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Moored All-Season Vertical Temperature Arrays in Lakes on Kodiak, Togiak, and Alaska Peninsula/Becharof National Wildlife Refuges

Final Project Report to the Western Alaska Landscape Conservation Cooperative

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Togiak National Wildlife Refuge, Dillingham, Alaska;
Alaska Peninsula/Becharof National Wildlife Refuges
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Bill Pyle, Patrick Walsh, and Ron Britton[1]

Abstract

The primary purpose of this project is to acquire long-term data series on temperature of selected lakes to support management of nursery habitat of lake-rearing juvenile sockeye salmon (*Oncorhynchus nerka*) in relation to climate change. We adopted protocol developed by the National Park Service (NPS) to establish moored all-season vertical temperature monitoring arrays in eight lakes of Kodiak, Togiak, and Alaska Peninsula/Becharof National Wildlife Refuges (NWR) in summer and fall 2011. We recorded lake temperature at a resolution of 0.02°C on an hourly basis at various depth strata between lake surfaces and lake bottoms. Monitoring sites were visited annually or biannially to extract data and to service monitoring equipment. A custom database utility was developed to facilitate data organization, basic analysis, and archiving. Initial evaluation of temperature data indicated that lake study sites conformed to a dimictic pattern of stratification and isothermy at Kodiak NWR and Togiak NWR. Although study sites exhibited similar overall patterns of interannual temperature variation, they differed in magnitude of variation during the summer-fall stratification period, which we attributed mainly to differences in lake volume. At Kodiak Island, variation in monthly mean air temperature was related to variation in monthly mean lake temperature at the 5 m depth strata. Annual mean air temperature was -1.8°C below the long-term (1981-2010) mean (i.e. normal) between Oct 2011 and Sep 2012 but near normal (0.3°C) between Oct 2012 and Sep 2013. However, seasonal differences were more pronounced. Prolonged ice cover of study sites was facilitated by below normal mean air temperature (-2.5°C) during Dec-Mar 2011-12. Conversely, above normal mean air temperature (1.3°C) during Jun-Sep likely triggered periodic exceedance of the Alaska Department of Environmental Conservation's (ADEC) 15°C water temperature standard at1, 5, and10 m depth strata between late-Jul and early Aug 2013. During this same period, we observed a rate of temperature change of up to 1°C/m between 5 and 10 m depth strata of Red Lake, which possibly indicated thermocline development. We conclude with recommendations for protocol refinement, measures to increase understanding of temporal and spatial variation in temperature estimates, and an interagency process to facilitate cooperative analysis of long-term series of lake temperature data for nursery lakes of sockeye salmon in the southwest Alaska region.

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INTRODUCTION

Water temperature influences all biological and physicochemical interactions within aquatic systems. Water temperature monitoring is an essential part of lake management capable of providing early warning signs of climate change using straight-forward, low-cost techniques. Water temperature data acquired in this study will be used to support analyses of trend of the lacustrine component of sockeye salmon habitat. The need for such analyses is acute because climate change will influence lake habitat quality; growth and survival of juvenile sockeye salmon; and subsistence, recreational, and commercial harvest opportunities. Additionally, data acquired in this project will be eventually combined with data collected by the National Park Service, the University of Washington, and the U.S. Geological Survey's Alaska Science Center (Jones et al. 2011) to facilitate analysis and interpretation of lake temperature trend across the entire Western Alaska Landscape Conservation Cooperative (Western Alaska LCC).

The primary goals of this project included: (1) establishment and operation of baseline water temperature monitoring in selected lakes of Kodiak NWR, Togiak NWR, and Alaska Peninsula/Becharof NWR; (2) distribution of initial data and summary results to theWestern Alaska LCC.

These data and results will provide a framework for improved understanding of trend in quality of lake environments and habitat of lake-rearing sockeye salmon in relation to climate change. All lakes outfitted with monitoring arrays are considered as productive rearing habitat of juvenile sockeye salmon. This monitoring effort will compliment analogous monitoring efforts by the Southwest Alaska Network of the NPS, University of Washington, and the U.S. Geological Survey, thereby providing a more comprehensive dataset that spans the entire Western Alaska LCC. This report details initial results from Kodiak NWR and Togiak NWR. Results from Alaska Peninsula/Becharof NWR were not available due to recent reductions in workforce capacity.

Study Area

The study area encompasses four National Wildlife Refuges in southwest Alaska (Figure 1). Study sites included: Karluk Lake and Red Lake, Kodiak NWR; Togiak Lake and Ongivinuk Lake, Togiak NWR; and), and Becharof Lake, upper Ugashik Lake, Needle Lake, and Mother Goose Lake, Alaska Peninsula/Becharof NWRs.

Methods

Lake Selection

We selected lake study sites based on several criteria. These included: (1) documented sockeye salmon habitat; (2) surface area larger than 10 ha; and (3) availability of relevant lake-specific technical information (e.g., limnology, bathymetry, fisheries inventory, monitoring, and/or research records). Study lakes differed substantially in physical characteristics especially lake watershed area, lake surface area, elevation, depth, and configuration (Table 1).

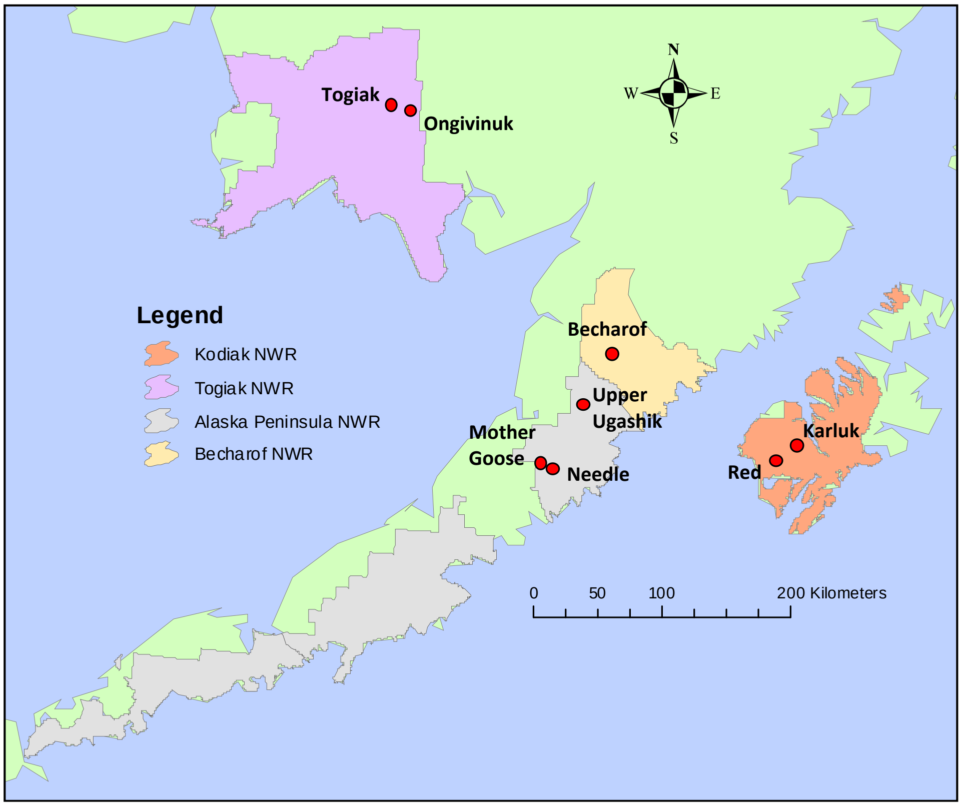


Figure 1. Location of study lakes in four National Wildlife Refuges of southwestern Alaska.

