Biological Responses to Increasing Water Temperatures in Lakes of the Barrow/Atqasuk Focus Watershed: An Interdisciplinary Bioenergetics and Contaminants Study

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Study Plan Summary

Climate change is expected to result in increasing air temperatures across Arctic Alaska. How aquatic ecosystems will respond to increasing air temperature is poorly understood. We will conduct an interdisciplinary, collaborative study on several lakes in the Barrow-Atqasuk watershed to better understand how and to what extent continued changes in thermal regimes will affect fish growth, food web structure, and bioaccumulation of mercury. Our research will include both collection of empirical data and modeling, and our overall aim is to enable better predictions of broad-scale ecological and ecotoxicological consequences of climate change in Arctic lakes. Study lakes will be selected from lakes monitored by the Circumarctic Lake Observation Network (CALON). Researchers in this program (funded by the NSF Arctic Observing Network) are monitoring a suite of physical and chemical parameters in several lakes in the Barrow-Atqasuk watershed through 2016. Lakes in the CALON network are distributed across a thermal gradient and we will use this gradient as a natural experiment to examine physical and biological response to a range of thermal regimes.

For example, lake surface temperatures in mid-June of 2010 ranged from near 0 °C in lakes near Barrow to 10 °C in lakes located further inland.

In this study, we will build upon the foundational data collected by CALON and examine how thermal changes affect aquatic ecosystems in Arctic Alaska. We will develop a predictive model that accurately simulates lake water temperature and ice thickness based on present and future atmospheric and landscape factors. We will apply biochronological tools to determine the relationship between water temperature (and other environmental variables) and growth histories of two representative species of fish (least cisco and broad whitefish). Bioenergetic models will be constructed to predict fish growth relative to water temperature. Food web structure will be examined by developing models using stable isotope, water chemistry, and growth data to describe energy and mercury transfer through aquatic communities under differing thermal regimes. Ultimately, integration of study findings will result in predictions of how increasing air temperature may influence ecology and ecotoxicology in lakes on the North Slope of Alaska.

Background and Justification

Climate change is expected to have profound effects on Arctic freshwater ecosystems (Williamson et al. 2009). These effects are difficult to predict due to lack of basic biological information, and incomplete understanding of how climate drives aquatic systems. Temperature, hydrologic fluxes, active layer depths, phenology of ice cover, biogeochemical processes, trophic ecology, food web structure, primary and secondary productivity, water chemistry, fish growth, distribution of species, and contaminant bioaccumulation in Arctic lakes will all be affected by climate change (Wrona et al. 2006, Clow et al. 2011), but it is the largely unknown interactions of these effects that will determine overall responses.

Temperature is a primary control for many ecosystem processes in Arctic lakes (e.g., Black et al. 2012). Climate models and observations show that intensification of the hydrologic cycle and rising air temperatures in Arctic regions will result in continuing increases in lake temperature during ice-free seasons. There is considerable uncertainty associated with projecting annual and seasonal water balances and heat budgets, however (Serreze et al. 2003, Richter-Menge et al. 2008). In closed basin lakes in cold climates, the dominant controls on water temperature are atmospheric forcings, which include air temperature, solar radiation, humidity, wind, and precipitation, but the influence of these factors is buffered by lake thermal capacity, ice cover, and ground heat flux. We are unaware of any lake temperature models that have focused on how climate change will affect Arctic Coastal Plain lakes, which are unique in their morphology, setting, and basin runoff hydrology. Quantifying lake temperature controls

and sensitivities related to changing climate conditions and runoff across a transect of Arctic Coastal Plain lakes is needed to improve our ability to predict changes in biological processes, such as fish production, associated with climate change (Martin et al. 2009).

Quantifying effects of climate change on lake water temperature and heat budgets will allow us to model effects on fish productivity. Lake water temperature is a primary regulator of fish growth and bioenergetics. Fishes that inhabit lakes on the Arctic coastal plain will likely show a diversity of responses to increasing water temperatures - these will vary among locations and depend on fish life history and range of habitats used (Reist et al. 2006a,b). Growth rates of individuals have long been used across plant and animal taxa to monitor population health and understand ecosystem change (Sebens 1987), and are typically linked to demographic rates and changes in population abundance through increased survival and reproduction of larger individuals (Reiss 1989). It is suggested that first order effects of climate change, including warmer lake temperatures and higher productivity, may result in increased growth of fishes (Reist et al. 2006b), at least for fishes that can tolerate increases in temperature. Temperature is generally considered to be one of the most influential environmental factors that control early growth rates in fish (Houde 1989), and it is likely that increasing temperatures in northern latitudes will result in faster summer growth of young-of-year (YOY) fish (e.g., von Biela et al. 2011). This will likely result in larger YOY relative sizes, which should predispose them to higher over-winter survival (Shuter et al. 1980, Reist et al. 2006b). The implications of higher lake temperatures on fish growth and bioenergetics have not, however, been thoroughly studied for fish populations in small lakes on the Arctic coastal plain; at this point, many of our predictions are based on research conducted in more temperate systems, or in larger and deeper lakes.

Climate-induced changes in lake temperature, water chemistry, and productivity will affect species distributions, prey availability, and fish growth rates which will in turn affect trophic ecology, food web structure, and contaminant bioaccumulation in Arctic lakes (e.g., Chu et al. 2005, Shuter et al. 2012, Wrona et al. 2005, Reist et al. 2006b, Chételat and Amyot 2009). It is expected that coldwater fishes will be extirpated from much of their northern range, whereas the distribution of coolwater and warmwater fishes will expand northward (e.g., Chu et al. 2005). Species composition and production of zooplankton will likely also respond to warming and predicted increases in productivity (e.g., Chételat and Amyot 2009, Carter and Schindler 2012). Coupling and relative importance of benthic and pelagic food webs and carbon sources will likely change; most unproductive Arctic lakes are primarily driven by benthic production, but importance of pelagic food/carbon sources may increase with increasing temperature and productivity (e.g., Sierszen et al. 2003, Wrona et al. 2005). These changes will affect

trophic ecology of individual species and overall food web structure which, when considered together with lower-order effects of climate change (i.e., temperature, water chemistry, productivity), will affect concentrations and accumulation of biomagnifying contaminants, such as mercury.

