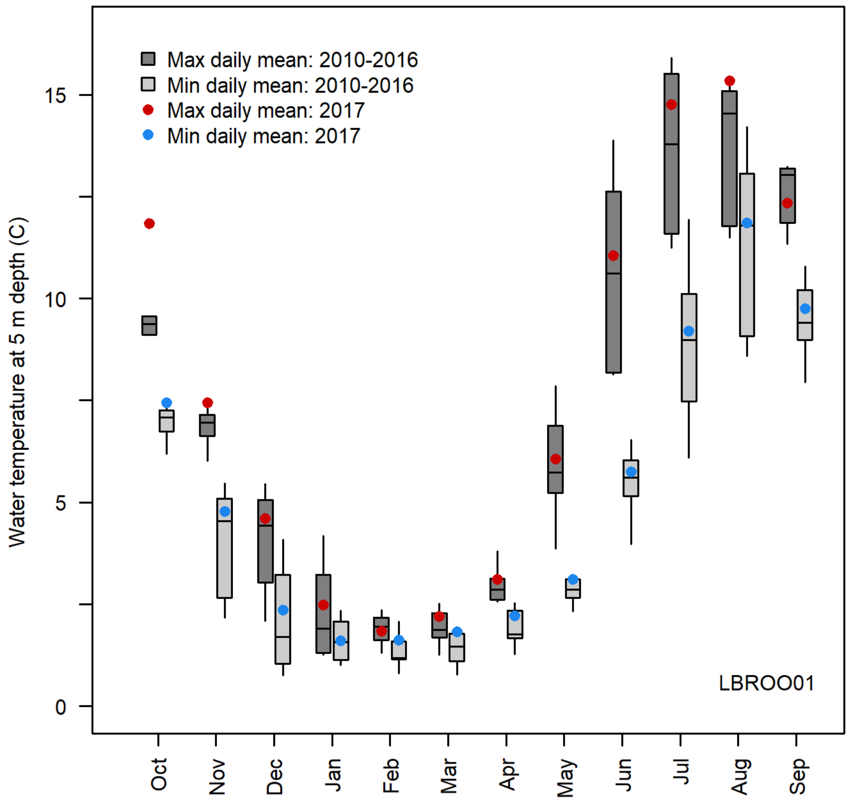

Figure 11. Boxplots of maximum and minimum daily mean temperatures at the 5 m depth in Lake Brooks (LBROO01), organized by month for water years on record before 2017 (2010–2016). Maximum and minimum daily means for 2017 (red and blue dots, respectively) are superimposed for comparison. In each box, the midline is the median, the lower and upper box edges are the 25th and 75th percentiles, and the whiskers extend up to 1.5 times the interquartile range from the edge to the furthest datum within that distance.

Trend Analysis — Means

Seasonal Kendall results indicated that monthly mean water temperature at the 5 m depth has warmed during the period of record at all six arrays (Table 4). The rate of warming at this depth varied among arrays from 0.05 to 0.24 °C per year. For some arrays, strong warming trends extended to deeper waters. Conversely, cooling trends were apparent at depths below 5 m at one array (Kijik). Overall, the strength of trends in KATM exceeded that in LACL. Lake-specific results are highlighted below.

Table 4. Results of seasonal Kendall tests for changes over time in mean water temperature by depth at six array sites. Periods of record included in the tests differ by site as shown. The test statistic (τ) indicates the direction of the trend. Positive τ values with p-values <0.05 (dark red) are interpreted as significant warming trends. Negative τ values with p-values <0.05 (dark blue) or 0.05–0.10 (light blue) are interpreted as significant or substantial cooling trends, respectively. For each value of τ, the Sen slope estimates the median annual change in temperature (Δ/yr, in °C). Cells with dashes represent no data at a given depth (gray). Values between −0.001 and 0.001 are rounded to 0.000.

Depth (m)	LCLAR01 [A] (9/2006–8/2018)			KIJIL01 [A] (8/2010–8/2018)			NAKNL01 [A] (9/2008–8/2018)			NAKNL02 [A, B] (9/2008–8/2018)			NAKNL03 [A] (8/2011–8/2018)			LBROO01 [A] (9/2010–8/2018)		
	τ	p	Δ/yr	τ	p	Δ/yr	τ	p	Δ/yr	τ	p	Δ/yr	τ	p	Δ/yr	τ	p	Δ/yr
5	0.184	0.004	0.047	0.203	0.013	0.063	0.426	0.000	0.154	0.320	0.000	0.123	0.460	0.000	0.244	0.315	0.000	0.139
10	0.173	0.006	0.037	−0.016	1.000	0.000	0.396	0.000	0.127	0.336	0.000	0.113	0.437	0.000	0.240	0.351	0.000	0.131
20	0.136	0.045	0.024	−0.291	0.001	−0.054	0.314	0.000	0.096	0.271	0.000	0.088	0.444	0.000	0.220	0.286	0.001	0.093
30	0.035	0.576	0.005	−0.113	0.228	−0.013	0.270	0.000	0.067	–	–	–	0.476	0.000	0.210	0.119	0.164	0.035
40	0.011	0.873	0.004	−0.294	0.004	−0.061	0.096	0.188	0.030	–	–	–	0.484	0.000	0.155	0.000	1.000	0.000
50	0.044	0.569	0.005	−0.024	0.940	0.000	0.163	0.025	0.044	–	–	–	0.421	0.000	0.143	−0.024	0.803	−0.009
60	−0.034	0.603	−0.005	0.020	0.707	0.003	0.089	0.225	0.019	–	–	–	0.500	0.000	0.142	–	–	–
70	0.005	0.968	0.001	−0.010	1.000	0.004	0.056	0.454	0.011	–	–	–	0.500	0.000	0.139	–	–	–
80	−0.057	0.395	−0.008	−0.179	0.055	−0.010	–	–	–	–	–	–	0.492	0.000	0.122	–	–	–
90	−0.081	0.230	−0.009	0.083	0.259	0.017	–	–	–	–	–	–	0.508	0.000	0.115	–	–	–
100	−0.041	0.532	−0.003	–	–	–	–	–	–	–	–	–	0.476	0.000	0.109	–	–	–

[A] LCLAR01 = Lake Clark; KIJIL01 = Kijik Lake; NAKNL01, NAKNL02, and NAKNL03 = Naknek Lake North, West, and Iliuk basins; LBROO01 = Lake Brooks.

[B] Results from other depths at the NAKNL02 array (i.e., 15 m and 25 m) indicate significant warming trends (see Appendix I for details).

Lake Clark and Kijik Lake
Water at the three shallowest depths (5, 10, and 20 m) exhibited significant warming trends during the period of record at the Lake Clark array, with increases ranging from 0.02 to 0.05 °C per year. Other depths had no significant trends. At Kijik Lake, the 5 m depth exhibited a significant warming trend during the period of record but, unlike other arrays, warming was limited to this depth stratum. Also unlike other arrays, significant cooling trends were apparent deeper in the water column, at the 20 m and 40 m depths. Rates of change varied from 0.06 °C per year at the 5 m depth to −0.06 °C per year at the 40 m depth.

Naknek Lake and Lake Brooks
Significant warming trends in Naknek Lake occurred not only near the surface, but also throughout the water column at two of the three arrays (NAKNL02 and NAKNL03). At the third array (NAKNL01), warming trends were limited to the upper strata (5 m to 30 m) and the 50 m depth. Rates of warming varied among these arrays from 0.04 to 0.24 °C per year (at NAKNL01 and NAKNL03, respectively). Finally, waters from 5 m to 20 m depth exhibited significant warming during the period of record at the Lake Brooks array, with increases of as much as 0.14 °C per year. Mean water temperatures below 20 m at Lake Brooks were stable over time.

Trend Analysis — Standard Deviations
Trends in the standard deviation (SD) of mean temperature were less uniform than trends in mean temperature, in that no particular depth exhibited consistent increases or decreases across all arrays. However, where significant trends in SD occurred, they generally indicated increased variation over time (Table 5). The magnitude of increase was small, ranging from 0.01 to 0.03 °C per year. As with the analysis of means, the analysis of SDs revealed stronger trends in KATM than in LACL. Lake-specific results are presented below.

Table 5. Results of seasonal Kendall tests for changes over time in water temperature standard deviation (SD) by depth at six array sites. Periods of record included in the tests differ by site as shown. The test statistic (τ) indicates the direction of the trend. Positive τ values with p-values <0.05 (dark red) or 0.05–0.10 (light red) are interpreted as significant or substantial warming trends, respectively. Negative τ values with p-values <0.05 (dark blue) are interpreted as significant cooling trends. For each value of τ, the Sen slope estimates the median annual change in SD (Δ/yr, in °C). Cells with dashes represent no data (gray). Values between −0.001 and 0.001 are rounded to 0.000.

Depth (m)	LCLAR01 [A] (9/2006–8/2018)			KIJIL01 [A] (8/2010–8/2018)			NAKNL01 [A] (9/2008–8/2018)			NAKNL02 [A, B] (9/2008–8/2018)			NAKNL03 [A] (8/2011–8/2018)			LBROO01 [A] (9/2010–8/2018)		
	τ	p	Δ/yr	τ	p	Δ/yr	τ	p	Δ/yr	τ	p	Δ/yr	τ	p	Δ/yr	τ	p	Δ/yr
5	−0.138	0.031	−0.010	0.190	0.020	0.020	0.052	0.486	0.005	0.180	0.012	0.020	0.071	0.461	0.009	0.149	0.080	0.018
10	−0.060	0.349	−0.004	0.178	0.042	0.008	0.085	0.245	0.008	0.252	0.001	0.028	0.056	0.573	0.007	0.185	0.029	0.016
20	−0.106	0.121	−0.004	0.050	0.598	0.003	0.147	0.072	0.010	0.261	0.000	0.023	0.167	0.075	0.015	0.185	0.029	0.015
30	−0.055	0.401	−0.003	0.119	0.228	0.002	0.200	0.006	0.012	–	–	–	0.270	0.004	0.018	0.143	0.093	0.010
40	−0.056	0.401	−0.001	−0.005	1.000	0.000	0.181	0.012	0.010	–	–	–	0.071	0.461	0.007	0.113	0.186	0.009
50	−0.001	1.000	0.000	−0.065	0.598	−0.001	0.211	0.004	0.011	–	–	–	0.000	1.000	0.000	0.077	0.372	0.003
60	0.010	0.873	0.001	−0.077	0.452	−0.001	0.207	0.004	0.012	–	–	–	−0.016	0.897	−0.001	–	–	–
70	−0.007	0.936	0.000	−0.142	0.132	−0.001	0.148	0.041	0.008	–	–	–	−0.008	0.965	0.000	–	–	–
80	−0.003	0.983	0.000	−0.029	0.821	0.000	–	–	–	–	–	–	−0.040	0.696	−0.002	–	–	–
90	0.056	0.424	0.001	0.104	0.228	0.000	–	–	–	–	–	–	−0.008	0.965	−0.001	–	–	–
100	−0.002	0.984	0.000	–	–	–	–	–	–	–	–	–	0.016	0.897	0.002	–	–	–

[A] LCLAR01 = Lake Clark; KIJIL01 = Kijik Lake; NAKNL01, NAKNL02, and NAKNL03 = Naknek Lake North, West, and Iliuk basins; LBROO01 = Lake Brooks.

[B] Results from other depths at the NAKNL02 array (i.e., 15 m and 25 m) indicate significant warming trends (see Appendix I for details).

Lake Clark and Kijik Lake

Lake Clark exhibited a significant decrease in SD at the 5 m depth during the period of record, with a rate of change of −0.01 °C per year. Conversely, Kijik Lake exhibited significant increases in SD at the 5 m and 10 m depths, with changes of 0.02 °C and 0.01 °C per year, respectively.

Naknek Lake and Lake Brooks

Trends in SD at Naknek Lake varied by basin. For example, in the West basin (NAKNL02), SD increased during the period of record throughout the water column. Elsewhere in the lake, SD increased only at the 30 m depth (i.e., NAKNL03) and below (i.e., NAKNL01). At Lake Brooks, waters at the 10 m and 20 m depths also exhibited significant increasing trends in SD. The rate of change in these lakes varied from 0.01 to 0.03 °C per year.

Stratification Patterns

Differences in temperature between the top and bottom depths suggested a dimictic stratification pattern at most arrays early and late in the time series, interspersed with monomictic or polymictic patterns in isolated years (Figures 12 and 13). Changes between patterns were driven by variability in the duration of winter stratification, which was unexpectedly asynchronous across arrays in some years (e.g., water year 2013). In general, the mean start dates of continuous stratification varied less than the mean end dates, when compared across arrays, for both winter and summer stratification. Also, winter stratification tended to be short or nonexistent in water years 2014–2016.