Table 1. Physical characteristics of lake study sites.

Lake	Lake watershed (ha)	River watershed	Surface area (ha)	Elevation (m)	Max depth (m)	Mean depth (m)	Length (km)	Width (km)
Red[1]	5,687	Ayakulik	750	62	47	27	6.4	1.7
Karluk[1]	27,091	Karluk	3,810	112	139	41	19.1	3.2
Becharof[2,3]	-	Egegik	114,270	15	181	57	60	24
Mother Goose[4,5]	-	King Salmon	-	23	45	-	9.6	5
Upper Ugashik[2,3]	-	Ugashik	19,940	4	150	28.6	27	10
Needle	-	King Salmon	-	27	-	-	1.4	0.9
Togiak[6]	303,021	Togiak	3,835	67	143	77	22.5	1.6
Ongivinuk[6]	3,166	Togiak	122	163	12	6	2	0.8

Data sources: [1]H. Finkle, Alaska Dept. of Fish and Game, pers. comm.; [2]Spafard and Edmundson (2000); [3]Orth (1967); [4]Schaefer et al. (2008); [5]Schaefer et al. (2011); and [6]MacDonald (1996).

Protocol

We followed protocol formulated and currently used by the Southwest Alaska Area Network of the National Park Service (NPS) for lakes of National Parks of southwestern Alaska (Shearer &

Moore, 2011). Accordingly, each temperature monitoring array consisted of a tandem instrument line and anchor line. Line sets consisted of anchors at the lake bottom, buoys near the lake surface, and intervening bridal lines. Length of instrument and anchor lines was determined by lake depth estimated generally from bathymetry maps and specifically by sonar at the deployment sites. To prevent ice entrapment, buoys were suspended 3 to 5 m below the lake surface. To facilitate array retrieval, maintenance, and data collection, instrument and anchor lines were interconnected below surface buoys with a 60 m length of bridal line. Individual temperature sensor units, hereafter referenced as “thermistor”, were attached to an instrument line at 5 m intervals where lake depth at a deployment site was less than 50 m; otherwise the interval was typically 10 m. No thermistors were deployed deeper than 110 m due to potential for pressure-related thermistor malfunction. Each thermistor consisted of a waterproof Onset® HOBO® U22 Water Temp Pro V2 of accuracy of 0.2°C over 0° to 50°C and resolution of 0.02°C at 25 °C. Refer to previous project reports for additional detailed information regarding application of NPS protocol in this study (USFWS 2011; Pyle et al. 2012; Pyle 2013).

Data Management and Analysis

In the office, data was transferred to a database, archived, and analyzed. In response to our request, the Inventory and Monitoring (IM) Program of the Service’s Alaska Regional Office developed a database utility to facilitate organization, basic analyses, and archiving tasks. Most summary analyses featured in this report were performed using various report functions of the database utility (Figure 2). Copies of the data and metadata generated by the database are archived in computer servers at each refuge.

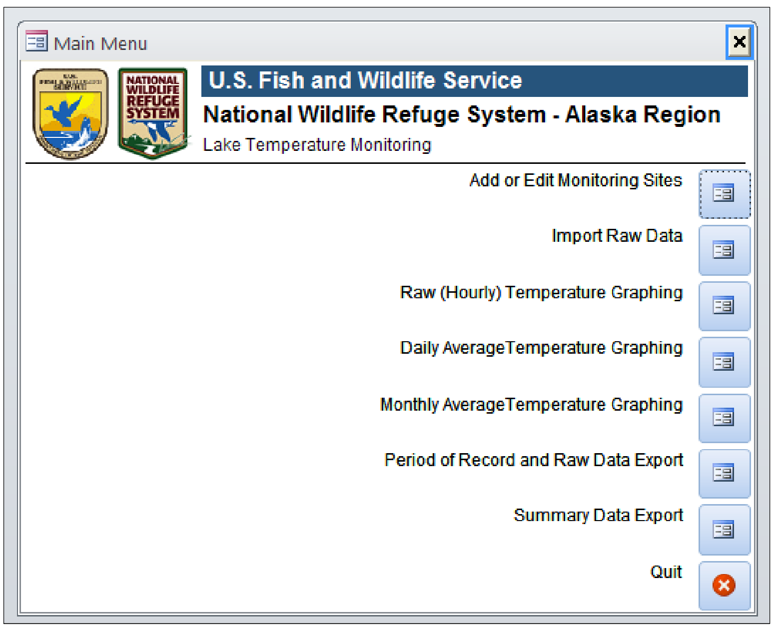


Figure 2. Main menu of custom Access® database utility developed to facilitate management of multi-refuge lake temperature data.

Analysis of data and presentation of results was based on the assumption of relatively static and constant depth of thermistors, the automated temperature recording devices. In reality, thermistor depth varied in direct response to variation to lake elevation. Field observations suggested that variation in lake elevation was minimal (i.e., up to 2 m); however, actual timing and magnitude of lake elevation was not quantified.

Since no convention existed for analysis we created one to satisfy this reporting requirement. Most of summary results presented in this report were based on selection of readily computed statistics presented in National Park Service reports (Shearer and Moore 2011) and various technical papers. Often preliminary analyses were performed via structured queries in the Access® database application developed for this project by the Service's IM Program. Additional basic analysis involved data export and processing in Excel®. The Alaska Climate Science Center provided climate data for primary weather stations adjacent to each of the Refuges (e.g., King Salmon, Kodiak, Dillingham).

We defined the growing season as the annual period of temperature that exceeded 4°C at a 5 m depth. This is a slight modification of Edmundson and Mazumder's (2002) criteria which used the same temperature threshold but different depth (1 m).