Mercury (Hg) is a neurotoxicant and contaminant of concern for both ecological and human health reasons (AMAP 2011, Mergler et al. 2007). The toxic, organic form of Hg, methylmercury (MeHg), bioaccumulates (increases over time within organisms) and biomagnifies (increases with each trophic level) through aquatic food webs to reach high concentrations in predatory fishes (e.g., Kidd et al. 1995, Wiener et al. 2002). Humans are primarily exposed to MeHg by eating fish (World Health Organization 1990) ($\geq$95% of total Hg in fish is in the MeHg form [Bloom 1992]), and this exposure can be particularly high in northern communities where consuming fish also contributes to nutritional, social, and economic well-being (Van Oostdam et al. 2003). At present, while temporal trend data are not readily available for Hg concentrations in human, fish, and wildlife from Alaska, data show that a "significant percentage" of indigenous women from Alaska have blood Hg values that exceed US EPA guidelines (AMAP 2011). Climate change will likely alter human exposure to Hg, through changes to both concentrations in fish and through changes in consumption patterns. A recent comprehensive review of temporal trend studies on Hg in the circumpolar Arctic found a general paucity of data for Alaska (only one temporal dataset versus 30 from Canada, 30 from Greenland and Scandinavia, 15 from Iceland, and 7 from the Faroe Islands; AMAP 2011). This makes it difficult to predict how human and wildlife exposure to Hg will be affected by climate change in Alaska.

In the executive summary, the editors of the AMAP report state that, "In order to monitor the impacts of climate change, human emissions and the effectiveness of mitigation strategies for mercury, it is recommended to continue monitoring of temporal trends of mercury in air, humans and wildlife, and extend coverage of such monitoring in particular in Alaska and the Russian Arctic" (AMAP 2011). This is important because Hg concentrations in freshwater fishes are often variable on local and regional spatial scales (AMAP 2011), and because Hg concentrations in some regions are expected to increase with climate change. In Alaska, for example, fish-eating birds such as loons (*Gavia spp.*) currently show relatively low concentrations of Hg (Schmutz et al. 2009). However, previous research has shown that most of the Hg in northern Alaskan lakes is derived from catchment erosion (Fitzgerald et al. 2005). Because climate change will result in permafrost melting and accelerated erosion, it is thought that Alaskan lakes may be especially vulnerable to climate-induced increases in Hg (AMAP 2011).

In addition to increased loading, there are biogeochemical reasons why Alaskan lakes may be especially vulnerable to climate-induced increases in fish Hg concentrations. Before Hg bioaccumulates and biomagnifies through aquatic food webs, it must first be converted from inorganic Hg to organic methylmercury (see Wiener et al. 2002). If inorganic Hg is not limiting for this process, increased loading from the catchment (from permafrost melting and erosion) would likely not affect concentrations in biota. Hammerschmidt et al. (2006) found in a series of northern Alaskan lakes, however, that availability of toxic methylmercury is limited by availability of inorganic Hg. This means that if climate change increases erosion and Hg delivery to lakes, Hg methylation and bioavailability will likely increase, and concentrations in fish will also increase. Increased methylation of Hg that results from higher catchment loading could also be exacerbated by climate-induced changes to any of several other variables that modulate rates of Hg methylation in lakes, including (but not limited to) lake productivity, lake pH, lake area, presence/absence of wetlands in the catchment, sulfate concentrations, and dissolved organic carbon concentrations (e.g., Wiener et al. 2002). Mercury concentrations in fishes are affected by all of these, as well as by habitat use (relative use of pelagic habitats/pelagic prey), growth rates, and trophic ecology/food web structure, and each of these variables are themselves susceptible to climate change. To untangle the relative importance of known ecological and biogeochemical predictors of fish Hg concentrations, we will perform a comprehensive analysis of the best predictors of fish Hg concentrations in a series of study lakes on the Arctic coastal plain, and use our results to inform predictions of how fish Hg concentrations will respond to climate change.

Objectives

We will conduct an interdisciplinary, collaborative study on several lakes in the Barrow-Atqasuk watershed to better understand how and to what extent continued changes in thermal regimes will affect fish growth, food web structure, and bioaccumulation of Hg. Our research will include both collection of empirical data and modeling, and our overall aim is to enable better predictions of broad-scale ecological and ecotoxicological consequences of climate change in shallow Arctic lakes. We will accomplish this by:

1. Developing a predictive model that accurately simulates lake water temperature and ice thickness based on present and future atmospheric and landscape factors. We will identify sensitive model parameters and consider how these sensitivities may change given expected climate trends. **Lead investigator:** Josh Koch

2. Applying biochronological tools to determine the relationship between water temperature (and other environmental variables) and growth histories of fishes (on two representative fish species). **Lead investigator**: Christian Zimmerman
3. Building bioenergetic models to predict fish growth and performance relative to water temperature (on two representative fish species). **Lead investigator:** Michael Carey
4. Developing models using stable isotope, water chemistry, and growth data to describe energy and Hg transfer through aquatic communities with different thermal regimes. **Lead investigator:** Heidi Swanson
5. Integrating the above objectives to allow predictions of how increasing air temperature may influence ecology and ecotoxicology in lakes on the North Slope of Alaska. **All investigators**.