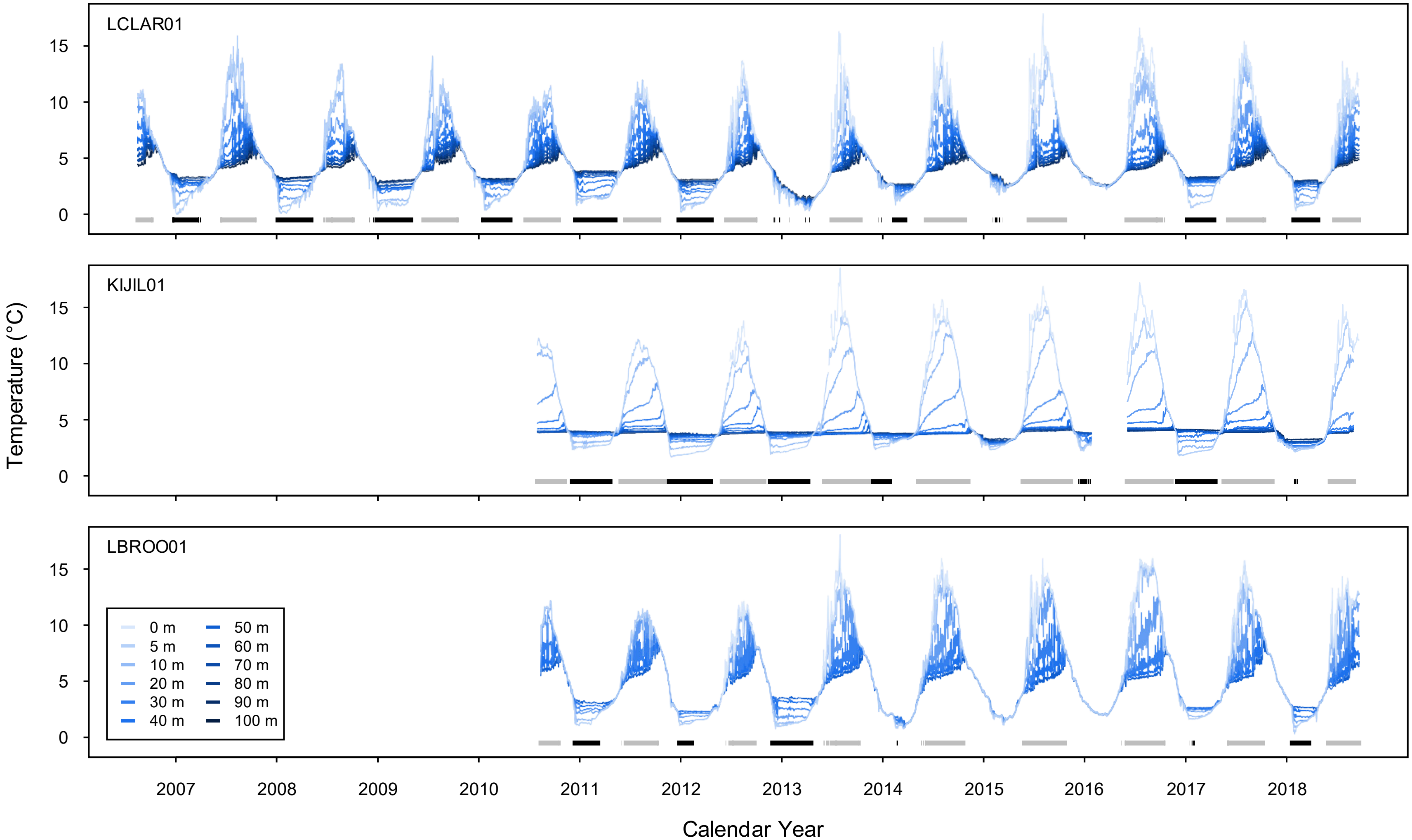

Figure 12. Daily mean water temperature by site, depth, and year for the Lake Clark (LCLAR01), Kijik Lake (KIJIL01), and Lake Brooks (LBROO01) arrays. Black and gray lines at the bottom of each plot represent days when the water column was stratified during winter and summer, respectively.

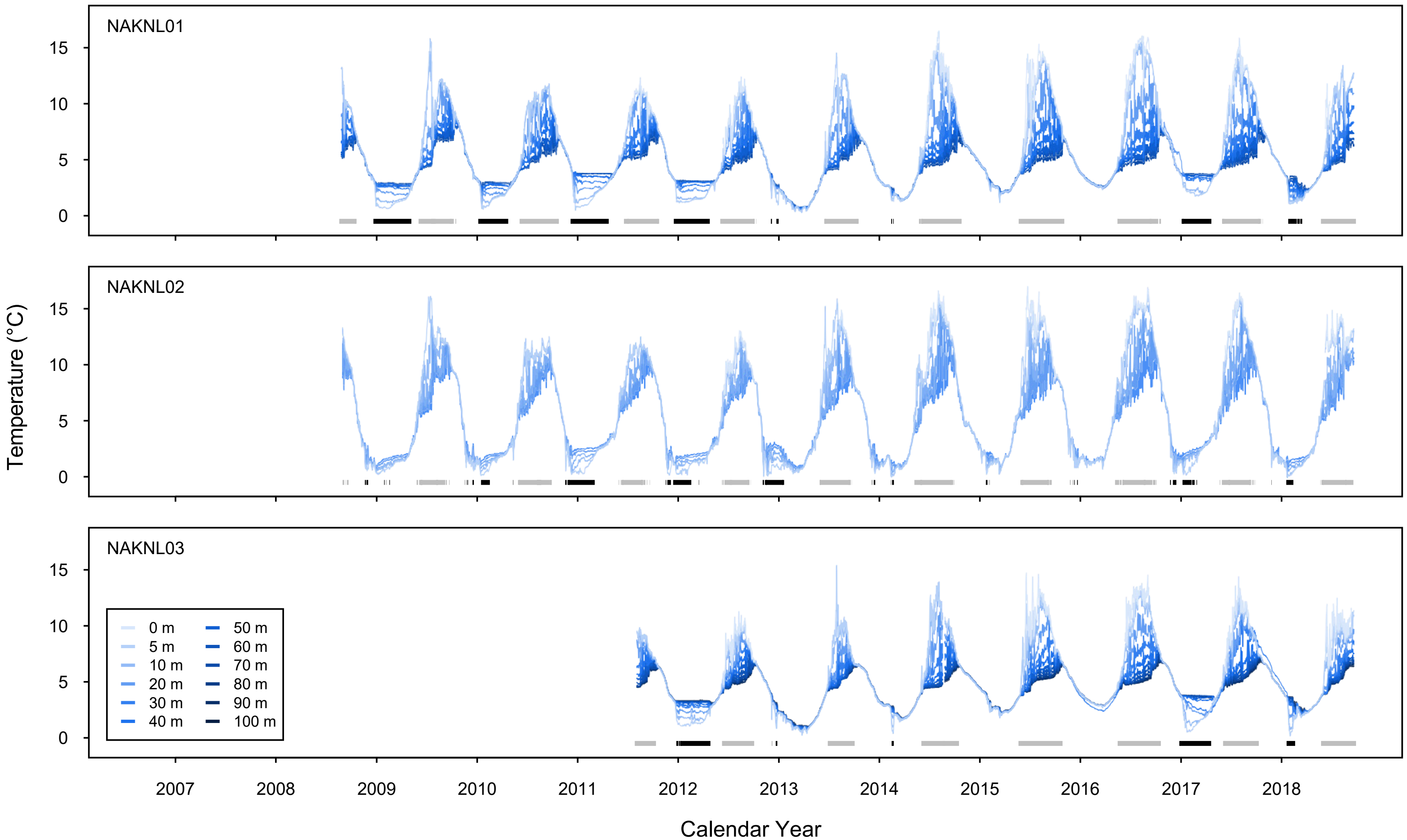

Figure 13. Daily mean water temperature by site, depth, and year for arrays located in the North (NAKNL01), West (NAKNL02), and Iliuk (NAKNL03) basins of Naknek Lake. Black and gray lines at the bottom of each plot represent days when the water column was stratified during winter and summer, respectively.

Lake Clark

The mean duration of summer stratification for water years 2007–2017 was 122 days (SD = 13 days; range = 102–139 days). Mean start and end dates were June 14 and October 13, respectively (Figure 14). The mean duration of winter stratification for water years 2007–2018 was 76 days (SD = 50 days; range = 0–145 days), with a mean start date of January 10 and a mean end date of April 3 (Figure 15). Lake Clark did not stratify in winter during water year 2016 at the location of the temperature array.

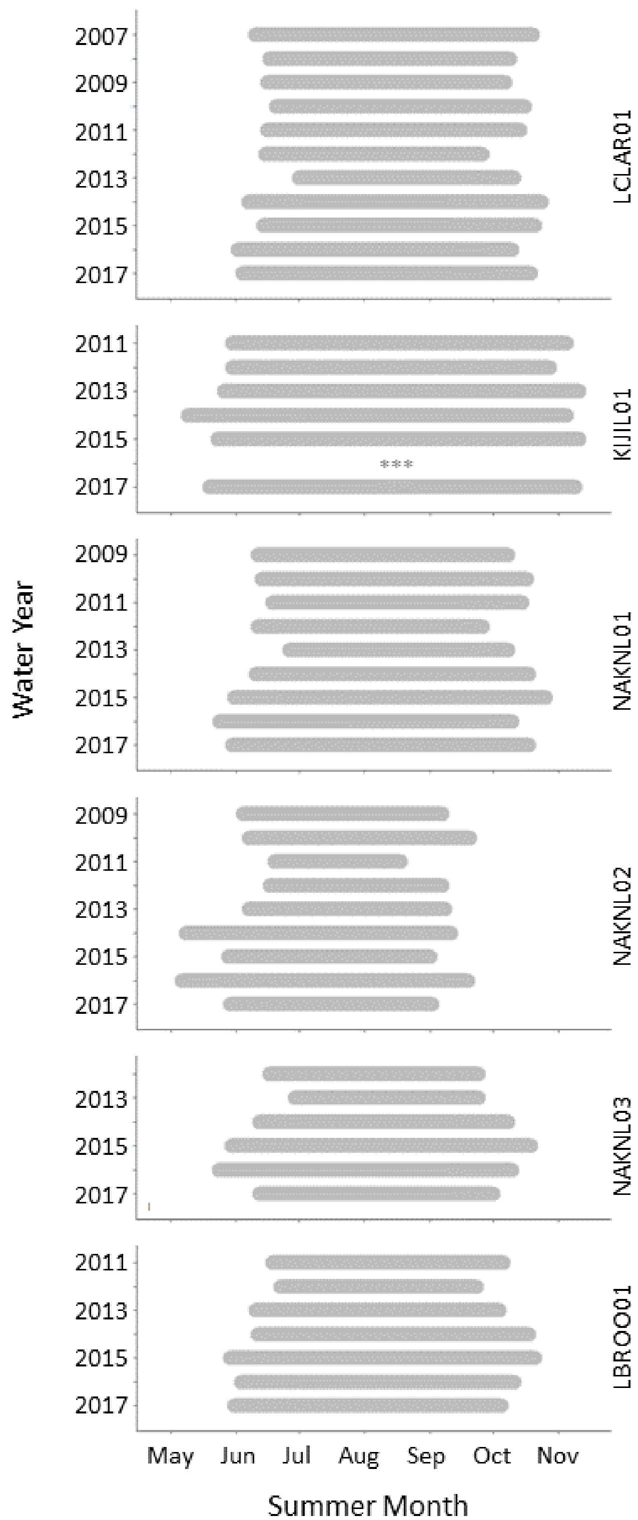

Figure 14. Duration of continuous summer stratification by water year at six temperature array sites. Asterisks at Kijik Lake (KIJIL01) in 2016 represent truncated data in that year. Abbreviations for other sites are as follows: LCLAR01 = Lake Clark; NAKNL01, NAKNL02, and NAKNL03 = Naknek Lake North, West, and Iliuk basins, respectively; and LBROO01 = Lake Brooks.

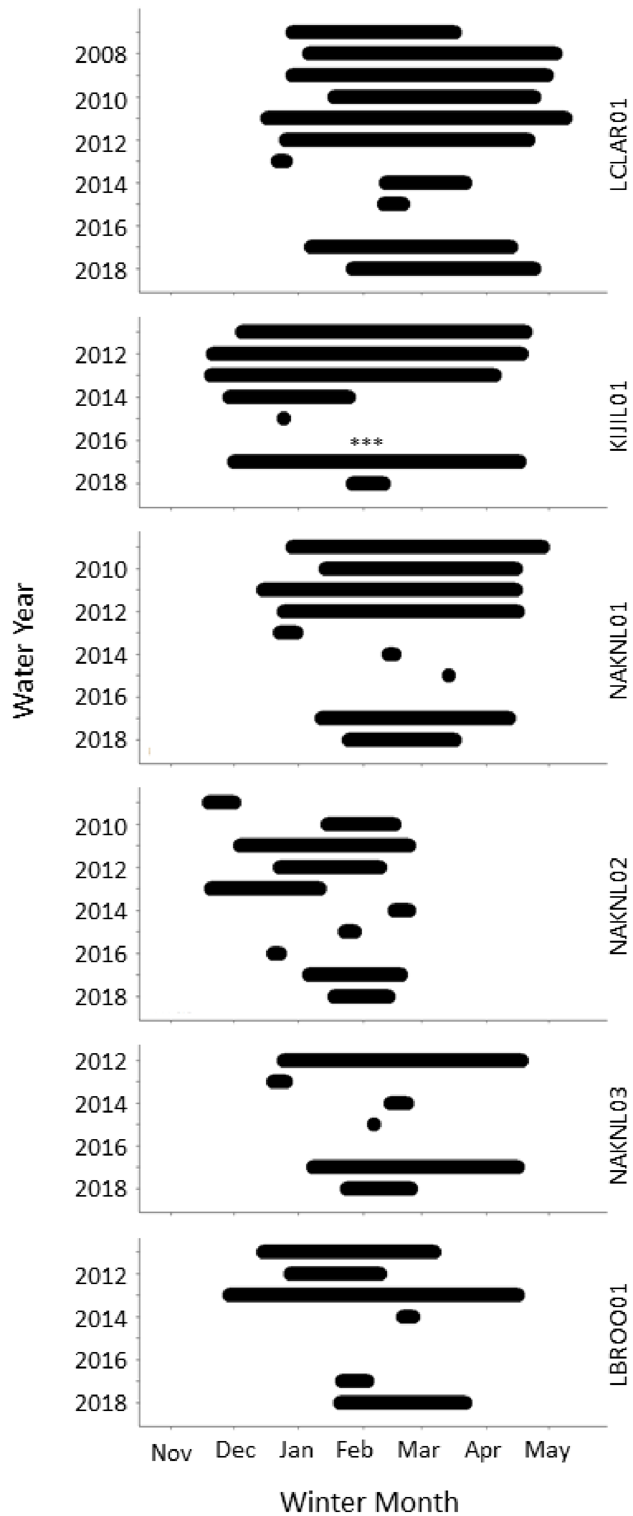

Figure 15. Duration of continuous winter stratification by water year at six temperature array sites. Blank years indicate no winter stratification; asterisks at Kijik Lake (KIJIL01) represent truncated data. Abbreviations for other sites are as follows: LCLAR01 = Lake Clark; NAKNL01, NAKNL02, and NAKNL03 = Naknek Lake North, West, and Iliuk basins, respectively; and LBROO01 = Lake Brooks.