We evaluated whether lake temperature exceeded the Alaska Department of Environmental Conservation's (ADEC) standard for maximum temperature in fish rearing areas (ADEC 2011). The Cook Inletkeeper executed a similar interpretation, evaluation, and application of ADEC's standards related to summer temperature of salmon streams in the Cook Inlet region of Alaska (Mauger 2012). We assumed that ADEC's exceedance standard of 15°C for "rearing areas" applied to salmonid rearing areas in both aquaculture and wildland settings. Our analysis entailed evaluation of daily and weekly mean temperature data, and classification of exceedance events for different temperature exceedance levels (≥15°C, ≥16°C, etc.) and depth strata. An exceedance event was defined as a period of one or more consecutive hours when temperature of particular depth strata met or exceeded different temperature exceedance levels.

We assessed the phenology of ice cover. At Kodiak NWR, we assumed that ice cover occurred when temperature observed at the 5 m strata was ≤0.4°C lower than temperature of the deepest-set thermistor (110 m at Karluk Lake, 35 m at Red Lake). We adapted this criterion from a study performed by Pierson et al. (2011), who empirically determined the relationship between visual and measured ice cover with measurements recorded via thermistors situated near lake surfaces (0.1-3 m) and lake bottoms. We assumed that the estimates we derived reasonably approximated the timing of ice formation and disintegration at monitoring sites. However, because we did not match Pierson et al.'s (2011) criteria, we cannot ascertain the extent of error, which may vary from 1-10 days. We corroborated our estimates through examining ice cover and extent in cloud-free scenes acquired with the MODIS sensor (moderate-resolution imaging spectroradiometer) of the Terra (EOS AM) satellite. At Togiak NWR, estimates of the period of ice cover were based on evaluation of the pattern of winter temperature differences between different depth strata.

For the sake of brevity we often dispense with reference to 'monitoring site' in our description of results. Instead we routinely reference the subject lake. Note, however, that we acknowledge that the domain of inference of our results is likely limited given the absence of replication in monitoring sites within each study lake. Additionally, it is likely that lake temperatures differed spatially in each lake during periods of stratification, especially during summer. Such differences are probably most pronounced in large lakes where magnitude of difference increased as a function of distance from monitoring site due to differential influences of surrounding mountains on weather. Furthermore, we expect temperature assessed at a monitoring site positioned in lake limnetic (offshore) regions differed from the littoral (shoreline) regions due to radiant heat absorbed and transferred from the periodically sunlit lake substrate to the adjacent water column.

Results and Discussion

Monitoring arrays were deployed between Jul and Sep 2011. In most cases arrays were subsequently visited twice yearly (e.g., May, Oct) for purposes of data extraction; maintenance; and deployment and retrieval of additional thermistors set to record hourly temperature at a 1 m depth (Figure 3). At Alaska Peninsula/Becharof NWR, most of the array sites were visited once annually for maintenance and data extraction but near-surface thermistors were not set. The following presentation addresses results for Kodiak NWR and Togiak NWR.

Figure 3. Eric Torvinen, Refuge Volunteer, operates a capstan winch to retrieve the instrument line at Karluk Lake, Kodiak NWR.

Kodiak NWR

Air Temperature

Air temperature differed between years of observation (Figure 4). Air temperature recorded at Kodiak State Airport was -1.8°C below normal during Oct 2011-Sep 2012, and 0.12°C above normal during Oct 2012-September 2013. Magnitude of interannual differences was most pronounced in winter and summer. Temperature was -2.5°C below normal during Dec-Mar 2011-12 yet 0.2°C above normal during Dec-Mar 2012-13. Furthermore, temperature was 0.6°C below normal during Jun-Sep 2012 yet 1.3°C above normal during Jun-Sep 2013. The above normal temperatures observed during summer 2013 were within the range projected for a near-future normal associated with climate warming in the Kodiak area (SNAP 2012).

Lake Temperature – General Characteristics

Monthly mean air temperature was correlated (r=0.88) with monthly mean lake temperature (5 m depth) for both lakes and years combined. Potential improvement in correlation was obtained (r=0.94) when we accounted for a one-month lag in water temperature change in response to air temperature change. These results generally correspond with the results of other studies that demonstrated the functional relationship between air and water temperature (Livingstone and Lotter 1998; Piccolroaz et al. 2013). Daily mean air temperature was moderately correlated (r=0.60) with daily mean water temperature (1 m depth) at Karluk Lake and Red Lake during July-August 2012-13. This general relationship was graphically apparent (Figure 4 and 5).

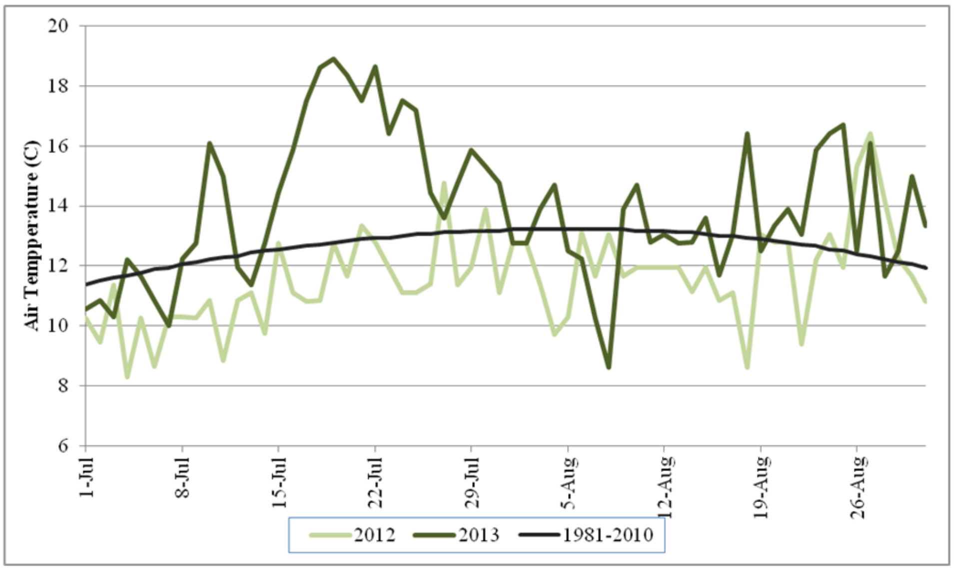


Figure 4. Daily mean air temperature, Jul-Aug 2012-13 and 1981-2010, Kodiak State Airport, Kodiak Island.