Relationships and conceptual integration among objectives is illustrated in Figure 1. While research for objective 4 will include sampling and analysis on whole food webs (periphyton, zooplankton, benthic invertebrates, all fish species present), research for objectives 2 and 3 will focus on two representative species – least cisco (*Coregonus sardinella*) and broad whitefish (*Coregonus nasus*). Both of these species are important consumer species in Arctic lakes, and they represent two different components of the food web; least cisco is a pelagic feeder consuming mostly zooplankton whereas broad whitefish forage primarily on benthic invertebrates. Moreover, broad whitefish is an important subsistence resource and least cisco is an important prey resource to top predators, such as northern pike (*Esox lucius*) and loons (*Gavia spp.*).

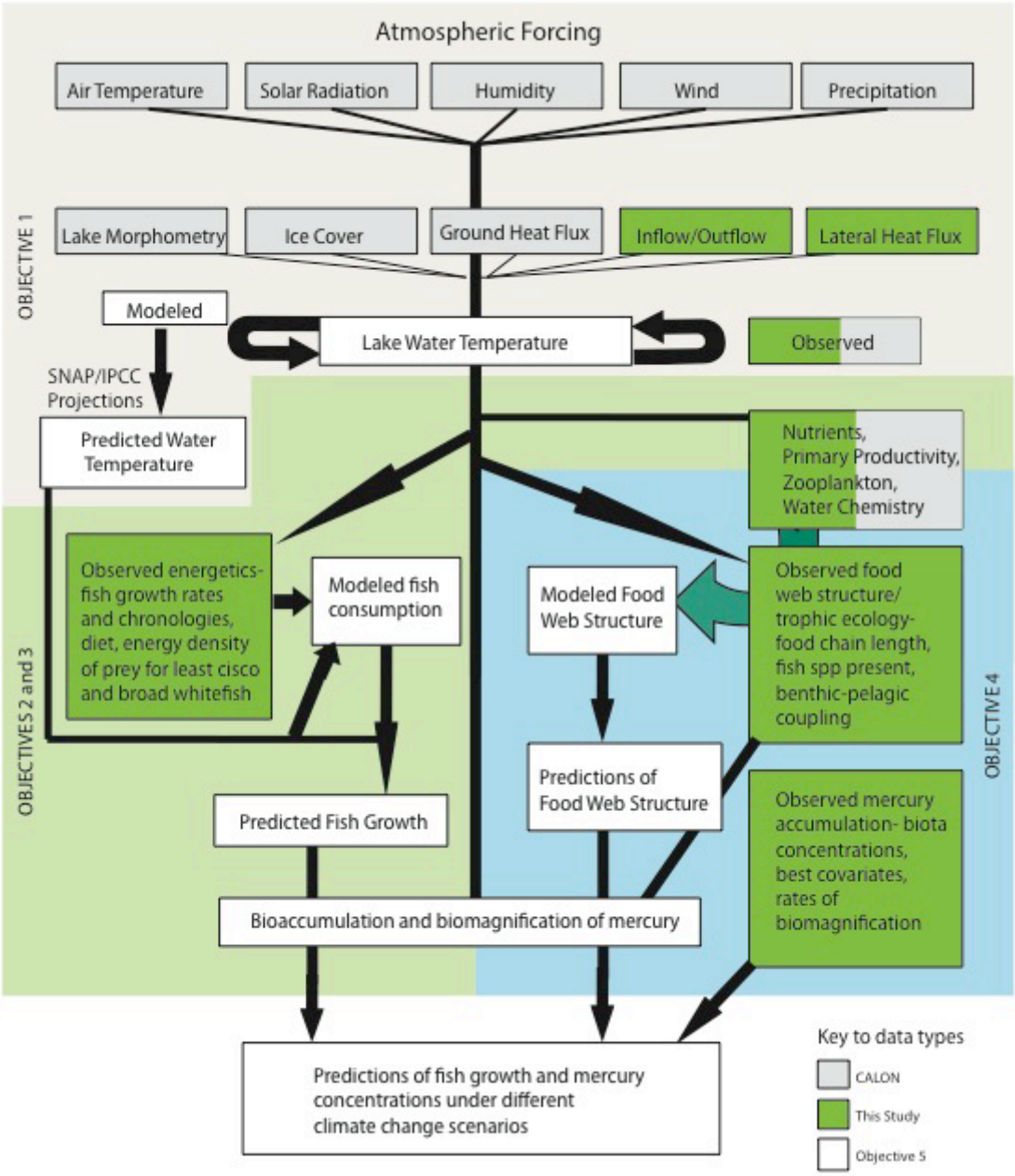

Figure 1. Conceptual diagram of the proposed study approach. Each objective is highlighted by different background color. Dark green boxes indicate data that will be collected by this project, light grey boxes indicate data gathered by the Circumarctic Lake Observation Network (CALON), and white boxes indicate results developed by this study in Objective 5.

Methods

Study area

Our research will take place in the Barrow/Atqasuk watershed (Figure 2), which includes the Meade River watershed and the portion of the northwest coastal plain located between Atqasuk and Barrow, Alaska. Encompassing an area of approximately 10,000 km^2, this watershed is located between the coast of the Arctic Ocean and the foothills of the Brooks Range between 69.4°N and 71.3°N within the National Petroleum Reserve Alaska. Study lakes will be selected from lakes monitored by the Circumarctic Lake Observation Network (CALON), an NSF Arctic Observing Network funded program that is monitoring a suite of physical and chemical parameters through 2016. More information about CALON is available at: https://sites.google.com/a/giesn.com/nsf-calon/. We will select three lakes from each of three nodes on the Western Transect of CALON: Barrow, Atqasuk, and Reindeer Camp (Figure 2). Within each node, CALON lakes are divided into a hierarchical scheme where some lakes are intensively monitored (*comprehensive* or *enhanced* instrumentation with continuous monitoring) and other lakes are sampled only seasonally (*basic* lakes with monitoring in early and late summer). The CALON transect provides a platform of study sites that covers a strong geomorphic and environmental gradient across the Arctic Coastal Plain ecoregion. For example, ice melt-out occurs about 2 – 4 weeks later on lakes near Barrow, compared to the inland lakes monitored by CALON (Hinkel et al. 2012). Similarly, water temperature, elevation, and length of growing season differ among the three lake nodes (Figure 3). Between 2012 and 2016, CALON will monitor hourly water temperature, standard meteorological data (including air temperature, pressure, humidity, solar radiation, wind speed), and measure a suite of water parameters: conductivity, pH, turbidity, Chl-a, dissolved oxygen, secchi depth, light penetration, DOC, DON, CDOM, and others. Given the differences in thermal regimes among the three nodes (e.g., Figure 3), the CALON lakes will provide a natural experiment for determining the role of temperature in controlling food web structure, fish growth and performance, and mercury concentrations in fishes in lakes of the Arctic Coastal Plain.