Kijik Lake

Summer stratification lasted, on average, 168 days (SD = 11 days; range = 151–180 days) during water years 2011–2015, and 2017, both the longest duration and smallest variation of all the arrays. Average start and end dates of summer stratification were May 23 and November 6, respectively (Figure 14). Winter stratification lasted an average of 90 days (SD = 64 days; range = 1–149 days) during the water years 2011–2015 and 2017–2018, with average start and end dates of December 10 and March 10 (Figure 15). Note that water year 2016 was excluded due to array movement (see Appendix B for details).

Naknek Lake

North Basin (NAKNL01)

Summer stratification varied in duration from 104 to 148 days (mean = 126, SD = 15) during water years 2009–2017. Mean start and end dates were June 9 and October 13, respectively (Figure 14). In comparison, winter stratification varied in duration from 0 to 121 days (mean = 57, SD = 59) during water years 2009–2018, with mean start and end dates of January 15 and March 22 (Figure 15). Like Lake Clark, the North basin of Naknek Lake did not stratify in winter during water year 2016 at the location of the temperature array.

West Basin (NAKNL02)

Summer stratification lasted, on average, 99 days (SD = 22 days; range = 60–136 days) during water years 2009–2017. Average start and end dates of summer stratification were May 31 and September 7, respectively (Figure 14). Winter stratification lasted an average of 31 days (SD = 25 days; range = 3–81 days) during the water years 2009–2018, with average start and end dates of December 29 and January 29 (Figure 15). Of the six sites with temperature arrays, this site displayed a consistent polymictic pattern, less discernable in Figures 14 and 15 (which display the longest continuous period of stratification) than in Figure 13 (which displays any period when the top and bottom-most depths differed by > 1 °C).

Iliuk Basin (NAKNL03)

The mean duration of summer stratification for water years 2012–2017 was 116 days (SD = 22 days; range = 87–142 days). Mean start and end dates were June 10 and October 4, respectively (Figure 14). The mean duration of winter stratification for water years 2012–2018 was 37 days (SD = 49 days; range = 0–115 days), with a mean start date of January 16 and a mean end date of February 28 (Figure 15). The Iliuk basin of Naknek Lake did not stratify in winter during water year 2016 at the location of the temperature array.

Lake Brooks

Summer stratification lasted, on average, 121 days (SD = 17 days; range = 93–145 days) during water years 2011–2017, with average start and end dates of June 9 and October 8, respectively (Figure 14). Like other arrays, the duration of winter stratification varied widely. It lasted an average of 43 days (SD = 49 days; range = 0–138 days) during the water years 2011–2018, with average start and end dates of January 7 and March 5 (Figure 15). Water years 2015 and 2016 failed to stratify during winter at this array.

Discussion

Water temperature regulates key physical processes in lakes (Schindler and Rogers 2009). It also regulates most biological processes in lake-dwelling organisms, nearly all of which have optimal temperature ranges for survival, growth, and reproduction. Here, we examined the status and trend of water temperature and the pattern of stratification at six sites in four lakes with high monitoring priority. Our findings indicate that: (1) temperature status metrics summarizing the most recent, complete water year on record generally fell within the range of previously recorded temperatures at the 5 m depth, (2) monthly mean water temperatures have warmed during the period of record at all sites at the 5 m depth, and (3) stratification patterns have vacillated during the period of record, driven by inconsistencies in winter water temperature.

Status Summary

Our finding that temperature metrics for the current year typically fell within the range of previous years depends, in part, on the definition of the terms "current" and "previous." This study defined current as the most recent complete year on record at the time of analysis (2017). Although generally warmer than normal, the mean annual air temperature in 2017 (−1.50 °C) was below the record-breaking temperatures of 2016 (−0.06 °C) and 2019 (0.17 °C) for the state of Alaska (NOAA NCEI 2020). Had either of these years been selected as current rather than 2017, the results of our status summary likely would have differed. Also, although metrics for 2017 were within the previously recorded range (2006–2016), they might not be within the historical range. In other words, the recorded range might denote a shifted baseline (Pauly 1995), relative to water temperatures experienced before monitoring began.

All lakes equipped with arrays support migration, spawning, and rearing of multiple Pacific salmon species, with sockeye salmon (*O. nerka*) being most abundant. Temperature preferences of salmon depend not only on species and population, but also on life stage. For example, subyearling sockeye tend to prefer warmer water temperatures than older juveniles and adults (Sauter et al. 2001). Subyearlings also tend to occupy shallow waters at lake edges, where peak temperatures are often warmer than those recorded at mid-lake arrays. For instance, daily mean temperatures at the Lake Brooks array in 2017 reached 15.33 °C and 15.74 °C at the 5 m and 0 m depths, respectively, but at a monitoring site on the lake shore nearby, the peak was 16.72 °C (K. Bartz, unpublished data). While warm lake edge temperatures might be optimal for young juveniles, they are suboptimal for adults, which also rely on lake edges for migration and spawning. Fortunately, adults are capable swimmers that can seek cooler, deeper waters and/or postpone spawning, but doing so has a metabolic cost for fish that stopped eating when they left saltwater (Fenkes et al. 2016).

At all six arrays, daily mean temperatures at 5 m depth exceeded the State's water quality threshold of 15 °C at some point during the period of record. Weekly mean temperatures at 5 m depth also exceeded this threshold at four of the six arrays (i.e., Kijik, Brooks, and the North and West basins of Naknek Lake; Appendices D, E, F, and H). This is noteworthy because the ability of fish to endure thermal stress decreases as the duration of the exceedance increases (Sullivan et al. 2000). Endurance also depends on the existence of cold water refugia at other depths. Our data indicate that daily mean

temperatures at three of the arrays exceeded the 15 °C threshold at deeper depths during the period of record. Conversely, none of the arrays had exceedances at or below 30 m depth. Although such deep pelagic waters are inaccessible to younger juvenile sockeye salmon, older juveniles make daily vertical migrations to this depth and beyond, occupying deeper waters during the day than they do at night (Levy 1987). Scheuerell and Schindler (2003) generally observed juvenile sockeye below 60 m during the day in three southwest Alaska lakes, and hypothesized that these migrations are intended to minimize the ratio of predation risk to foraging gain, rather than select temperatures to maximize their growth rate, as proposed by Brett (1971).

Trend Analysis — Means

Mean water temperature at the 5 m depth increased during the periods of record at all arrays. At some arrays, particularly those in KATM, warming trends extended down the water column. Of the 57 time series examined, 28 exhibited significant warming trends, while only 2 exhibited significant cooling. Although the periods of record were relatively short (i.e., 7 to 12 years), the consistency in direction of the trends was noteworthy. Also noteworthy were the rates of change (e.g., increases of 0.02 to 0.24 °C per year, across all depths). At the low end of this range, the rates are small, when considered on an annual timestep. However, if the rates persist, they may amount to ecologically significant changes over time, especially given findings of exceedances of the 15 °C threshold during the periods of record at all arrays.

These rates — if converted to a decadal time scale — would fit or exceed the range reported in a global synthesis of summer surface water trends for 246 lakes (i.e., significant increases of 0.13 to 1.35 °C per decade; O'Reilly et al. 2015). According to this synthesis, other lakes in southwest Alaska also exhibited accelerated rates of change (1.03 and 0.85 °C per decade at Iliamna Lake and Lake Aleknagik, where the time series spanned 14 and 21 years, respectively).That we observed rates of change exceeding those noted by O'Reilly et al. (particularly in the Iliuk basin of Naknek Lake) is likely a function of the abbreviated time series at that site (7 years), and the start and end years of that time series (2011–2018), as opposed to unique characteristics of the lake basin.

The cooling trends observed in deeper waters of Kijik Lake might reflect the short length of the time series at that site (2010–2018), as these results fluctuated from nonsignificant to significant with the addition of the final year of data, during the course of the analysis. Alternatively, the results could reflect processes identified by Niedrist et al. (2018) to explain similar cooling below the epilimnion of a mountain lake in Austria. Specifically, they hypothesized that cooling at deeper depths could result from a lengthening of summer stratification, which could shorten the duration of mixing, limiting heat transfer from the surface to the deeper water layers. We did not examine trends in the duration of stratification due to the brevity of the time series, but this could be assessed in the future as the period of record lengthens.

Trend Analysis — Standard Deviations

The frequency of extreme air temperatures is increasing globally, and the increase is related to climate change (Coumou and Rahmstorf 2012, Bathiany et al. 2018). Therefore, anticipating the effects of climate change requires incorporating trends in variation, as well as trends in means, when examining air temperature (Bathiany et al. 2018). Given that air temperature is a major driver of

water temperature, the same is likely true of variation and means within aquatic systems (Steel et al. 2012). Of the 57 water temperature time series examined in our study, most had no significant trend in variation. However, in time series where a significant trend was observed, all but one exhibited increases.

The biological consequences of increasing means are well studied, for both air and water temperature. The consequences of increasing variation have become a topic of interest more recently, with the majority of studies focusing on effects in terrestrial systems (Thompson et al. 2013). These studies have identified a range of potential effects of increasing variation, either independent of or in conjunction with increasing means. The effects include altered thermal tolerances, development, and survival of individuals, modified growth rates of populations, and shifted distributions and performance of species (Harley et al. 2009, Bozinovic et al. 2011, Steel et al. 2012, Vasseur et al. 2014). One particularly relevant study exposed salmon eggs to experimental thermal regimes with differing means and variances, and found that variation affected both emergence timing and development at emergence, independent of warming (Steel et al. 2012).

Stratification Patterns

The stratification pattern assigned to a lake depends mainly on the presence of ice cover and the frequency of stratification each year (Lewis 1983, Woolway and Merchant 2019). The pattern, in turn, determines the timing and intensity of various processes in lake ecosystems, including nutrient upwelling, biogeochemical cycling, and oxygenation (North et al. 2014, Yankova et al. 2017). Hence, changes in pattern could have cascading effects on multiple ecosystem processes.

Changes in stratification pattern due to warming climate have already been documented at several lakes in Europe (Ficker et al. 2017, Kainz et al. 2017). These changes are likely to become more widespread by the end of this century, according to a recent study of 635 lakes worldwide (Woolway and Merchant 2019). The study used outputs from a representative suite of climate models as inputs to a one-dimensional lake model, in order to project changes in surface water temperature, lake ice duration, and stratification pattern. Many lakes were projected to shift their stratification pattern, (i.e., from dimictic to monomictic, or from monomictic to meromictic), mixing less frequently in response to climate change. Furthermore, lakes that were normally ice-covered in winter and classified as dimictic — but that were also currently experiencing occasional ice-free winters — were more likely to shift patterns, from dimictic to monomictic, by the year 2100. Lakes in our study, which are primarily dimictic, might share this trajectory, given the short or absent winter stratification in some recent years (e.g., 2015, 2016) and the short duration of ice cover in those years (P. Kirchner, unpublished data).

Considerations and Next Steps

One potentially confounding factor in our protocol is the fact that the arrays are moored at the bottom of the lake, not the surface. Therefore, while any given 5 m logger is theoretically 5 m below the water surface, in practice it is located at a fixed depth from the bottom, and the water level fluctuates above it as dictated by the annual hydrograph. Stated another way, the 5 m logger is a known distance above the bottom, but it is not always 5 m below the surface.

Another potentially confounding (and related) factor is variation in the deployment location of the instrument line over time. If all locations for a given array have identical bathymetry (i.e., equal maximum depths), then this is not an issue. However, if some locations are shallower than others, then an unaccounted for source of variation exists in the dataset. Clearly, it would be problematic if, for example, deployment locations were becoming shallower over time. Unfortunately, systematic metadata on deployment depths do not exist prior to 2018. Instead, latitude and longitude were recorded for the full time series, under the assumption that consistency in X-Y coordinates would ensure roughly comparable Z coordinates (depths). Bathymetry maps for these lakes are not very accurate, so estimating depths from coordinates is tenuous. However, if the maps are taken as truth, then they suggest that deployment locations at three arrays have crossed 5-m bathymetry contour lines over time (LCLAR01, NAKNL01, and LBROO01; Figures 16–18).