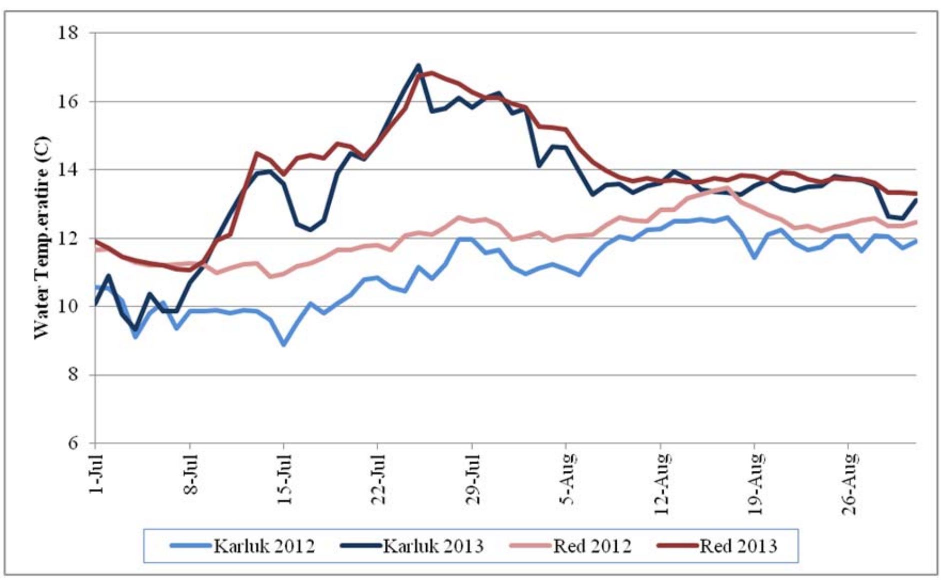


Figure 5. Daily mean water temperature (°C), July-August 2012-13, Karluk Lake and Red Lake (1 m depth), Kodiak NWR.

Despite differences in size, orientation, and volume, Karluk Lake and Red Lake exhibited similar patterns of lake temperature variation. Monthly mean temperature was highly correlated (r=0.99) between lakes at the 5 m depth strata (Table 2).

Table 2. Monthly mean, mean maximum, and mean minimum water temperature (ºC), and mean degree days recorded at 5 m depth at Karluk Lake and Red Lake, Kodiak NWR, Oct 2011-Aug2013.

Lake & Month	Mean[1] $\bar{x}$ (1 SD[5]); ºC		Mean Maximum[2] $\bar{x}$ (1 SD[5]); ºC		Mean Minimum[3] $\bar{x}$ (1 SD[5]); ºC		Mean Degree Days[4]	
	2011-12	2012-13	2011-12	2012-13	2011-12	2012-13	2011-12	2012-13
Karluk Lake								
October	8.8 (0.0)	7.8 (0.0)	8.8 (1.0)	7.9 (0.9)	8.7 (1.0)	7.8 (0.9)	273	248
November	4.5 (0.1)	4.6 (0.0)	4.6 (1.7)	4.6 (0.9)	4.4 (1.8)	4.5 (0.9)	135	137
December	1.6 (0.0)	1.1 (0.1)	1.7 (0.4)	1.2 (0.9)	1.6 (0.4)	1.0 (0.8)	53	33
January	1.0 (0.0)	0.3 (0.0)	1.0 (0.1)	0.3 (0.1)	1.0 (0.1)	0.2 (0.1)	31	0
February	1.2 (0.0)	0.2 (0.0)	1.2 (0.1)	0.3 (0.0)	1.2 (0.1)	0.2 (0.0)	29	0
March	1.3 (0.0)	0.4 (0.0	1.3 (0.0)	0.5 (0.1)	1.3 (0.0)	0.4 (0.1)	31	7
April	1.8 (0.0)	1.5 (0.0)	1.8 (0.4)	1.6 (0.6)	1.7 (0.3)	1.5 (0.5)	51	46
May	3.5 (0.1)	4.1 (0.1)	3.7 (1.0)	4.3 (1.2)	3.4 (0.9)	3.9 (0.9)	111	126
June	8.0 (0.4)	8.9 (0.4)	8.6 (2.0)	9.6 (1.8)	7.4 (1.6)	8.1 (1.8)	238	266
July	11.2 (0.2)	12.6 (0.4)	11.5 (0.5)	13.2 (1.8)	10.9 (0.5)	11.9 (1.4)	349	389
August	12.3 (0.1)	13.7 (0.2)	12.4 (0.4)	14.0 (0.7)	12.1 (0.3)	13.4 (0.4)	379	426
September	10.5 (0.1)	11.3 (0.1)	10.6 (0.9)	11.4 (1.4)	10.4 (0.9)	11.1 (1.5)	314	338
Red Lake								
October	8.0 (0.0)	7.5 (0.0)	8.1 (0.8)	7.6 (0.5)	8.0 (0.8)	7.4 (0.5)	247	232
November	5.5 (0.0)	5.7 (0.0)	5.6 (0.8)	5.8 (0.5)	5.4 (0.8)	5.7 (0.5)	163	169
December	3.1 (0.1)	3.4 (0.1)	3.3 (0.9)	3.6 (0.8)	3.0 (1.0)	3.3 (0.9)	98	106
January	1.0 (0.0)	2.1 (0.1)	1.0 (0.1)	2.3 (0.2)	1.0 (0.1)	2.0 (0.4)	31	62
February	1.3 (0.0)	1.5 (0.1)	1.3 (0.1)	1.6 (0.2)	1.3 (0.1)	1.4 (0.3)	29	45
March	1.4 (0.0)	1.4 (0.1)	1.4 (0.0)	1.5 (0.1)	1.4 (0.0)	1.3 (0.2)	31	43
April	2.0 (0.1)	1.8 (0.1)	2.0 (0.5)	2.0 (0.2)	1.9 (0.4)	1.7 (0.3)	61	60
May	3.4 (0.1)	3.3 (0.1)	3.5 (0.5)	3.5 (0.8)	3.2 (0.5)	3.1 (0.6)	104	101
June	7.8 (0.3)	8.3 (0.4)	8.3 (2.1)	8.9 (2.3)	7.3 (2.0)	7.6 (2.1)	232	249
July	10.2 (0.2)	13.0 (0.4)	10.6 (0.8)	13.6 (2.3)	9.8 (0.8)	12.3 (2.4)	318	404
August	11.8 (0.2)	13.6 (0.3)	12.1 (0.5)	14.0 (0.7)	11.5 (0.6)	13.2 (0.8)	365	423
September	9.8 (0.1)	10.8 (0.1)	10.1 (1.1)	11.0 (1.2)	9.5 (1.1)	10.5 (1.2)	292	323

[1]Mean of daily temperature; [2]mean of daily maximum temperature; [3]mean of daily minimum temperature; [4]monthly cumulative total difference between daily mean temperature and 0ºC; [5]standard deviations <0.05ºC are reported as 0.0ºC.

The 5 m depth strata averaged slightly warmer in 2013 compared to 2012 (Table 2). Moreover, comparison of monthly mean temperature indicated that Karluk Lake was 0.6°C warmer in 2013 and Red Lake was 0.1°C warmer in 2013. Although annual means were similar, seasonal means differed between years. Compared to 2012, temperature in 2013 during Jul-Aug was 1.8-2.9°C warmer at Karluk Lake and 1.4-1.5°C warmer at Red Lake. At Red Lake, the increase in mean summer temperature was seemingly offset by a decrease in mean winter temperature, which averaged 0.9°C colder during Dec-Mar.