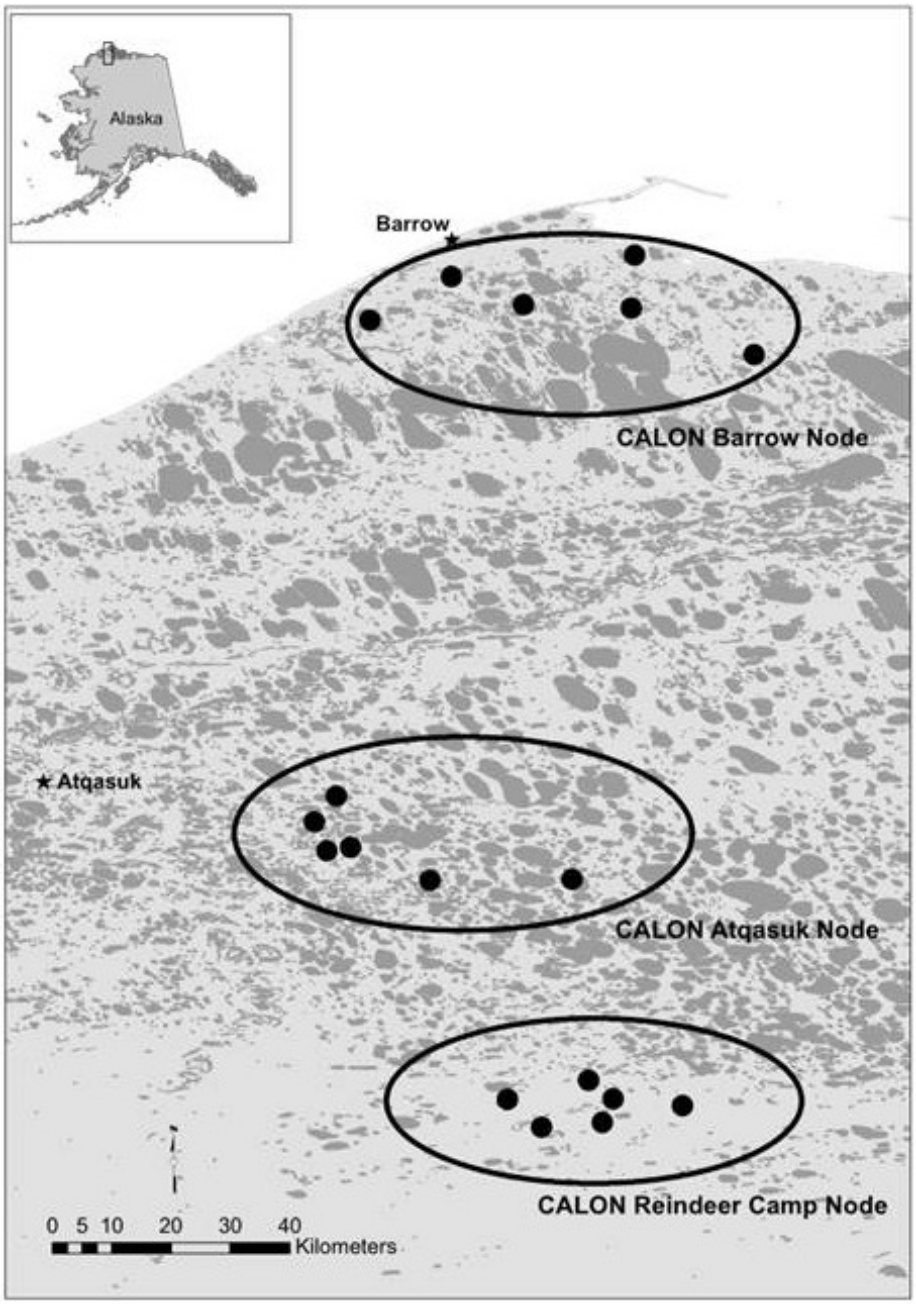

Figure 2. Map of study area. Black dots indicate the locations of lakes monitored by the Circumarctic Lake Observation Network (CALON) in the Barrow, Atqasuk, and Reindeer Camp nodes. Stars indicate the location of the communities of Barrow and Atqasuk.