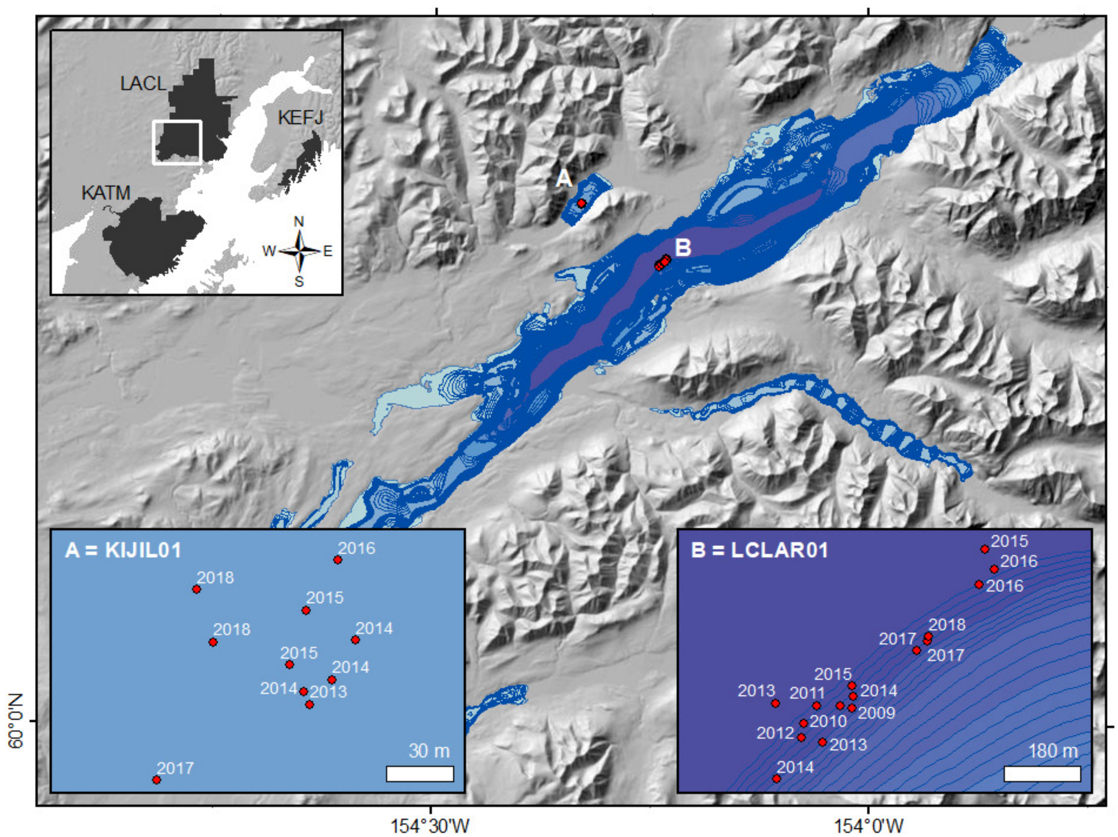

Figure 16. Map of instrument line locations over time for two arrays in Lake Clark National Park and Preserve (LACL). Park boundaries are shown in the upper inset, along with boundaries of two nearby parks: Katmai National Park and Preserve (KATM) and Kenai Fjords National Park (KEFJ). In the lower insets, contour lines represent 5 m depth increments. The maximum distance between instrument line locations is 128 m and 734 m at Kijik Lake (KIJIL01) and Lake Clark (LCLAR01), respectively.

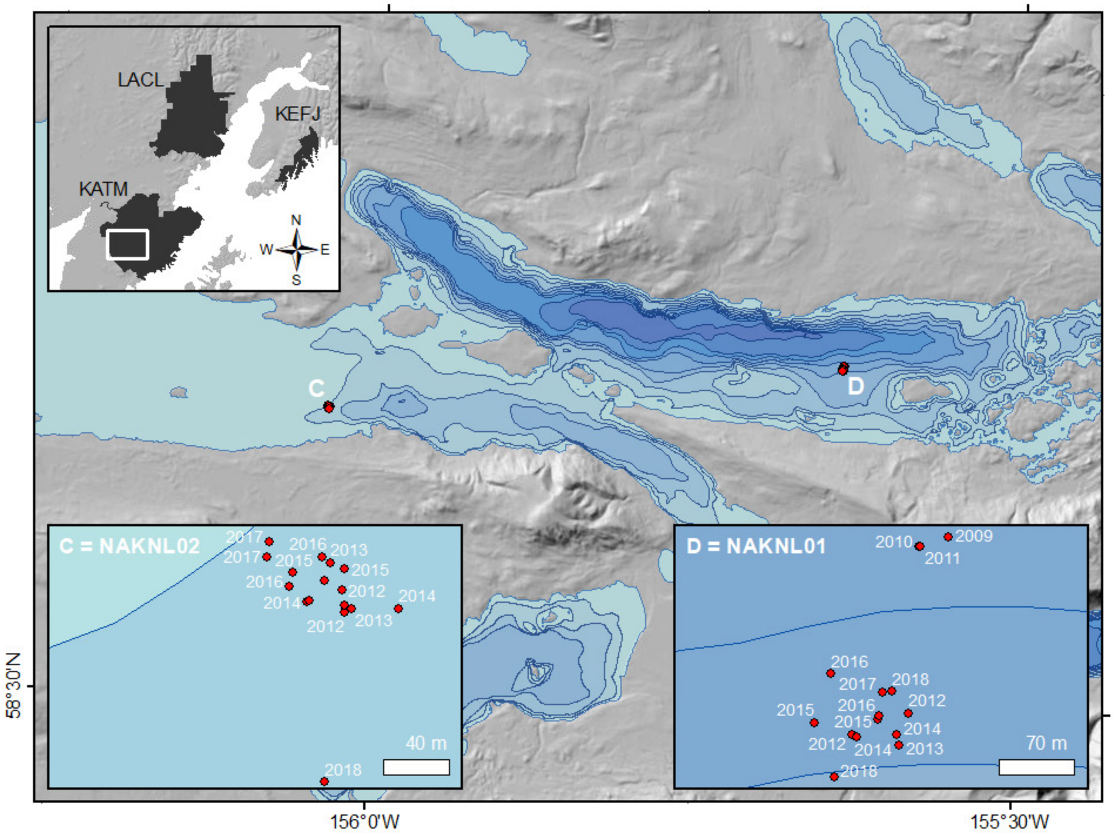

Figure 17. Map of instrument line locations over time for two arrays in Katmai National Park and Preserve (KATM). Park boundaries are shown in the upper inset, along with boundaries of two nearby parks: Lake Clark National Park and Preserve (LACL) and Kenai Fjords National Park (KEFJ). In the lower insets, contour lines represent 5 m depth increments. The maximum distance between instrument line locations is 249 m and 150 m at the North (NAKNL01) and West (NAKNL02) basins of Naknek Lake, respectively.

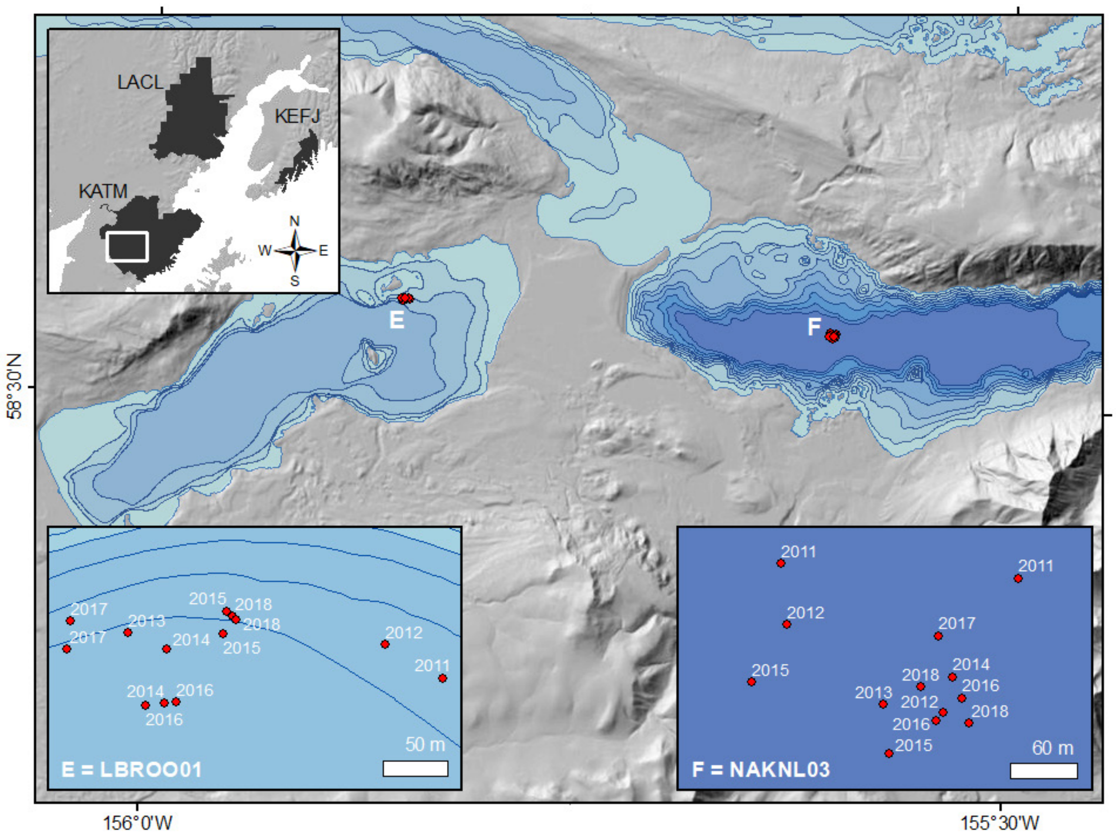

Figure 18. Map of instrument line locations over time for two arrays in Katmai National Park and Preserve (KATM). Park boundaries are shown in the upper inset, along with boundaries of two nearby parks: Lake Clark National Park and Preserve (LACL) and Kenai Fjords National Park (KEFJ). In the lower insets, contour lines represent 5 m depth increments. The maximum distance between instrument line locations is 259 m and 291 m at the Iliuk basin of Naknek Lake (NAKNL03) and Lake Brooks (LBROO01), respectively.

One way to explore these confounding factors is to co-locate a water level logger with a water temperature logger on each array (e.g., the 5 m logger). Although all arrays are now equipped with level loggers year-round at the 5 m depth, this was not the norm in the past. The longest available array-specific level logger record pertains to the 5 m depth at the Lake Clark array and dates back to 2007 (Figure 19). It contains numerous data gaps and high day-to-day variation. More troubling is the year-to-year variation in water level, presumably caused by differing deployment locations. If the majority of the discrepancy from 5 m occurred later in the time series and was biased shallow, then the trend analysis results would show greater warming than what actually occurred. Instead, the overall bias later in the time series was deep, albeit increasing, so the trend analysis results could represent a conservative estimate of warming at this site. Also, the warming trend found at 5 m persisted when the seasonal Kendall analysis was redone using data averaged across depths from 5 m to 20 m ($\tau = 0.15$, $p = 0.03$, slope = 0.03 °C per year), suggesting that the trend was robust throughout the epilimnion at this array.

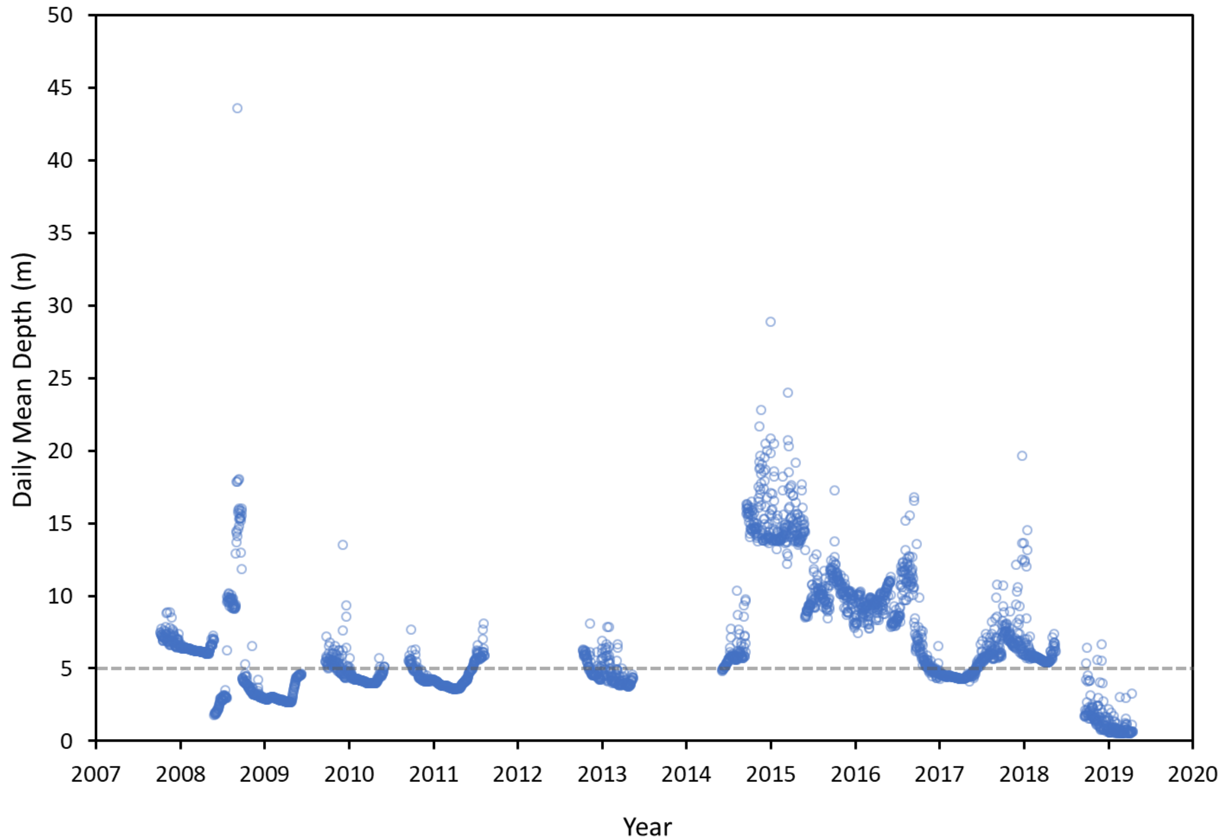

Figure 19. Daily mean depth recorded by a water level logger co-located with the "5 m" water temperature logger on the Lake Clark array. Ideally, these data should be centered around the 5 m depth (dotted line), although some seasonal variation is expected. These data were not used to adjust the inputs to the status summary or trend analysis.