Annual mean temperature of the 5 m depth strata was slightly colder (0.2°C) at Red Lake compared to Karluk Lake between Oct 2012 and Sep 2013 (Table 2). Although winter temperature (Dec-Mar) averaged 0.7°C colder at Red Lake compared to Karluk Lake, summer temperature averaged 0.4°C warmer at Red Lake. We attributed this difference primarily to an interaction of air temperature with substantially different lake volumes (i.e., 1,843 x $10^6 m^3$ in Karluk Lake and 178 x $10^6 m^3$ in Red Lake).

We had data sufficient for estimation of the 2012 growing season (i.e., period when temperature ≥4°C at 5 m depth). It ranged from 182 days in Red Lake to 196 days in Karluk Lake. If this difference was indicative of long-term relationship, then it may partly account for the consistently higher (zooplankton) biomass observed in Red Lake compared to Karluk Lake between 2010 and 2012 (H. Finkle, Alaska Dept. Fish & Game, pers. comm.). We attributed this potential difference primarily to an interaction of air temperature with substantially different lake volumes. Whereas the 2012 growing season ended later than the 2013 growing season (Karluk Lake-9 d; Red Lake-3 d), the 2013 growing season started earlier than the 2012 growing season (Red Lake-8 d; Karluk Lake-3 d).

Temperature exceeded ADEC's 15°C minimum standard for salmonid rearing areas during Jul-Aug 2013 (Table 3). The duration and magnitude of exceedance events ranged from 5-43 h and 15-17.9°C, respectively, for 1-10 m depth strata of Karluk Lake, and 5-71 h and 15-17.4°C, respectively, for the 1-5 m depth strata of Red Lake. Cumulative exceedance totaled 779 hours at Karluk Lake and 685 hours at Red Lake. The three longest exceedance events lasted 6.5-6.6 days at Karluk Lake and 12.1 days at Red Lake.

Table 3. Temperature exceedance[1] characteristics, July-August 2013, Karluk Lake and Red Lake, Kodiak Island, Alaska.

Lake	Depth (m)	Temp. (°C)	Events[2] (n)	Hours ($\bar{x}$)	Hours (range)	Hours (∑)	Dates (range)
Karluk Lake							
	1	≥15	10	28	(1-160)	284	7/19-8/5
		≥16	9	13	(1-42)	113	7/23-7/31
		≥17	3	7	(3-9)	20	7/24-7/25
	5	≥15	6	43	(3-159)	259	7/22-8/5
		≥16	6	12	(9-16)	70	7/24-7/31
	10	≥15	6	5	(1-8)	33	7/24-7/31
Red Lake							
	1	≥15	5	71	(3-292)	353	7/22-8/5
		≥16	5	32	(4-100)	162	7/24-8/1
		≥17	2	5	(1-9)	10	7/24-7/26
	5	≥15	19	8	(1-36)	160	7/23-8/3

1Exceedance minimum standard of 15°C for water temperature in [salmonid] rearing habitat (ADEC2011).
[2]An event consists of one or more consecutive hours exceeding a temperature threshold value.

Perhaps these exceedance events influenced the distribution of sockeye salmon fry and smolts. However, probability of influence was likely greatest in the littoral areas of lakes where higher temperatures, possibly exceeding 20°C, may have occurred due to transfer of additional radiant heat absorbed and subsequently transferred to the adjacent water column. We questioned the applicability of ADEC's 15°C exceedance standards as applied to daily or weekly mean temperature of nursery habitat of sockeye salmon in wildland areas such as the study sites. At least one study identified 15°C as an optimal temperature for rearing sockeye salmon (Brett et al. 1969). To facilitate future interpretation of potential influence of high water temperatures on sockeye salmon nursery habitat we recommend further review and synthesis of relevant technical literature coupled with experimental study of temperature influences to refine knowledge of exceedance criteria.

Stratification and Isothermy

Examination of temperature data indicated that both lakes were dimictic—where a period of vertical temperature stratification alternates with periods of vertical temperature uniformity (i.e., isothermy) on an annual basis (Lewis 1983). The dimictic pattern was usually characterized by distinctive differences in water temperature among depth strata in winter and summer yet minimal difference (i.e., generally <0.5°C) during spring and fall.

Between Jun and mid-Oct stratification was characterized by distinctive non-uniform decline in water temperature from the lake surface to bottom. During the peak of stratification, coincident with maximum surface warming, up to 80% of the 12-14°C temperature difference between the surface and bottom occurred within 20 m of the lake surface (e.g., Figures 6 and 7). The maximum rate of change in daily mean temperature among adjacent depth strata ranged from 0.51°C/m in 2012 to 0.76°C/m in 2013 between 10 and 20 m depth strata at Karluk Lake. At Red Lake it ranged from 0.57°C/m in 2012 to 1.02°C in 2013 between 5 and 10 m depth strata. In particular, the 1°C/m rate observed at Red Lake may have indicated thermocline occurrence or development. A thermocline is generally defined as an abrupt change in water temperature over depth, typically a rate ≥1°C/m (Wetzel 2001). Thermoclines were not observed in either lake during 2009-2011 (Finkle and Ruhl 2011; Finkle and Ruhl 2012; Finkle 2012).

During Dec-Apr we usually observed inverse stratification, which was characterized by distinctive non-uniform decline in water temperature from the lake bottom to the surface. Notably Karluk Lake stratified despite strong evidence that most of the limnetic zone was ice-free during winter 2012-13. Though inverse stratification may occur in the absence of ice cover, duration is usually limited to a few days (Pierson et al. 2011). Concurrently, we observed weak and intermittent stratification associated with intermittent and partial ice cover of Red Lake.

Extended periods of isothermy occurred during Apr-May, and again during Oct-Dec. Duration of spring isothermy was greater at Karluk Lake (22-57 d) in 2012-13 compared to Red Lake (19-28 d). Contrastingly, duration of fall isothermy was greater in Red Lake (56-78 d) in 2011-12 compared to Karluk Lake (46-49 d). If these observations typified the long-term pattern then perhaps the more extensive period of isothermy observed in fall partly accounted for the higher productivity of Red Lake compared to Karluk Lake.