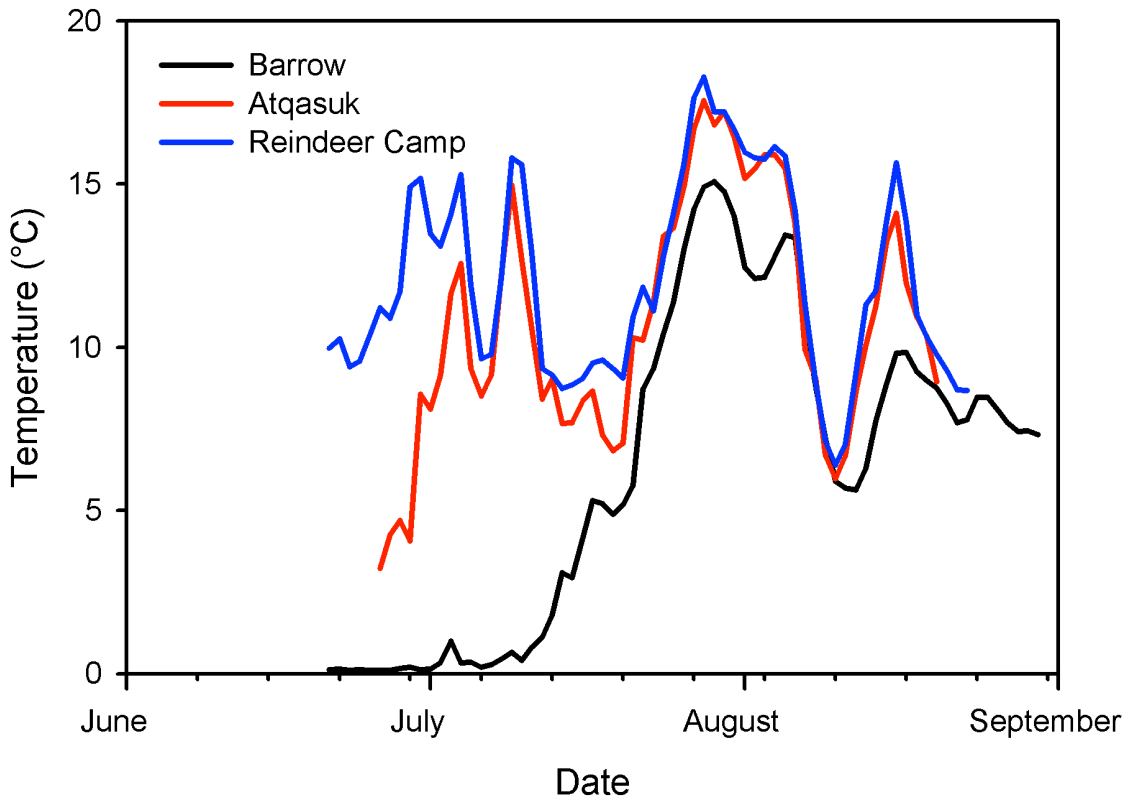

Figure 3. Surface water temperature in selected lakes from the Barrow (black line), Atqasuk (red line), and Reindeer Camp (blue line) nodes of the Circumarctic Lake Observation Network (CALON) collected in the Summer of 2010 (see Hinkel et al. 2012 for details). Note the differences in temperature at the beginning of the season.

Objective 1: Water Temperature Model

We will simulate water temperature using the Hostetler Lake Model, which is a one-dimensional heat diffusion model capable of simulating lake temperature, heat fluxes, evaporation, and ice cover in response to meteorological forcings (Hostetler 2009). This model has been used to predict lake temperature on the continental scale driven with climate change scenarios (Hostetler and Small 1999), suggesting that it is an appropriate choice for simulating future Arctic lake temperatures. The model will be run on daily timesteps to provide resolution on the short duration of the open-water season. Lake temperature will be simulated for every lake in each node chosen for the study.

By focusing field efforts on lakes that are intensively monitored by CALON, we will have access to the major meteorological fluxes and ground heat flux data that are

needed to simulate water temperature, as well as data that can be used to calibrate and validate the model. The model will be calibrated using data collected at the 'Comprehensive' (CALON) lake of each node, and verified by comparing simulated and observed temperature at the 'Enhanced' and 'Basic' (CALON) lakes. A simple sensitivity analysis will be used to identify the dominant controls on water temperature, and the potential importance of current and future lateral heat fluxes.

We will collect data relevant to potential lateral heat fluxes (stream flow, subsurface flow, and runoff) at each study lake. The location of inlet and outlet streams will be identified by speaking with members of CALON and by using maps before site visits. At each lake, inflow and outflow discharge will be quantified using a wading rod and flow meter. A coupled pressure transducer and temperature sensor will be installed to log stream stage and water temperature between site visits. Soil cores will be excavated to identify the dominant soil types of each node. Representative cores will be retained and brought to the lab to measure moisture and organic matter content. Soil hydraulic conductivity will be quantified in the field using falling-head slug tests analyzed with the method developed by Philip (1993). Associated with each soil core, three depth-to-ice measurements will be made using a metal probe. The potential for runoff and subsurface flow will be determined by combining soil characteristics with basin areas and land surface slopes delineated in ArcMap. For lakes that CALON has identified as having significant differences in water temperatures at shallow and deep sensors, we will log water temperature from multiple depths. This will be most necessary at sites with deeper lakes (i.e., Reindeer Camp Lakes). Should our one-dimensional model prove too simple to accurately predict water temperature, lateral heat fluxes will be included. Once the model is properly calibrated, we will use it to predict future lake temperatures.

Future water temperatures will be predicted by running the simulation with Scenarios Network for Alaska and Arctic Planning (SNAP) climate data that are down-scaled to 2 km. Whenever possible, model inputs will be derived directly from the SNAP outputs, average temperature, total precipitation, day of freeze, and day of thaw. Daily timestep data will be computed via linear interpolation of SNAP monthly outputs. When necessary, model inputs will be calculated given analytical relationships, or estimated given empirical relationships with known values, consistent with methods from similar studies (Hostetler and Small 1999; see Appendix 1:Table 1). Climate data will be used to simulate current conditions (i.e., the control period) before simulating the future. Model uncertainty will be assessed using a Monte Carlo approach.