Surface water temperatures are closely tied to air temperatures, which are warming in Alaska at twice the rate of the national average (Markon et al. 2018). In the Bristol Bay region, where these arrays are located, climate change is already apparent in the seasonal air temperature records. For example, the Bristol Bay region's average air temperature in winter (December–February), spring (March–May), and summer (June–August) increased by 4.2 °C, 2.2 °C and 0.8 °C, respectively, from 1949 to 2012, all of which were statistically significant increases at the 95% level (Bieniek et al. 2014). These warming trends are projected to continue (Chapin III et al. 2014), with winter air temperatures expected to continue warming faster than other seasons (Lader et al. 2017).

Indeed, a recent study by Jones and Arp (2014) used empirical lake temperature data from western Alaska to hindcast water temperatures at 0 m depth back to 1985 for 22 lakes. Results were then used to forecast water temperatures at 0 m depth to the year 2100, via a global climate model (GFDL-CM3) under two trajectories of future greenhouse gas concentrations (RCP 6.0 and RCP 8.5). The study included empirical data from arrays at Lake Brooks and Naknek Lake (LBROO01 and NAKNL01). It projected increases in maximum daily mean temperatures of 2–3 °C in Lake Brooks

(from 12.0 °C to 14.2–15.1 °C) and 4–5 °C in Naknek Lake (from 12.1 °C to 15.9–17.5 °C) by 2100, but our arrays are already recording temperatures exceeding the upper ends of those ranges.

Future field work should focus on ensuring that arrays are re-deployed in the same location where they were retrieved, or at a location with a comparable total depth. Future analyses could explore several areas of interest. For example, the time series at the Lake Clark array could be extended to include comparable data collected from 1999 to 2000 at a similar location (Wilkens 2002). A meta-analysis using data collected by arrays in other locations would also be worthwhile (e.g., Kodiak and Togiak National Wildlife Refuges and parks within the Great Lakes Network). Clearly, level logger data could be incorporated as a covariate when examining trends in lake temperature. Other covariates, such as air temperature, wind speed, and ice cover, could also be incorporated to determine the sensitivity of lake temperature at various depths to changes in these variables. Preliminary analyses suggest that years with shorter ice cover have colder lake temperature at depth, and that days with higher wind speed have larger drops in lake temperature at the surface (P. Gabriel, unpublished data). Addition of these covariates to future analyses would strengthen our understanding of water temperature changes in these lakes.

Conclusions

The temperature array data synthesized here represent the longest running continuous time series collected by the SWAN freshwater monitoring program. It is a rich dataset, comprised of 6 sites with 6–12 depths per site, totaling 57 separate time series. It is also applicable for addressing monitoring objectives, stated as questions in our protocol, such as: what are the status and trend of lake temperature and stratification patterns in priority lake systems?

For status, we found that temperature metrics summarizing the most recent, complete water year on record (2017) generally fell within the range of previous years' temperatures at the 5 m depth. Water year 2017 was selected because it was the most recent complete year on record at the time of analysis, and the 5 m depth was highlighted for the sake of brevity. We expect that the selected year and highlighted depth play large roles in determining current status results. Hence, the results should be considered a snapshot of lake temperature in time and space.

For trends, we found that monthly mean water temperatures at the 5 m depth have warmed during the period of record at all array sites. Monthly standard deviations exhibited no comparable pattern at the 5 m depth. However, where significant trends in standard deviation occurred at other depths, they generally indicated increased variation over time.

For stratification, we found that differences in temperature between the top and bottom depths suggested a dimictic stratification pattern at most arrays early and late in the time series, interspersed with monomictic or polymictic patterns in isolated years. The mean start dates of continuous stratification tended to vary less than the mean end dates, when compared across arrays, for both winter and summer stratification. Also, winter stratification tended to be short or nonexistent in water years 2014–2016, likely due to the brief duration or absence of ice cover in those years.

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Appendix A

Table A-1. List of data deleted in AQUARIUS, itemized by park, site, depth (in meters), time period (from/to date and time), count of hours deleted, and a brief account of why the data were deemed erroneous, graded as unusable, and subsequently deleted. Site abbreviations are as follows: LCLAR01 = Lake Clark; KIJIL01 = Kijik Lake; NAKNL01, NAKNL02, and NAKNL03 = Naknek Lake North, West, and Iliuk basins, respectively; and LBROO01 = Lake Brooks.

Park	Site ID	Depth(s)	From	To	Count	Deletion Rationale
LACL	LCLAR01	All	06/19/2007 19:00	06/19/2007 21:00	3	Air temperature
LACL	LCLAR01	All	06/20/2007 09:00	06/20/2007 10:00	2	Air temperature
LACL	LCLAR01	All	10/09/2007 15:00	10/09/2007 20:00	6	Air temperature
LACL	LCLAR01	All	10/15/2007 15:00	10/15/2007 17:00	3	Air temperature
LACL	LCLAR01	All	05/28/2008 15:00	05/28/2008 19:00	5	Air temperature
LACL	LCLAR01	All	07/23/2008 11:00	07/23/2008 13:00	3	Air temperature
LACL	LCLAR01	All	09/26/2008 10:00	09/26/2008 10:00	1	Air temperature
LACL	LCLAR01	All	06/10/2009 15:00	06/11/2009 11:00	15	Air temperature
LACL	LCLAR01	All	09/15/2009 10:00	09/15/2009 10:00	1	Air temperature
LACL	LCLAR01	All	06/04/2010 11:00	06/04/2010 13:00	3	Air temperature
LACL	LCLAR01	All	09/17/2010 16:00	09/17/2010 17:00	2	Air temperature
LACL	LCLAR01	0	08/18/2011 00:00	08/18/2011 12:00	13	Air temperature
LACL	LCLAR01	All	09/23/2011 16:00	09/23/2011 16:00	1	Air temperature
LACL	LCLAR01	All	06/15/2012 16:00	06/15/2012 16:00	1	Air temperature
LACL	LCLAR01	All	10/09/2012 15:00	10/09/2012 15:00	1	Air temperature
LACL	LCLAR01	100	01/03/2013 23:00	01/04/2013 02:00	4	Battery spike
LACL	LCLAR01	60	05/09/2013 14:00	05/09/2013 16:00	3	Battery spike
LACL	LCLAR01	20	05/18/2013 14:00	05/18/2013 16:00	3	Battery spike
LACL	LCLAR01	All	06/13/2013 15:00	06/13/2013 16:00	2	Air temperature
LACL	LCLAR01	10	06/15/2013 17:00	06/15/2013 20:00	4	Battery spike
LACL	LCLAR01	20	09/23/2013 00:00	09/23/2013 02:00	3	Battery spike
LACL	LCLAR01	All	10/21/2013 15:00	10/21/2013 15:00	1	Air temperature
LACL	LCLAR01	All	06/04/2014 11:00	06/04/2014 11:00	1	Air temperature
LACL	LCLAR01	All	09/15/2014 13:00	09/15/2014 14:00	2	Air temperature
LACL	LCLAR01	All	05/29/2015 18:00	05/29/2015 18:00	1	Air temperature
LACL	LCLAR01	All	07/14/2015 11:00	07/14/2015 11:00	1	Air temperature
LACL	LCLAR01	All	09/15/2015 15:00	09/15/2015 16:00	1	Air temperature
LACL	LCLAR01	All	06/03/2016 12:00	06/03/2016 12:00	1	Air temperature
LACL	LCLAR01	All	07/14/2016 15:00	07/14/2016 15:00	1	Air temperature
LACL	LCLAR01	All	09/13/2016 14:00	09/13/2016 16:00	3	Air temperature
LACL	LCLAR01	All	06/13/2017 14:00	06/13/2017 14:00	1	Air temperature

Park	Site ID	Depth(s)	From	To	Count	Deletion Rationale
LACL	LCLAR01	All	09/25/2017 13:00	09/25/2017 14:00	2	Air temperature
LACL	LCLAR01	All	05/16/2018 14:00	05/16/2018 15:00	2	Air temperature
LACL	LCLAR01	All	09/19/2018 15:00	09/19/2018 15:00	1	Air temperature
LACL	KIJIL01	All	10/04/2011 14:00	10/04/2011 14:00	1	Air temperature
LACL	KIJIL01	All	06/26/2012 15:00	06/26/2012 15:00	1	Air temperature
LACL	KIJIL01	30	09/10/2012 22:00	09/11/2012 00:00	3	Battery spike
LACL	KIJIL01	30	11/06/2012 20:00	11/06/2012 23:00	4	Battery spike
LACL	KIJIL01	70	01/11/2013 11:00	01/11/2013 13:00	3	Battery spike
LACL	KIJIL01	10	03/06/2013 17:00	03/06/2013 20:00	4	Battery spike
LACL	KIJIL01	70	03/22/2013 20:00	03/22/2013 23:00	4	Battery spike
LACL	KIJIL01	5	06/19/2013 09:00	06/19/2013 12:00	4	Battery spike
LACL	KIJIL01	All	06/25/2013 19:00	06/25/2013 19:00	1	Air temperature
LACL	KIJIL01	All	06/04/2015 13:00	06/04/2015 14:00	2	Air temperature
LACL	KIJIL01	All	01/27/2016 04:00	06/02/2016 13:00	3058	Array movement
LACL	KIJIL01	All but 40	06/02/2016 15:00	06/02/2016 15:00	1	Air temperature
LACL	KIJIL01	All	06/21/2017 14:00	06/21/2017 14:00	1	Air temperature
LACL	KIJIL01	All	06/21/2018 17:00	06/21/2018 17:00	1	Air temperature
KATM	NAKNL01	All	09/23/2009 15:00	09/23/2009 18:00	4	Air temperature
KATM	NAKNL01	All but 5	08/09/2010 11:00	08/09/2010 11:00	1	Air temperature
KATM	NAKNL01	All	07/07/2011 15:00	07/08/2011 11:00	21	Air temperature
KATM	NAKNL01	All	10/07/2011 12:00	10/07/2011 12:00	1	Air temperature
KATM	NAKNL01	All	06/11/2012 14:00	06/11/2012 14:00	1	Air temperature
KATM	NAKNL01	All	10/08/2012 13:00	10/08/2012 13:00	1	Air temperature
KATM	NAKNL01	All	06/13/2014 15:00	06/13/2014 15:00	1	Air temperature
KATM	NAKNL01	0, 5, 10	09/23/2014 11:00	09/23/2014 11:00	1	Air temperature
KATM	NAKNL01	All	06/10/2015 16:00	06/10/2015 16:00	1	Air temperature
KATM	NAKNL01	All	10/14/2015 13:00	10/14/2015 13:00	1	Air temperature
KATM	NAKNL01	All	06/08/2016 12:00	06/08/2016 12:00	1	Air temperature
KATM	NAKNL01	All	09/08/2016 10:00	09/08/2016 12:00	3	Air temperature
KATM	NAKNL01	20	01/11/2017 11:00	02/23/2017 20:00	3553	Logger malfunction
KATM	NAKNL01	All	06/08/2017 10:00	06/08/2017 11:00	2	Air temperature
KATM	NAKNL01	All	09/08/2017 12:00	09/08/2017 12:00	1	Air temperature
KATM	NAKNL01	0	06/06/2018 15:00	06/06/2018 15:00	1	Air temperature
KATM	NAKNL01	0	06/19/2018 10:00	06/19/2018 10:00	1	Battery spike
KATM	NAKNL02	All	09/28/2009 14:00	09/28/2009 15:00	2	Air temperature
KATM	NAKNL02	All	08/09/2010 18:00	08/09/2010 18:00	1	Air temperature
KATM	NAKNL02	20, 25	08/25/2011 11:00	08/25/2011 11:00	1	Air temperature
KATM	NAKNL02	All	06/13/2012 12:00	06/13/2012 12:00	1	Air temperature