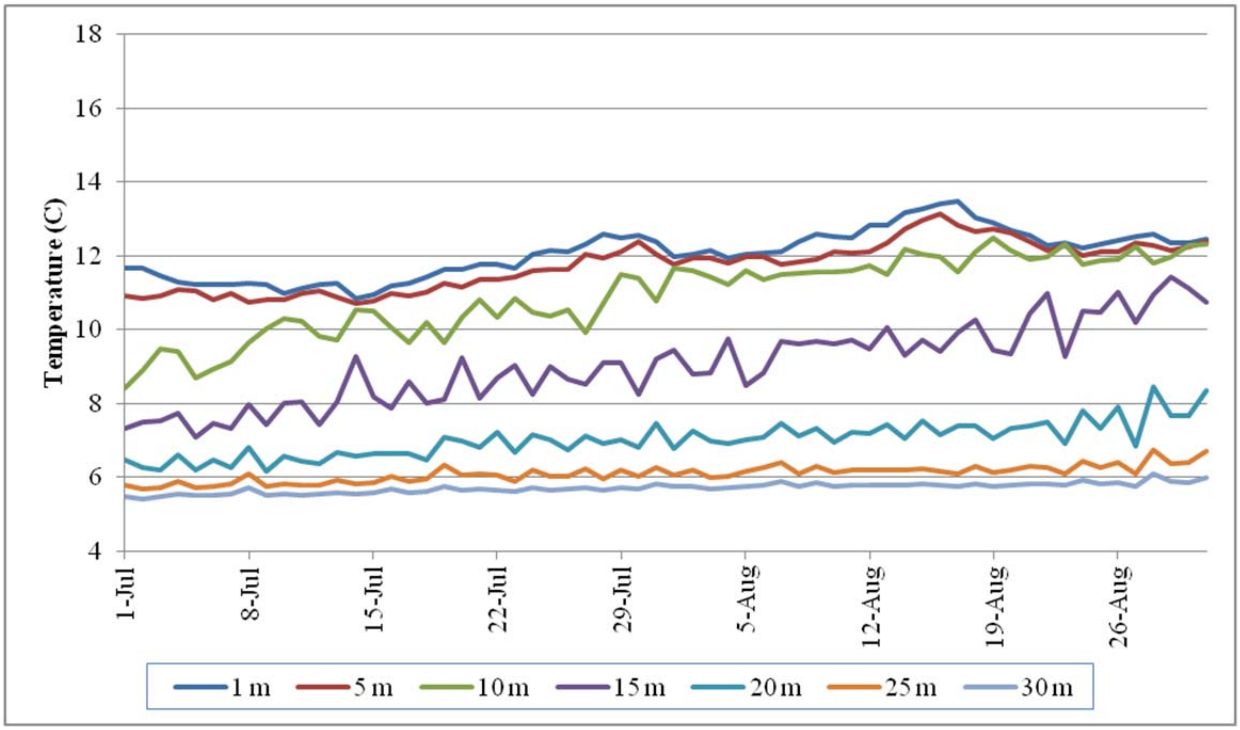


Figure 6. Thermal stratification during Jul-Aug 2012 of the 1–30 m depth zone of Red Lake, Kodiak NWR.

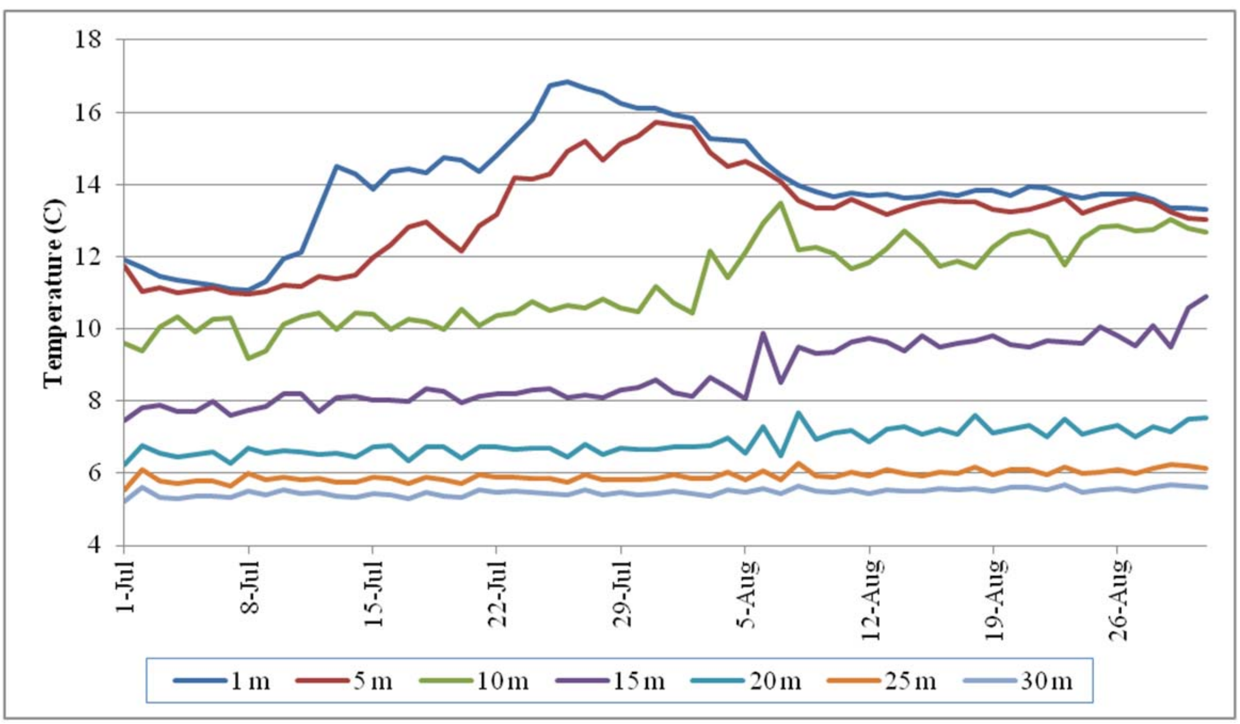


Figure 7. Thermal stratification during Jul-Aug 2013 of the 1–30 m depth zone of Red Lake, Kodiak NWR.

Ice Cover

During winter 2011-12 the surfaces of Karluk Lake and Red Lake froze. Estimated maximum continuous period of ice cover at monitoring site vicinities was 133 d (Dec 23- May 3) at Karluk Lake, and 112 d (Dec 26-Apr 15) at Red Lake. During winter 2012-13, offshore areas of Karluk Lake and Red Lake inclusive of monitoring sites remained mostly ice-free. Estimated maximum continuous period of ice cover was 13 d (Dec 21-31) at Red Lake. We also estimated that ice cover occurred during 21-31 Dec 2012 at the monitoring site at Karluk Lake; however, this seemed unlikely since daily mean temperature never declined below 1°C. Usually, formation and continuous ice cover can be reliably estimated when [daily mean] temperature declines below 1°C followed by rebound but sustained minimal variation (<0.03°C SD). These opposing patterns were apparent in data plots (Figure 8). Observed annual minimum temperatures were: 0.69°C on 31 Dec 2011 (Karluk Lake); 0.87°C on 28 Dec 2011 (Red Lake); 1.1°C on 21 Feb 2013 (Karluk Lake) and 0.06°C on 22 December 2012 (Red Lake).