Objectives 2,3, (Fish only) and 4: Field collections and processing

Field sampling will occur in August 2014 and August 2015. Much of the water chemistry data that we require will be provided by CALON. The CALON program has three levels of sampling/analytical intensity, however, and both supplemental and validation water samples will be required. At each lake, we will measure pH, conductivity, turbidity, secchi depth, dissolved oxygen and temperature (profiles) with hand-held meters. We will then collect water samples from the subsurface and from one meter off of the lake bottom. Samples will be analyzed for a suite of standard water chemistry parameters (e.g., nutrients, major ions, alkalinity) and for total and methyl Hg (using clean hands-dirty hands Hg sampling technique) concentration at the University of Alberta Biogeochemical Analytical Service Laboratory, Edmonton, AB.

Fish will be captured from each of the nine study lakes using gill nets, fyke nets, minnow traps, and angling. While the primary aim will be to capture a minimum of 8-10 individuals/fish species/lake, standard gear will be used in each lake and effort, habitat type, and depth will be recorded to enable future comparisons of catch-per-unit effort. We will collect all fish species present, and we will collect as large a size range as possible. For growth and age analyses of least cisco (*Coregonus sardinella*) and broad whitefish (*Coregonus nasus*), we will strive to collect 50 individuals of each species from each lake. Previous sample collections in the region suggest that fish species will include northern pike (*Esox lucius*), broad whitefish, least cisco, ninespine stickleback (*Pungitius pungitius*), Alaska blackfish (*Dalia pectoralis*) and Arctic grayling (*Thymallus arcticus*).

Benthic invertebrates will be collected from the littoral zone of each lake with an Ekman dredge and kick nets. Profundal benthic invertebrates will be collected with an Ekman dredge that is deployed at the deepest point of each lake. Because Arctic grayling are known to feed on terrestrial insects, these will be collected using aspirators. Sampling will occur along lake shorelines until an adequate mass has been collected for stable isotope and mercury analyses (~50 mg). Zooplankton will be collected using vertical tows of a 153 μm net (0.5 m opening) whereas epilithon will be collected by scraping material from bottom sediments in littoral zones. Submerged and emergent aquatic vegetation will be sampled by hand, and agitated in lake water to remove epiphyton. Epiphyton will be then be collected on filters.

For all species except ninespine stickleback, fish will be measured (nearest mm), weighed (nearest g), and photographed in the field before being dissected for dorsal muscle tissue and sagittal otoliths. Sex and maturity will be determined, and stomach contents will be removed. Muscle tissue will be frozen immediately after processing, otoliths will be cleaned and dried, and stomach contents will be preserved in 70% ethanol. Ninespine stickleback will be measured, weighed, and frozen whole in the field; previous research has shown that stable isotope ratios and total mercury concentrations

do not differ significantly between muscle and whole body samples for this species (Swanson 2009).

Zooplankton will be sieved to separate taxa greater than and less than 250 μm. For each size fraction, one subsample will be frozen for stable isotope and mercury analyses whereas another subsample will be preserved in ethanol for taxonomic analysis. Benthic invertebrates will be kept in clean lake water for 24 hours to evacuate gut contents. If time permits, samples will be sorted in the field into rough taxonomic (Order) or functional groups. A small amount of clean water will be added to samples before freezing in the field. Aquatic macrophytes, periphyton, epiphyton, and terrestrial insect samples will be frozen in the field.

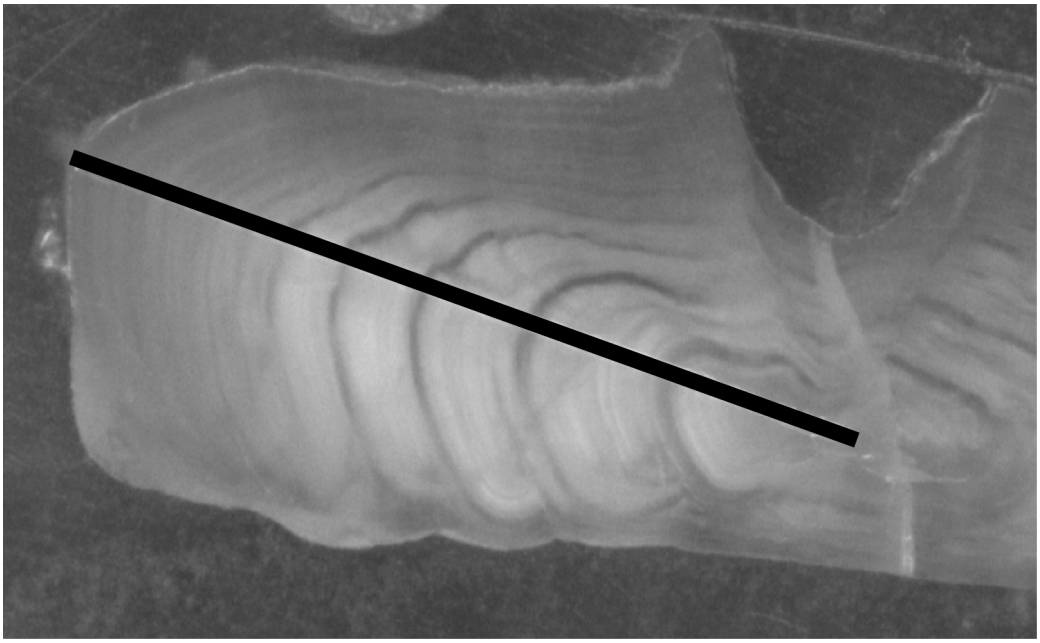

Figure 4. Photomicrograph of a transverse section of a least cisco otolith. The black line indicates the standard transect used to measure annual increment width.

Objective 2: Growth chronologies and climate effects

Fish growth analyses will focus on least cisco and broad whitefish but ages will be determined for all fishes collected. Further analyses on otoliths collected from least cisco and broad whitefish will be conducted to determine annual growth rates, and linear mixed effects models will be used to determine the effects of environmental variables as controls of fish growth. Otoliths and length and weight data will be collected from fish in the field. In the laboratory, otoliths will be cleaned, weighed, and embedded in epoxy and allowed to cure for 24 hours. A thin, transverse section through the nucleus will be excised using a low-speed wafering saw fitted with two

diamond blades. Otolith sections will be mounted on glass slides and digital images captured using a digital camera mounted on a Leica MZ6 scope.