Park	Site ID	Depth(s)	From	To	Count	Deletion Rationale
KATM	NAKNL02	20	11/10/2012 09:00	11/10/2012 11:00	3	Battery spike
KATM	NAKNL02	All	08/07/2013 15:00	08/07/2013 15:00	1	Air temperature
KATM	NAKNL02	All	06/13/2014 17:00	06/13/2014 17:00	1	Air temperature
KATM	NAKNL02	All	10/14/2015 11:00	10/14/2015 11:00	1	Air temperature
KATM	NAKNL02	All	06/09/2016 10:00	06/10/2016 09:00	24	Air temperature
KATM	NAKNL02	All	09/08/2016 14:00	09/08/2016 14:00	1	Air temperature
KATM	NAKNL02	All	09/08/2017 10:00	09/08/2017 11:00	2	Air temperature
KATM	NAKNL02	All	06/04/2018 13:00	06/04/2018 17:00	5	Air temperature
KATM	NAKNL02	All	06/05/2018 12:00	06/06/2018 12:00	25	Air temperature
KATM	NAKNL02	All	09/12/2018 13:00	09/12/2018 13:00	1	Air temperature
KATM	NAKNL03	All	06/11/2012 16:00	06/11/2012 16:00	1	Air temperature
KATM	NAKNL03	All	08/19/2014 22:00	08/20/2014 16:00	19	Air temperature
KATM	NAKNL03	All	06/10/2015 12:00	06/10/2015 12:00	1	Air temperature
KATM	NAKNL03	All	06/08/2016 14:00	06/08/2016 15:00	2	Air temperature
KATM	NAKNL03	All	09/07/2016 15:00	09/07/2016 16:00	2	Air temperature
KATM	NAKNL03	All	06/08/2017 15:00	06/08/2017 15:00	2	Air temperature
KATM	NAKNL03	All	09/12/2018 10:00	09/12/2018 10:00	1	Air temperature
KATM	LBROO01	All	07/19/2011 15:00	07/19/2011 16:00	2	Air temperature
KATM	LBROO01	All	05/20/2012 10:00	05/20/2012 10:00	1	Air temperature
KATM	LBROO01	50	07/21/2013 17:00	07/21/2013 19:00	3	Battery spike
KATM	LBROO01	10	08/20/2013 14:00	08/20/2013 16:00	3	Battery spike
KATM	LBROO01	All	09/24/2013 10:00	09/24/2013 10:00	1	Air temperature
KATM	LBROO01	All	06/24/2014 12:00	06/24/2014 12:00	1	Air temperature
KATM	LBROO01	All	09/23/2014 14:00	09/23/2014 14:00	1	Air temperature
KATM	LBROO01	All	06/11/2015 10:00	06/11/2015 10:00	1	Air temperature
KATM	LBROO01	All	10/06/2015 16:00	10/06/2015 16:00	1	Air temperature
KATM	LBROO01	All	06/07/2016 17:00	06/07/2016 18:00	2	Air temperature
KATM	LBROO01	All	09/13/2016 14:00	09/13/2016 16:00	2	Air temperature
KATM	LBROO01	All	06/13/2017 14:00	06/13/2017 14:00	1	Air temperature
KATM	LBROO01	5	09/07/2017 12:00	09/07/2017 12:00	1	Air temperature
KATM	LBROO01	All	06/07/2018 10:00	06/07/2018 11:00	2	Air temperature

Table A-2. List of data downgraded in AQUARIUS, itemized by park, site, depth (in meters), time period (from/to date and time), and a brief account of why the data were deemed less than good and subsequently downgraded. Site abbreviations are as follows: LCLAR01 = Lake Clark; KIJIL01 = Kijik Lake; NAKNL01 = Naknek Lake, North basin; NAKNL03 = Naknek Lake, Iliuk basin; and LBROO01 = Lake Brooks.

Park	Site ID	Depth(s)	From	To	Downgrade Rationale
LACL	LCLAR01	All	06/19/2007 20:00	09/26/2008 11:00	Time stamp off the hour
LACL	LCLAR01	All but 50	06/15/2009 06:00	09/15/2009 11:00	Time stamp off the hour
LACL	LCLAR01	30	09/20/2009 07:00	06/04/2010 12:00	Time stamp off the hour
LACL	LCLAR01	10	06/13/2010 10:00	09/17/2010 16:00	Time stamp off the hour
LACL	LCLAR01	30	06/04/2014 13:00	05/29/2015 17:00	Time stamp off the hour
LACL	KIJIL01	All	10/04/2011 14:00	07/02/2014 13:00	Time stamp off the hour
KATM	NAKNL01	60	06/13/2014 16:00	09/23/2014 10:00	Time stamp off the hour
KATM	NAKNL03	30	06/10/2015 13:00	09/12/2018 09:00	Temperature sensor drift
KATM	LBROO01	All but 0	07/19/2011 16:00	09/24/2013 10:00	Time stamp off the hour
KATM	LBROO01	10	06/24/2014 12:00	09/23/2014 14:00	Time stamp off the hour

Appendix B

Below is an overview of key features and data gaps in the time series at each temperature array site. Data gaps are also summarized visually in Figure B-1.

Lake Clark

Water temperature in Lake Clark has been monitored continuously via array since August, 2006 for depths from 5 m to 100 m, and since June, 2012 for the 0 m depth. Prolonged data gaps occurred early in the time series at 20, 50, 80, and 90 m depths, as well as later in the time series at 20 m depth. In July, 2015, the array was removed, rebuilt, and redeployed during the course of four days. Of the six arrays, this occupies the deepest lake and was the first deployed.

Kijik Lake

Water temperature in Kijik Lake has been monitored continuously via array since August, 2010 for depths from 5 m to 90 m, and since June, 2012 for the 0 m depth. The time series contained no extended data gaps until January, 2016 when, presumably, wind-driven movement followed by lake ice entrainment caused the array to drift substantially (Booher et al. 2018). The array was re-positioned in June, 2016 but the 40 m logger failed to launch after downloading, so the data gap at that depth continued through June, 2017, when the logger was again serviced. Of the six arrays, this occupies the smallest lake.

Naknek Lake

North Basin (NAKNL01)

Water temperature in the North basin of Naknek Lake has been monitored continuously since August, 2008 at depths from 5 m to 70 m, and since June, 2012 at the 0 m depth. The instrument line was removed, rebuilt, and redeployed within 24 hours in July, 2011, and in 2013 the 0 m logger was not deployed. Aside from that and one data gap in 2017, when the 20 m logger malfunctioned, no prolonged gaps have occurred.

West Basin (NAKNL02)

Water temperature in the West basin of Naknek Lake has been monitored continuously since August, 2008 at depths from 5 m to 25 m, and since June, 2012 at the 0 m depth. No protracted data gaps have occurred during this time frame. The longest gap (48 hours) happened in June, 2018 when the instrument line was removed, rebuilt, and redeployed. Of the six arrays, this is the shallowest.

Iliuk Basin (NAKNL03)

Water temperature in the Iliuk basin of Naknek Lake has been monitored continuously since August, 2011 at depths from 5 m to 100 m, and since June, 2012 at the 0 m depth. A splice failure in July, 2013 left the instrument line deployed solo in the water column, without the usual means of retrieval (Booher et al. 2016). As a result, two summers of 0 m data were lost (2013 and 2014). Eventually, the instrument line was recovered and rebuilt, causing a week-long data gap in August, 2014 across all depths. Of the six arrays, this has the shortest time series.

Lake Brooks

Water temperature in Lake Brooks has been monitored continuously since August, 2010 at depths from 5 m to 50 m, and since May, 2012 at the 0 m depth. No prolonged data gaps have occurred during this time span. The longest gaps (3 hours at 10 and 50 m depths) resulted from battery voltage spikes in 2013.

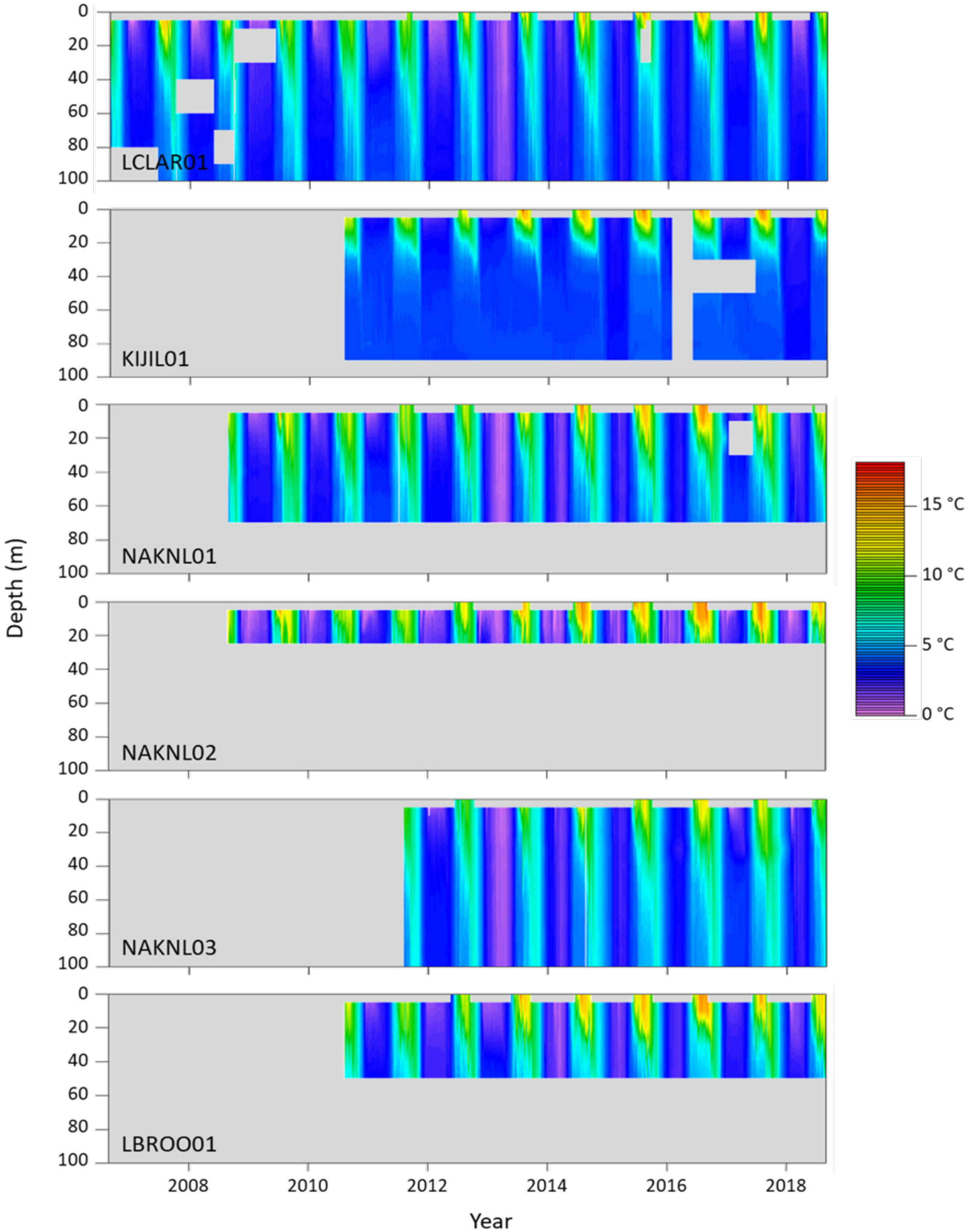

Figure B-1. Isotherms for six temperature arrays. Gray areas represent depths/times with no data. Site abbreviations are as follows: LCLAR01 = Lake Clark; KIJIL01 = Kijik Lake; NAKNL01, NAKNL02, and NAKNL03 = Naknek Lake North, West, and Iliuk basins, respectively; and LBROO01 = Lake Brooks.

Appendix C

Table C-1. Highest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Lake Clark, 2006–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2006	WY 2007	WY 2008	WY 2009	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	7.52	8.11	7.44	8.01	7.94	7.78	6.80	6.91	8.22	8.28	8.01	8.34
November	–	5.74	5.57	4.92	5.85	5.56	5.46	5.07	5.42	5.66	5.88	5.65	5.90
December	–	3.76	4.44	3.64	4.24	4.30	3.66	3.24	4.14	4.70	4.37	4.46	4.50
January	–	0.66	2.74	1.14	3.20	1.43	0.87	2.31	2.99	4.06	3.48	2.85	3.75
February	–	1.91	1.11	1.18	1.26	1.62	1.03	1.82	2.71	2.81	2.89	1.09	0.91
March	–	2.41	1.53	1.08	1.62	1.56	1.32	1.31	1.93	2.78	2.38	1.22	0.93
April	–	3.39	2.27	2.01	2.34	2.33	2.41	1.44	2.57	2.91	3.23	3.09	2.22
May	–	4.28	3.69	3.56	3.46	3.85	3.34	2.39	3.63	3.75	5.10	4.06	3.47
June	–	9.90	8.46	8.51	8.50	8.23	7.85	4.41	9.58	10.21	10.42	10.82	6.75
July	–	14.96	11.01	14.11	10.49	11.80	10.27	10.15	13.76	*	14.39	14.75	11.11
August	*	15.91	13.04	12.09	11.02	11.98	13.01	12.60	15.03	14.38	14.28	14.89	11.31
September	11.14	13.53	10.17	10.93	11.50	10.90	11.03	11.58	11.67	12.01	12.67	11.41	*

Table C-2. Lowest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Lake Clark, 2006–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2006	WY 2007	WY 2008	WY 2009	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	5.79	5.54	4.91	5.81	5.66	5.26	5.07	5.51	5.69	5.87	5.58	5.95
November	–	3.82	4.47	3.18	4.28	4.35	3.55	3.09	4.22	4.75	4.42	4.57	4.50
December	–	0.52	2.54	0.55	2.42	0.77	1.05	0.95	2.23	4.06	3.20	2.55	3.62
January	–	0.02	0.08	0.29	0.34	0.94	0.19	0.67	2.27	2.38	2.56	0.55	0.60
February	–	0.72	0.11	0.64	0.35	1.37	0.48	0.80	0.81	1.71	2.58	0.78	0.30
March	–	1.40	0.59	0.76	1.12	1.32	0.86	0.36	1.15	1.94	2.16	1.00	0.78
April	–	1.95	1.22	0.79	1.63	1.42	1.35	0.33	1.96	2.50	2.61	1.25	0.91
May	–	2.98	1.78	2.08	2.32	2.39	2.31	1.48	2.61	2.94	3.17	2.71	2.39
June	–	4.03	3.64	3.58	3.51	3.86	3.39	2.42	3.69	3.74	4.82	4.52	3.50
July	–	8.89	7.16	5.92	8.65	7.22	5.49	4.95	8.33	*	10.79	7.51	6.37
August	*	10.30	10.52	8.10	8.20	9.99	9.78	6.69	9.19	11.47	10.33	9.59	8.98
September	7.67	7.92	6.35	7.93	7.62	7.49	4.47	6.83	8.08	8.56	7.63	8.09	*

Table C-3. Standard deviation of daily mean water temperatures (°C) at the 5 m depth, summarized by month for Lake Clark, 2006–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2006	WY 2007	WY 2008	WY 2009	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	0.52	0.78	0.86	0.54	0.73	0.68	0.52	0.40	0.73	0.58	0.83	0.63
November	–	0.61	0.35	0.44	0.51	0.37	0.57	0.44	0.37	0.24	0.50	0.32	0.41
December	–	1.11	0.53	0.81	0.48	1.35	0.66	0.66	0.71	0.20	0.34	0.52	0.22
January	–	0.22	0.87	0.26	1.03	0.13	0.24	0.40	0.17	0.48	0.28	0.78	0.92
February	–	0.41	0.32	0.16	0.27	0.08	0.15	0.32	0.64	0.32	0.09	0.10	0.15
March	–	0.26	0.25	0.11	0.16	0.07	0.10	0.27	0.20	0.25	0.12	0.06	0.04
April	–	0.51	0.32	0.35	0.22	0.28	0.35	0.33	0.20	0.12	0.17	0.62	0.45
May	–	0.36	0.58	0.48	0.37	0.49	0.32	0.26	0.29	0.27	0.44	0.33	0.32
June	–	2.07	1.55	1.58	1.45	1.38	1.43	0.54	1.84	2.26	1.48	1.80	0.98
July	–	1.29	1.05	2.27	0.57	1.14	1.30	1.59	1.28	*	1.07	1.99	1.18
August	*	1.46	0.92	1.29	0.74	0.56	0.90	1.78	1.82	0.92	1.01	1.25	0.68
September	1.17	1.62	0.96	0.87	0.98	0.97	1.22	1.05	1.11	1.15	1.58	0.85	*

Table C-4. Warmest day, warmest week, and days exceeding 15 °C at the 5 m depth, summarized by water year for Lake Clark, 2006–2018. Asterisks indicate water years with one or more missing months of data.