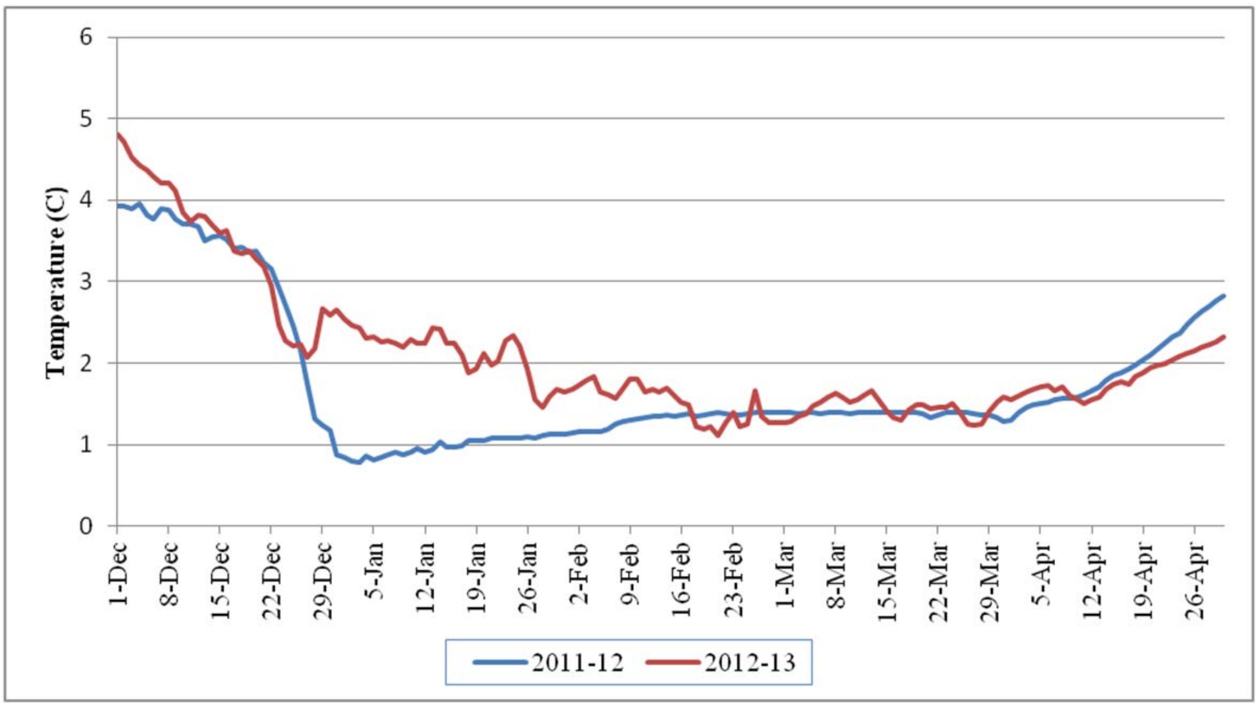


Figure 8. Daily mean temperature at 5 m depth at monitoring site in Karluk Lake, Kodiak NWR, during winter 2011-12 and 2012-13.

Review of MODIS imagery tended to corroborate estimates of ice cover in vicinities of monitoring sites. In winter 2011-12, ice covered >95% of Karluk Lake including the monitoring site on Dec 31; ice completely covered both lakes by mid-Jan; and ice cover persisted through Mar. During the following winter, ice-free states were prevalent in the vicinity of the monitoring sites at Karluk Lake and Red Lake. We noted that ice disintegration proceeded from shoreline to offshore areas during Apr-May 2012. Although MODIS proved a valuable adjunct tool for interpretation of ice phenology, its practical utility was limited in our study area due the low frequency of image acquisition and low frequency (1-5/month) of useable cloud-free scenes.

Togiak NWR

Temperature was recorded at Onigivinuk Lake over 25 months between Jul 2011 and Sep 2013. At Togiak Lake, the record spanned 12 months between Jul 2011 and Jun 2012. Analysis of monthly mean temperature (5 m depth) indicated that Ongivinuk Lake was consistently warmer than Togiak Lake during most of the growing season between Jun and Nov (Table 4). Comparison of three years of data at Ongivinuk Lake indicated that temperature was highest in Jul 2011 and lowest in Jul 2012. During winter, temperatures were substantially lower and persisted substantially longer in 2012 compared to 2013, consistent with the pattern observed at Kodiak NWR.

Both lakes were classified as dimictic based on evaluation of the pattern of temperature variation concurrently recorded at different water depths during 2011-13. At Ongivinuk Lake, ice covered the lake for approximately 7 months in both winters (Figure 9). Ice formation was denoted by decline to <1°C of water temperature of near-surface depth strata, which was usually simultaneously coupled with onset of deviation in temperature between surface and bottom depth strata. Occurrence and persistence of ice cover was characterized by minimal variation in daily mean temperature of all strata but especially those nearest to the lake surface. Complete ice disintegration was denoted by resumption to an isothermic state. Transition to this state was gradual in 2012 and abrupt in 2013.

Recommendations

1. Maintain long-term operation of lake temperature monitoring at Kodiak, Togiak and Alaska Peninsula/Becharof NWRs.

2. Investigate the relationship among lake temperature and air temperature recorded at lake study sites, and air temperature recorded at lake study sites and primary offsite weather stations managed by the National Weather Service at airports in Dillingham, King Salmon, and Kodiak.

3. Assess annual variation in level of lakes to improve estimates of variation in depth strata subject to temperature monitoring.

4. Investigate the relationship between summer temperatures recorded at monitoring sites in the limnetic and adjacent littoral zones.