For least cisco and broad whitefish, otolith growth increment widths will be measured along a standardized transect from the nucleus to the outer edge of the otolith along the longest possible radius between the nucleus and the dorsal edge of the transverse section using Image Pro software (Figure 4). An annual increment is defined as the distance from the outer edge of one translucent zone (appears as the narrow dark area in transmitted light) to the outer edge of the next translucent zone. To determine annual growth rates of fish, length-at-age will be back-calculated for each age using the methods of Francis (1990) and Campana and Jones (1992). Growth rates as determined in this objective will be used in objectives 3 and 5 to inform bioenergetics models and as covariates in analyses of Hg bioaccumulation in fish.

To determine the influence of environmental factors in controlling growth of least cisco and broad whitefish, linear mixed effects models will be used to account for repeated sampling of each fish and avoid shortcomings of fixed effects models (Weisberg et al. 2010). In constructing mixed effects models, the random effect will be the individual fish, because of the repeated otolith growth measurements from each individual (one measurement for each year) and fixed effects will include average monthly water temperature during summer, length of open water season, growing degree days, and ice break-up date. Other fixed effects may be included after review of all available data. Akaike Information Criterion with a second-order correction for small sample sizes will be used to determine how well each model fit the data (Burnham and Anderson 2002). Ordinary least squares regression will then be used to determine how much variation in fish growth was explained by each environmental factor. Otolith growth increment data will be transformed as needed to meet assumptions of normal distribution. Growth patterns and the sensitivity of growth to climate forcing will be compared across lakes and nodes for both species.

Objective 3: Energetic Model and Prediction of Fish Growth

Stomach contents of least cisco and broad whitefish will be identified to lowest possible taxonomic resolution. Diet composition will then be compared to stable isotope values to ensure passive gear collection in August represents long-term diet trends. Prey energy densities for each diet item will be taken from previous studies (Yako et al. 2000; Wiese et al. 2008; Maranto et al. 2010), but will be validated using samples collected from this study. In each node, approximately 10 samples of each of 3 fish species, (least cisco (each size class), broad whitefish (each size class), ninespine stickleback), as well as 10 samples from each functional group of zooplankton (e.g., Daphnia, cyclopoid, and calanoid) and benthic invertebrates (e.g., grazers, scavengers)

will be freeze-dried and ground to a fine powder with a mortar and pestle. One-gram subsamples will be combusted using a Parr 1261 isoperibol bomb calorimeter. Energy density will be converted to joules per gram of wet weight using known dry weight: wet weight ratios.

We will assess the metabolic response of least cisco and broad whitefish to the landscape gradient of temperature using the Wisconsin bioenergetics model (Hansen et al. 1997). This model is a mass-balance equation where consumption is equal to growth minus the energy cost of respiration and waste. Growth is determined by somatic growth and gonad production. Metabolism involves respiration, active metabolism, and specific dynamic action whereas waste includes egestion and excretion. For each species, we will use the generalized coregonid (*Coregonus spp.*) model with physiological variables (respiration, waste, and growth) parameterized according to Rudstam et al (1994). We will also adjust the respiration rate as suggested by Madenjian et al (2006).

We will model proportion of maximum consumption needed to produce the observed growth of fish based on diet composition, prey energy density, and daily temperature throughout the year. Within each lake, we will model consumption based on annual growth of individual fish determined by otolith growth rates and back-calculation of fish growth (Objective 2). Different consumption estimates will be produced for each age class and compared across the landscape gradient of temperature for each fish species. Predicting consumption of both species will quantify energy flow and also facilitate hypotheses testing about food web dynamics (Madenjian et al. 2006).

Subsequent to modeling consumption of least cisco and broad whitefish using existing conditions, projected fish growth will be modeled using predicted water temperatures under different climate scenarios for both species. Climate scenarios will be SNAP projections based on three emission scenarios (A1, A1B, and A2). SNAP projections predict air temperature that will inform our water temperature model for forecasting future water temperature regimes across the landscape. Fish growth will be modeled by holding constant the consumption estimate and diet composition for each species using the values we determined previously for existing conditions. We will then predict fish growth by age class in all nine lakes with temperature from the climate scenarios.

Objective 4: Food web ecology and Hg accumulation

For zooplankton samples preserved in ethanol, four consecutive subsamples will be obtained with a calibrated Hensen- Stempel pipette. Using a stereomicroscope, microcrustacea (cladocerans and copepods) will be identified to lowest feasible taxonomic level and counted under 10x – 70x magnification until 500 individual

plankters are counted and identified. Counting and identification of rotifers will be performed on a compound microscope (100 x magnification) using two additional subsamples. For microcrustacea, body lengths will be measured to the nearest 0.01 mm for 50 animals from each lake. Zooplankton abundance, size, and species composition will then be compared among the three nodes and related to climate variables.

Fish muscle, whole benthic invertebrates (shells will be removed, if present), and frozen zooplankton samples will be freeze-dried and ground to a fine powder with a mortar and pestle. When single benthic invertebrates do not provide enough mass for stable isotope and mercury analysis, multiple individuals will be pooled to form a composite sample. A minimum of five samples (composite or individual) per benthic invertebrate taxon or functional group will be analyzed for stable isotope ratios for each lake. For zooplankton, 5 composite samples from each size fraction will be analyzed from each lake as well as 3-5 representative samples of periphyton, epiphyton, and macrophytes.