Water Year	Warmest Day Date	Warmest Day 24-hr mean (°C)	Warmest Week Dates	Warmest Week 7-day mean (°C)	Days >15 °C (n)
2006*	09/06	11.14	08/24–08/30	10.78	0
2007	08/13	15.91	08/11–08/17	14.72	1
2008	08/25	13.40	08/21–08/27	13.05	0
2009	07/18	14.11	07/14–07/20	13.35	0
2010	09/19	11.50	09/13–09/19	11.25	0
2011	08/16	11.98	08/12–08/18	11.41	0
2012	08/17	13.01	08/13–08/19	12.54	0
2013	08/02	12.60	08/25–08/31	11.93	0
2014	08/03	15.03	08/01–08/07	14.55	1
2015*	08/16	14.38	08/11–08/17	14.03	0
2016	07/30	14.39	07/26–08/01	13.78	0
2017	08/03	14.89	07/29–08/04	14.33	0
2018*	08/11	11.31	08/11–08/17	10.65	0

Appendix D

Table D-1. Highest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Kijik Lake, 2010–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	9.23	9.01	7.29	8.17	9.83	8.58	9.35	9.74
November	–	5.63	5.71	4.41	5.45	5.20	5.98	5.70	5.76
December	–	3.35	1.91	2.22	2.67	3.86	3.81	2.82	3.24
January	–	2.79	1.99	2.32	3.14	3.02	3.04	2.11	2.68
February	–	2.79	2.19	2.45	3.25	2.66	*	2.23	2.39
March	–	2.77	2.26	2.68	3.33	3.13	*	2.34	2.48
April	–	3.40	3.23	3.93	3.90	3.57	*	3.75	2.99
May	–	4.87	5.27	6.01	8.56	6.51	*	6.14	4.44
June	–	9.72	9.22	11.29	11.12	13.14	*	11.94	9.27
July	–	12.19	11.84	13.05	13.87	14.62	13.81	14.83	13.06
August	12.28	12.17	12.04	14.27	14.27	15.10	14.07	15.58	13.69
September	11.78	11.40	11.55	13.17	13.08	12.67	12.76	13.01	*

Table D-2. Lowest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Kijik Lake, 2010–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	5.75	5.82	4.52	5.53	5.35	6.17	5.76	5.80
November	–	3.09	1.72	1.94	2.64	3.67	3.77	3.44	3.04
December	–	2.33	1.74	2.09	2.36	2.56	2.24	1.79	2.66
January	–	2.43	1.89	2.13	2.60	2.33	2.45	1.92	2.14
February	–	2.59	1.97	2.33	2.89	2.39	*	2.11	2.15
March	–	2.67	2.15	2.45	3.20	2.63	*	2.23	2.39
April	–	2.74	2.28	2.69	3.33	3.15	*	2.35	2.44
May	–	3.43	3.35	3.96	3.95	3.63	*	3.80	3.01
June	–	5.29	5.48	5.93	7.87	6.82	*	6.40	4.60
July	–	9.87	9.49	11.00	11.05	12.86	11.18	11.67	9.37
August	11.32	11.02	10.74	13.15	13.21	12.86	12.24	13.25	11.03
September	9.30	9.21	7.39	8.35	10.00	8.80	9.59	9.92	*

Table D-3. Standard deviation of daily mean water temperatures (°C) at the 5 m depth, summarized by month for Kijik Lake, 2010–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	1.07	1.01	0.90	0.79	1.27	0.64	1.19	1.28
November	–	0.67	1.29	0.83	0.80	0.39	0.77	0.65	0.80
December	–	0.26	0.05	0.04	0.08	0.38	0.48	0.24	0.19
January	–	0.10	0.03	0.05	0.16	0.22	0.13	0.06	0.17
February	–	0.07	0.06	0.04	0.09	0.08	*	0.04	0.07
March	–	0.03	0.03	0.06	0.05	0.14	*	0.03	0.03
April	–	0.20	0.30	0.40	0.18	0.11	*	0.47	0.21
May	–	0.38	0.56	0.54	1.56	0.81	*	0.79	0.42
June	–	1.38	1.20	1.65	0.89	1.91	*	1.66	1.53
July	–	0.72	0.64	0.79	0.91	0.44	0.83	1.12	1.14
August	0.33	0.36	0.42	0.36	0.28	0.58	0.59	0.69	1.01
September	0.66	0.61	1.15	1.41	0.91	1.24	1.11	0.80	*

Table D-4. Warmest day, warmest week, and days exceeding 15 °C at the 5 m depth, summarized by water year for Kijik Lake, 2010–2018. Asterisks indicate water years with one or more missing months of data.

Water Year	Warmest Day Date	Warmest Day 24-hr mean (°C)	Warmest Week Dates	Warmest Week 7-day mean (°C)	Days >15 °C (n)
2010 *	08/06	12.28	08/03–08/09	12.14	0
2011	07/31	12.19	07/31–08/06	12.07	0
2012	08/23	12.04	08/18–08/24	11.88	0
2013	08/07	14.27	08/03–08/09	13.95	0
2014	08/08	14.27	08/06–08/12	13.86	0
2015	08/11	15.10	08/06–08/12	14.92	2
2016 *	08/03	14.07	07/30–08/05	13.79	0
2017	08/05	15.58	08/04–08/10	15.34	9
2018 *	08/09	13.69	08/06–08/12	13.57	0

Appendix E

Table E-1. Highest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Naknek Lake's North basin, 2008–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2008	WY 2009	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	9.64	10.05	9.63	9.21	8.19	8.33	10.35	9.94	11.13	10.20
November	–	6.18	7.63	6.69	7.10	6.20	6.86	6.77	7.13	7.46	7.41
December	–	4.06	4.98	4.93	3.96	3.33	5.18	5.75	5.40	5.69	5.41
January	–	1.17	3.22	1.03	1.38	2.44	3.20	4.70	3.87	3.65	4.10
February	–	1.02	1.51	1.69	1.47	1.46	2.74	3.14	3.09	2.17	1.65
March	–	1.34	1.93	2.37	1.58	0.86	1.94	2.63	2.70	2.13	2.15
April	–	1.97	2.51	3.28	2.76	1.35	2.39	2.72	3.65	3.64	2.88
May	–	3.82	3.89	4.95	3.89	2.91	6.18	4.91	7.24	5.89	4.65
June	–	9.35	9.46	7.78	7.95	7.56	9.90	12.30	12.07	11.29	9.04
July	–	15.83	11.07	11.01	10.38	14.55	15.07	12.32	15.30	14.83	11.95
August	*	12.24	11.31	11.98	11.89	13.28	15.39	14.09	15.58	14.47	13.44
September	12.02	11.92	11.77	11.05	11.55	12.59	13.28	13.31	14.65	12.88	*

Table E-2. Lowest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Naknek Lake's North basin, 2008–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2008	WY 2009	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	6.22	7.73	6.77	7.16	6.19	6.83	6.82	6.64	7.01	7.32
November	–	4.05	4.95	4.99	3.89	3.41	5.26	5.79	5.45	5.74	5.44
December	–	0.87	3.22	0.50	1.25	0.98	3.17	4.71	3.90	3.61	4.16
January	–	0.69	0.59	0.76	1.17	1.05	2.72	3.16	3.10	2.15	1.06
February	–	0.66	0.75	0.98	1.23	0.47	1.29	2.19	2.72	1.77	1.06
March	–	1.00	1.51	1.74	1.48	0.34	1.27	1.19	2.35	1.78	1.29
April	–	1.35	1.78	2.38	1.60	0.44	1.50	2.16	2.68	2.17	2.09
May	–	2.07	2.56	3.29	2.19	1.36	2.42	2.72	3.72	3.52	2.91
June	–	3.90	3.94	4.77	3.88	2.99	4.78	5.05	3.29	6.27	4.80
July	–	6.76	5.84	7.95	5.96	7.48	9.73	6.90	11.84	9.69	9.30
August	*	8.19	7.22	9.39	10.15	6.99	10.71	12.66	11.33	11.49	8.32
September	7.31	10.11	9.76	7.43	7.93	7.58	8.38	10.11	11.67	9.93	*

Table E-3. Standard deviation of daily mean water temperatures (°C) at the 5 m depth, summarized by month for Naknek Lake's North basin, 2008–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2008	WY 2009	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	1.06	0.64	0.97	0.72	0.60	0.44	1.08	0.95	1.30	0.77
November	–	0.60	0.88	0.48	1.03	0.74	0.49	0.26	0.55	0.51	0.61
December	–	0.76	0.59	1.60	0.89	0.76	0.70	0.31	0.47	0.57	0.38
January	–	1.13	1.04	0.08	0.06	0.39	0.16	0.45	0.25	0.46	1.06
February	–	0.10	0.24	0.23	0.08	0.35	0.53	0.24	0.11	0.13	0.16
March	–	0.10	0.09	0.19	0.02	0.17	0.19	0.35	0.08	0.09	0.27
April	–	0.18	0.27	0.29	0.39	0.26	0.27	0.17	0.30	0.45	0.24
May	–	0.55	0.39	0.49	0.42	0.47	1.05	0.58	0.96	0.61	0.47
June	–	1.79	1.86	0.96	1.17	1.24	1.42	2.11	1.83	1.54	1.32
July	–	2.83	1.38	0.89	1.20	2.24	1.44	1.64	1.19	1.51	0.78
August	*	1.18	0.82	0.50	0.50	1.50	1.24	0.39	1.16	0.70	1.20
September	0.95	0.53	0.60	0.98	0.95	1.43	1.12	1.09	1.01	0.69	*

Table E-4. Warmest day, warmest week, and days exceeding 15 °C at the 5 m depth, summarized by water year for Naknek Lake's North basin, 2008–2018. Asterisks indicate water years with one or more missing months of data.

Water Year	Warmest Day Date	Warmest Day 24-hr mean (°C)	Warmest Week Dates	Warmest Week 7-day mean (°C)	Days >15 °C (n)
2008 *	08/29	13.23	08/27–09/03	12.63	0
2009	07/15	15.83	07/14–07/20	15.36	6
2010	09/20	11.77	09/14–09/20	11.59	0
2011	08/17	11.98	08/12–08/18	11.59	0
2012	08/13	11.89	08/28–09/04	11.47	0
2013	07/29	14.55	07/26–08/01	13.80	0
2014	08/03	15.39	07/31–08/06	15.03	4
2015	08/17	14.09	08/16–08/22	14.00	0
2016	08/10	15.58	08/06–08/12	15.48	20
2017	07/30	14.83	07/26–08/01	14.45	0
2018 *	08/11	13.44	08/05–08/11	12.99	0

Appendix F

Table F-1. Highest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Naknek Lake's West basin, 2008–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicated no data.