5. Improve the accuracy of estimates of the phenology of ice cover at monitoring sites.

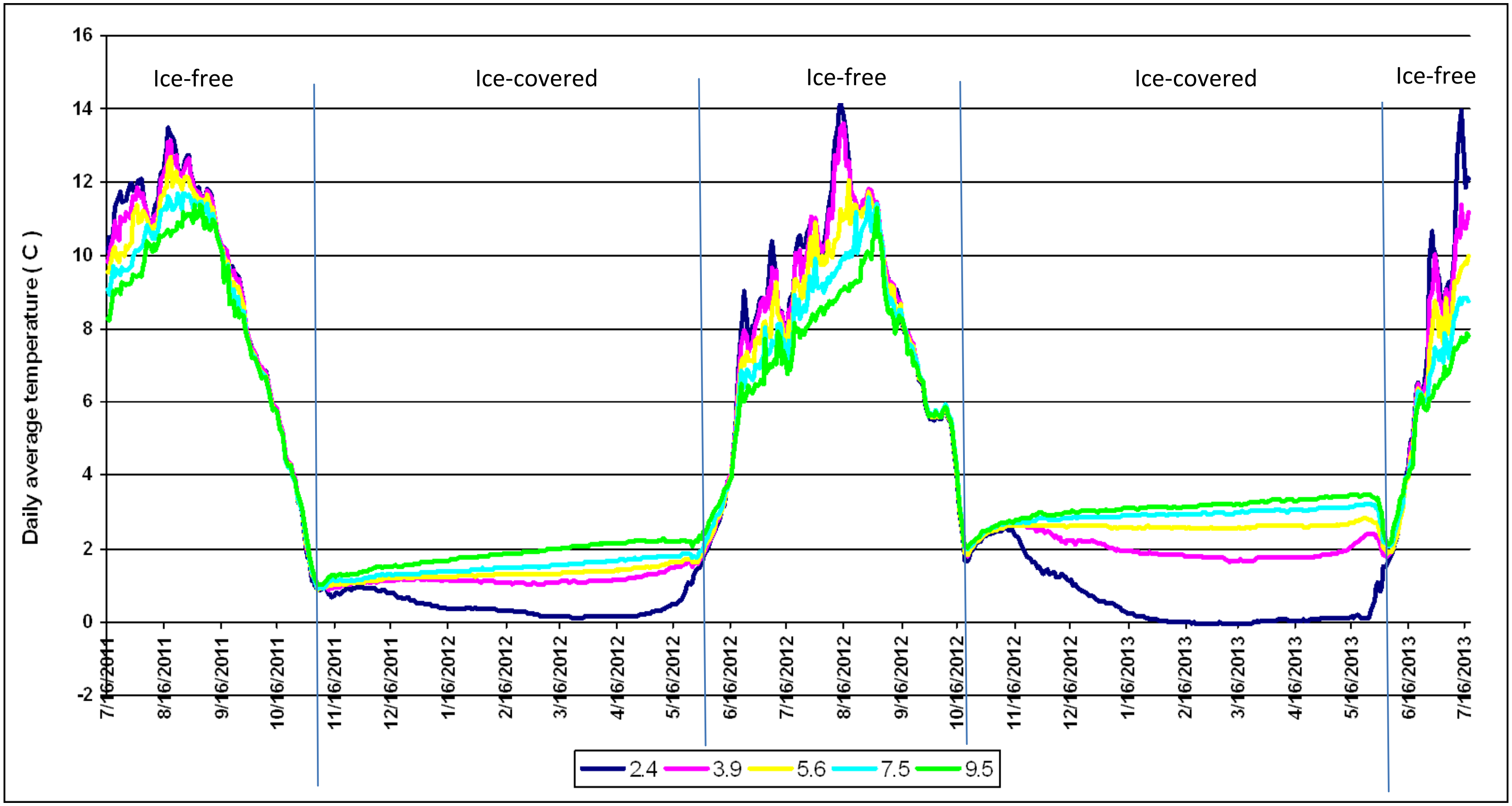
6. Meet with interagency partners to discuss, formulate, and establish a Memorandum of Understanding addressing cooperation on, and scheduling of, analysis, interpretation, and reporting of results from monitoring of temperature of nursery lakes of sockeye salmon in the southwest Alaska region.

Table 4. Monthly mean, mean maximum, and mean minimum water temperature (ºC) recorded at 5 m depth at Ongivinuk Lake and 10 m depth at Togiak Lake, Togiak NWR, Oct 2011-Aug 2013.

	Mean[1] $\bar{x}$ (1 SD[4]); ºC			Mean Maximum[2] $\bar{x}$ (1 SD[4]); ºC			Mean Minimum[3] $\bar{x}$ (1 SD[4]); ºC		
Lake and month	2011	2012	2013	2011	2012	2013	2011	2012	2013
Ongivinuk Lake									
October	5.3(0.1)	3.8 (0.1)		5.4 (1.6)	3.9 (1.7)		5.2 (1.6)	3.7 (1.7)	
November	1.1(0.0)	2.6 (0.0)		1.1 (0.3)	2.6 (0.1)		1.0 (0.2)	2.6 (0.1)	
December	1.2(0.0)	2.6 (0.0)		1.2 (0.0)	2.6 (0.0)		1.2 (0.0)	2.6 (0.0)	
January		1.2 (0.2)	2.6 (0.0)		1.2 (0.2)	2.6 (0.0)		1.2 (0.0)	2.6 (0.0)
February		1.3 (0.0)	2.6 (0.0)		1.3 (0.0)	2.6 (0.0)		1.3 (0.0)	2.6 (0.0)
March		1.3 (0.0)	2.6 (0.0)		1.3 (0.0)	2.6 (0.0)		1.3 (0.0)	2.6 (0.0)
April		1.4 (0.0)	2.6 (0.0)		1.4 (0.0)	2.6 (0.0)		1.4 (0.0)	2.6 (0.0)
May		1.6 (0.0)	2.7 (0.0)		1.6 (0.1)	2.7 (0.1)		1.6 (0.1)	2.6 (0.1)
June		4.6 (0.3)	4.4 (0.2)		5.4 (3.3)	4.8 (2.6)		4.3 (1.9)	4.1 (2.0)
July	10.2 (0.2)	8.7 (0.4)	8.9 (0.3)	10.6 (0.5)	9.3 (1.7)	9.4 (0.8)	9.8 (0.5)	8.0 (1.0)	8.3 (0.9)
August	11.6 (0.2)	10.8 (0.3)		11.9 (0.7)	11.4 (0.8)		11.2 (0.5)	10.3 (0.7)	
September	10.1 (0.1)	8.3 (0.1)		10.3 (1.2)	8.5 (1.6)		10.0 (1.3)	8.1 (1.6)	
Togiak Lake									
October	7.2 (0.1)			7.3 (1.0)			7.1 (1.1)		
November	3.7 (0.1)			3.9 (1.3)			3.5 (1.5)		
December	1.4 (0.1)			1.5 (0.2)			1.3 (0.2)		
January		1.1 (0.0)			1.1 (0.1)			1.1 (0.1)	
February		1.0 (0.0)			1.0 (0.0)			1.0 (0.0)	
March		1.0 (0.0)			1.0 (0.0)			1.0 (0.0)	
April		1.1 (0.0)			1.1 (0.1)			1.1 (0.1)	
May		1.9 (0.0)			2.0 (0.4)			1.9 (0.4)	
June		3.2 (0.1)			3.3 (0.5)			3.0 (0.4)	
July	8.0 (0.3)			8.5 (0.8)			7.6 (0.5)		
August	9.4 (0.2)			9.7 (1.1)			8.9 (1.3)		
September	9.7 (0.1)			9.8 (0.4)			9.6 (0.4)		

[1]Mean of daily temperature; [2]mean of daily maximum temperature; [3]mean of daily minimum temperature; [4]standard deviations <0.05 are reported as 0.0.

Figure 9. Water temperature profile and approximate times of open water and ice cover at Ongivinuk Lake, Togiak NWR, between July 2011 and July 2013. Legend indicates depth (m) from surface.



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