Month	WY 2008	WY 2009	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	9.80	9.74	9.77	9.55	8.71	8.24	10.82	9.11	11.51	10.08
November	–	4.64	7.02	6.22	6.39	3.22	6.79	5.56	7.05	6.95	6.89
December	–	1.39	1.82	1.40	1.76	1.20	1.90	4.23	3.56	1.86	2.10
January	–	0.71	1.55	0.86	0.76	1.37	1.88	2.83	1.95	1.34	1.63
February	–	1.06	1.50	1.82	1.38	1.06	1.88	1.58	1.63	1.69	0.96
March	–	1.43	1.97	2.65	1.45	0.92	1.12	1.68	2.01	2.93	1.68
April	–	2.28	2.75	3.39	2.61	2.34	3.32	3.68	5.41	4.66	2.79
May	–	6.75	6.60	6.46	4.39	7.05	10.92	8.66	10.71	8.15	7.51
June	–	12.12	12.36	9.92	10.22	15.22	11.90	14.21	13.74	12.95	*
July	–	16.12	12.18	12.00	11.62	15.90	14.82	14.80	15.67	16.23	14.08
August	*	13.43	12.38	12.51	12.80	15.54	15.98	14.94	15.74	16.10	14.45
September	12.59	12.38	12.53	11.54	11.94	12.82	14.00	12.67	16.30	13.10	*

Table F-2. Lowest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Naknek Lake's West basin, 2008–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2008	WY 2009	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	4.11	7.06	6.04	6.83	3.09	6.83	5.49	6.97	7.05	6.85
November	–	0.55	0.84	0.53	0.17	0.05	1.59	4.18	1.74	1.62	0.83
December	–	0.36	0.54	0.22	0.19	0.28	0.30	2.42	0.80	0.27	1.11
January	–	0.21	0.12	0.24	0.20	0.62	0.84	0.22	0.83	0.17	0.02
February	–	0.64	0.49	0.86	0.18	0.27	0.01	0.85	1.00	0.44	0.19
March	–	1.00	1.27	1.87	1.00	0.39	0.63	0.23	0.69	1.58	0.91
April	–	1.45	1.77	2.56	1.15	0.98	1.03	1.78	2.09	2.87	1.71
May	–	2.30	1.50	3.32	2.43	2.32	3.50	3.57	5.21	3.47	2.88
June	–	6.08	6.50	6.86	4.65	6.46	7.53	8.35	8.62	8.65	*
July	–	11.89	10.39	10.28	8.95	10.02	11.06	11.48	13.50	11.46	11.66
August	*	11.69	10.29	10.71	11.14	12.67	13.78	12.33	14.62	13.23	10.80
September	9.68	9.73	9.89	9.62	8.71	8.32	11.05	8.60	11.62	10.17	*

Table F-3. Standard deviation of daily mean water temperatures (°C) at the 5 m depth, summarized by month for Naknek Lake's West basin, 2008–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2008	WY 2009	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	1.74	0.68	1.08	0.86	1.51	0.41	1.42	0.53	1.46	1.09
November	–	1.23	1.97	1.75	2.28	0.88	1.62	0.31	1.69	1.95	1.93
December	–	0.34	0.41	0.35	0.49	0.24	0.44	0.58	0.77	0.44	0.31
January	–	0.14	0.52	0.20	0.18	0.22	0.32	0.80	0.29	0.33	0.59
February	–	0.13	0.37	0.28	0.34	0.24	0.70	0.19	0.15	0.32	0.24
March	–	0.12	0.21	0.25	0.11	0.14	0.15	0.43	0.31	0.36	0.26
April	–	0.23	0.29	0.24	0.48	0.44	0.72	0.52	1.02	0.46	0.35
May	–	1.32	1.26	0.93	0.51	1.17	2.46	1.19	1.31	1.24	1.37
June	–	1.82	1.79	0.84	1.74	2.33	1.17	1.90	1.48	1.28	*
July	–	1.40	0.54	0.55	0.89	1.75	0.93	0.85	0.65	1.25	0.79
August	*	0.54	0.59	0.44	0.47	0.73	0.62	0.58	0.30	1.02	1.21
September	0.87	0.74	0.66	0.58	0.78	1.32	0.84	1.25	1.47	0.74	*

Table F-4. Warmest day, warmest week, and days exceeding 15 °C at the 5 m depth, summarized by water year for Naknek Lake's West basin, 2008–2018. Asterisks indicate water years with one or more missing months of data.

Water Year	Warmest Day Date	Warmest Day 24-hr mean (°C)	Warmest Week Dates	Warmest Week 7-day mean (°C)	Days >15 °C (n)
2008 *	08/30	13.32	08/30–09/05	12.62	0
2009	07/15	16.12	07/14–07/20	15.88	11
2010	09/19	12.53	08/24–08/30	12.18	0
2011	08/18	12.51	08/12–08/18	11.98	0
2012	08/14	12.80	08/12–08/18	12.37	0
2013	07/31	15.90	07/27–08/02	15.26	6
2014	08/06	15.98	08/04–08/10	15.66	16
2015	08/08	14.94	08/05–08/11	14.39	0
2016	09/04	16.30	08/31–09/06	15.86	37
2017	07/31	16.23	07/29–08/04	15.93	24
2018 *	08/05	14.45	07/31–08/06	14.12	0

Appendix G

Table G-1. Highest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Naknek Lake's Iliuk basin, 2011–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	7.26	6.99	6.70	8.36	7.95	8.89	8.26
November	–	6.06	5.64	6.23	6.00	6.46	6.69	6.65
December	–	3.82	3.95	4.79	5.32	5.27	5.28	5.27
January	–	1.38	2.33	3.21	4.45	4.03	3.78	4.21
February	–	1.80	1.62	2.95	3.39	3.35	1.30	2.81
March	–	1.56	1.04	2.14	2.75	2.99	1.88	2.57
April	–	2.85	4.23	2.46	2.74	3.80	3.44	2.94
May	–	3.83	2.52	4.07	5.50	6.31	5.04	4.28
June	–	8.31	6.47	8.70	11.99	10.30	9.19	9.93
July	–	9.95	15.40	13.60	11.71	12.84	13.15	11.10
August	9.87	10.61	11.90	*	12.97	13.18	12.96	10.29
September	9.25	10.26	10.38	10.66	11.56	12.72	11.11	*

Table G-2. Lowest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Naknek Lake's Iliuk basin, 2011–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	6.11	5.69	6.28	5.98	6.56	6.71	6.65
November	–	3.83	3.95	4.81	5.32	5.34	5.38	5.28
December	–	1.39	0.86	3.27	4.48	4.05	3.78	4.23
January	–	1.09	1.30	2.88	3.01	3.36	0.52	0.21
February	–	1.08	0.70	0.41	2.27	3.00	0.60	0.22
March	–	1.25	0.25	1.42	1.79	2.70	1.31	1.83
April	–	1.41	0.41	1.75	2.28	3.04	1.95	2.22
May	–	2.74	1.27	2.52	2.77	6.84	3.15	2.96
June	–	3.98	2.58	4.14	5.66	6.27	5.24	4.70
July	–	6.20	5.49	8.81	8.27	9.41	7.71	7.48
August	8.62	8.30	8.50	*	10.85	11.61	10.82	8.53
September	7.35	7.06	6.66	8.55	7.45	9.36	8.37	*

Table G-3. Standard deviation of daily mean water temperatures (°C) at the 5 m depth, summarized by month for Naknek Lake's Iliuk basin, 2011–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	0.40	0.41	0.12	0.65	0.45	0.69	0.50
November	–	0.70	0.45	0.46	0.18	0.39	0.40	0.43
December	–	0.81	0.94	0.52	0.27	0.38	0.42	0.30
January	–	0.09	0.32	0.11	0.38	0.22	1.09	1.31
February	–	0.17	0.31	0.92	0.27	0.11	0.23	0.77
March	–	0.07	0.21	0.20	0.27	0.07	0.17	0.18
April	–	0.41	0.21	0.23	0.13	0.24	0.43	0.23
May	–	0.29	0.37	0.49	0.64	0.72	0.50	0.38
June	–	1.40	0.91	1.27	1.92	1.38	1.33	1.29
July	–	0.90	2.65	1.29	1.05	1.15	1.40	1.12
August	0.43	0.61	0.90	*	0.67	0.53	0.61	0.55
September	0.64	0.76	1.13	0.65	1.06	1.10	0.59	*

Table G-4. Warmest day, warmest week, and days exceeding 15 °C at the 5 m depth, summarized by water year for Naknek Lake's Iliuk basin, 2011–2018. Asterisks indicate water years with one or more missing months of data.

Water Year	Warmest Day Date	Warmest Day 24-hr mean (°C)	Warmest Week Dates	Warmest Week 7-day mean (°C)	Days >15 °C (n)
2011 *	08/15	9.87	08/13–08/19	9.63	0
2012	08/18	10.61	08/14–08/20	10.04	0
2013	07/30	15.40	07/27–08/02	12.82	1
2014 *	07/27	13.60	07/31–08/06	13.33	0
2015	08/08	12.97	08/05–08/11	12.69	0
2016	08/08	13.18	08/03–08/09	13.04	0
2017	07/28	13.15	07/28–08/03	12.58	0
2018 *	07/08	11.10	07/27–08/02	10.17	0

Appendix H

Table H-1. Highest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Lake Brooks, 2010–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	9.56	9.27	8.14	9.11	10.99	9.49	11.84	10.27
November	–	6.88	7.15	6.02	7.34	6.63	7.04	7.44	7.44
December	–	4.31	3.04	2.10	4.57	5.45	5.06	4.61	4.94
January	–	1.39	1.31	1.26	2.41	4.18	3.22	2.48	3.57
February	–	1.74	1.62	1.31	2.17	2.17	2.36	1.84	1.41
March	–	2.52	1.68	1.72	1.26	2.02	2.29	2.21	1.83
April	–	3.13	2.56	3.10	2.61	2.63	3.81	3.11	3.18
May	–	5.46	3.86	5.24	6.88	6.02	7.85	6.06	5.59
June	–	8.18	8.14	11.22	10.02	13.88	12.63	11.05	12.15
July	–	11.24	11.58	15.91	14.04	13.52	15.51	14.76	13.07
August	*	11.49	11.77	14.15	14.93	15.08	15.26	15.33	13.88
September	12.20	11.33	11.50	13.14	13.24	13.03	15.71	12.34	*

Table H-2. Lowest daily mean water temperatures (°C) at the 5 m depth, summarized by month for Lake Brooks, 2010–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	6.96	7.26	6.19	7.35	6.74	7.20	7.45	7.45
November	–	4.35	2.66	2.17	4.75	5.47	5.09	4.78	4.99
December	–	1.06	1.04	0.76	2.34	4.08	3.23	2.36	3.43
January	–	1.22	1.14	1.01	1.94	2.08	2.34	1.61	0.33
February	–	1.15	1.21	1.15	0.81	1.59	2.08	1.63	0.52
March	–	1.78	1.61	1.32	0.78	1.10	1.87	1.83	1.38
April	–	2.54	1.67	1.77	1.28	1.77	2.34	2.22	1.39
May	–	3.12	2.33	2.93	2.66	2.79	3.90	3.11	3.05
June	–	5.24	3.97	5.15	5.98	6.54	6.04	5.75	5.55
July	–	7.98	6.09	10.12	9.99	7.48	11.93	9.21	9.64
August	*	8.59	9.07	10.91	12.68	13.06	14.21	11.86	9.12
September	9.41	8.75	7.95	9.23	10.79	9.62	12.12	9.75	*

Table H-3. Standard deviation of daily mean water temperatures (°C) at the 5 m depth, summarized by month for Lake Brooks, 2010–2018 water years (WY). Asterisks indicate that data in a given month did not meet criteria of the 3/5 rule at the time of analysis, and dashes indicate no data.

Month	WY 2010	WY 2011	WY 2012	WY 2013	WY 2014	WY 2015	WY 2016	WY 2017	WY 2018
October	–	0.82	0.64	0.68	0.47	1.21	0.76	1.49	0.83
November	–	0.71	1.42	1.11	0.81	0.31	0.72	0.76	0.80
December	–	1.20	0.65	0.34	0.83	0.44	0.60	0.59	0.45
January	–	0.04	0.04	0.08	0.13	0.63	0.28	0.27	1.11
February	–	0.21	0.14	0.04	0.54	0.16	0.09	0.06	0.26
March	–	0.22	0.02	0.10	0.16	0.27	0.10	0.12	0.15
April	–	0.19	0.31	0.41	0.38	0.25	0.45	0.26	0.44
May	–	0.60	0.46	0.59	1.28	0.80	1.04	0.77	0.71
June	–	1.00	1.34	1.84	1.18	2.27	1.75	1.73	1.48
July	–	0.87	1.32	1.9.	1.46	1.53	1.24	1.56	0.89
August	*	0.57	0.66	0.82	0.68	0.48	0.29	0.86	1.07
September	0.86	0.84	1.02	1.18	0.70	1.08	1.20	0.56	*

Table H-4. Warmest day, warmest week, and days exceeding 15 °C at the 5 m depth, summarized by water year for Lake Brooks, 2010–2018. Asterisks indicate water years with one or more missing months of data.

Water Year	Warmest Day Date	Warmest Day 24-hr mean (°C)	Warmest Week Dates	Warmest Week 7-day mean (°C)	Days >15 °C (n)
2010 *	09/17	12.20	09/14–09/20	12.06	0
2011	08/17	11.49	08/29–09/06	11.24	0
2012	08/30	11.77	08/27–09/02	11.53	0
2013	07/31	15.91	07/25–07/31	15.00	4
2014	08/06	14.93	08/02–08/08	14.55	0
2015	08/03	15.08	08/15–08/21	14.23	1
2016	09/03	15.71	08/31–09/06	15.40	32
2017	08/03	15.33	07/29–08/04	14.85	2
2018 *	08/10	13.88	08/05–08/11	13.51	0

Appendix I

Table I-1. Results of seasonal Kendall tests for changes over time in water temperature means and standard deviations at the array located in the West basin of Naknek Lake (NAKNL02). The test statistic (τ) indicates the direction of the trend. Positive τ values with p-values <0.05 are interpreted as significant warming trends. For each value of τ, the Sen slope estimates the median annual change (Δ/yr, in °C). Values between −0.001 and 0.001 are rounded to 0.000.

Depth (m)	NAKNL02 – Means (9/2008–8/2018)			NAKNL02 – Standard Deviations (9/2008–8/2018)		
	τ	p	Δ/yr	τ	p	Δ/yr
5	0.320	0.000	0.123	0.180	0.012	0.020
10	0.336	0.000	0.113	0.252	0.001	0.028
15	0.306	0.000	0.112	0.260	0.000	0.023
20	0.271	0.000	0.088	0.261	0.000	0.023
25	0.289	0.000	0.074	0.317	0.000	0.027

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