Analyses of stable carbon and nitrogen isotope ratios will be performed at the Environmental Isotope Laboratory at the University of Waterloo, Waterloo, Canada. All biota samples will be analyzed, and carbon and nitrogen content will be analyzed simultaneously, converted to molar ratios (C:N), and used as a proxy of lipid content (Post 2007). Ratios of stable sulfur isotopes will be determined for all fish and for 3 benthic invertebrate/zooplankton taxa that represent littoral, pelagic, and profundal food sources. These analyses will be performed at the Colorado Plateau Stable Isotope Laboratory, Flagstaff, AZ.

Total mercury concentrations [THg] will be determined on fish samples at the University of Waterloo, whereas methyl mercury concentrations [MeHg] will be determined on invertebrate, zooplankton, and vegetation samples at Quicksilver Scientific, Lafayette, CO. This is necessary because MeHg is the species of Hg that bioaccumulates and biomagnifies through aquatic food webs (e.g., Wiener et al. 2002). In fish, more than 95% of Hg in muscle is in the toxic, MeHg form (Bloom 1992). This means that THg (which is much easier and cheaper to analyze) can be used as a proxy. Speciation of Hg in invertebrates, zooplankton, and vegetation is much more variable, and must be determined directly.

When ratios of stable nitrogen isotopes ($\delta^{15}N$) are compared among lakes, it is necessary to correct for differences at the base of the food web (e.g., Post 2002). To do this, representative, relatively long-lived primary consumers are chosen as 'baseline' organisms, and $\delta^{15}N$ data for higher-level taxa are adjusted to mean baseline $\delta^{15}N$. In more southerly systems, clams and snails are often ideal baseline organisms. As these are often not present in Arctic systems, other invertebrates may be used, such as mysids (e.g., Swanson and Kidd 2010). The baseline invertebrate organism must be present in

all lakes, and will be selected once we have completed sampling. Fish $\delta^{15}N$ will then be adjusted for baseline $\delta^{15}N$ using the following formula:

1. $$\text{adjusted } \delta^{15}N\ (\delta^{15}N_{adj}) = \delta^{15}N_{fish} - \delta^{15}N_{baseline}$$

where $\delta^{15}N_{baseline}$ will be an arithmetic mean $\delta^{15}N$ for the baseline organism in each lake.

Overall food web structure will be quantified using data from stable isotope analyses; total food web length, isotopic area, breadth of carbon sources used (pelagic vs littoral vs profundal), and food web redundancy will be determined. These metrics, developed by Layman et al. (2007) will then be compared among the three nodes and related to climate variables. Covariates and confounding factors (including number of fish species present, lake size, exact time of sampling, etc) will be accounted for in mixed effects models. Trophic ecology (e.g., trophic level ($\delta^{15}N$), food source (carbon; $\delta^{13}C$ and sulfur; $\delta^{34}S$)) of individual fish species will be adjusted for fish size, standardized to isotopic baselines, compared among the three nodes, and related to climate variables. Analyses of trophic ecology will include estimates of isotopic niche size and trophic overlap among fish species (Jackson et al. 2011). Species-specific fish C:N ratios (indicator of lipid content and thus, energy stores) will also be compared among the three nodes and related to climate variables.

Fish [Hg] will be related to fish (e.g., size, age, growth rate, $\delta^{15}N$, $\delta^{13}C$) and ecosystem (e.g., total phosphorus, conductivity, pH, lake area, DOC, $[Hg]_{water}$) variables with multiple regression. Fish [Hg] and significant predictors of fish [Hg] will then be compared among the three nodes, and related to climate variables. When significant predictors of fish [Hg] are related to lake temperature, predictive models will be developed using SNAP data. Biomagnification of Hg through lake food webs will be quantified with [Hg]-$\delta^{15}N$ regressions, compared among the three nodes, and also related to climate variables. Again, if there is a significant relationship with temperature, predictive models will be developed using SNAP data. Finally, fish [Hg] and rates of biomagnification through lake food webs will be related to distance from the coast, to explore a possible effect of Arctic Mercury Depletion Effects (e.g., Poissant et al. 2008).

Budget Justification and Timeline

Details for our budget estimates can be found in the following three tables. We are providing annual budgets in three scenarios as discussed with Philip Martin on 6 December 2012. Scenario 1 presents the budget for two grants (one to University of Waterloo and one to USGS) that are prepared by ALCC through USFWS contracting. Scenario 2 presents the budget as a single grant to USGS and USGS will handle the contracting with University of Waterloo. Scenario 3 presents the budget as two grants but is contingent upon University of Waterloo becoming a signatory member of a CESU.

There is no certainty that Scenario 3 is plausible as it requires 1) the University of Waterloo to accept the lower CESU overhead rate, and 2) acceptance into a CESU. Currently, there are two Canadian Universities that are members of CESUs. IN all budget scenarios, ALCC will contract directly with vendors for aircraft support as discussed with Philip Martin on 21 December 2012.

We propose to conduct most of the fieldwork in Year 1; supplementary fieldwork will be conducted in Year 2. Laboratory analyses will be completed in Years 2 and 3. Final results will be available in Year 4 (no monies requested). We request funds for logistics, laboratory analyses, field and conference travel, partial salary for a Ph.D. student (supervised by H. Swanson), and partial salary for J. Koch. In-kind salary support for C. Zimmerman, H. Swanson, M. Carey, and J. Schmutz is provided by USGS and University of Waterloo.

FY2014 (~$205,000) – Funds are requested to support the Ph.D. student salary, J. Koch salary, field travel, collaborative travel, and logistics (including charter aircraft support, equipment, and freight).

FY2015 (~$180,000) – Funds are requested to support the Ph.D. student salary, J. Koch salary, field travel, collaborative travel, logistics for a short field season, and laboratory analyses (stable isotope and total Hg analyses).

FY2016 (~$150,000) – Funds are requested to support the Ph.D. student salary, J. Koch salary, methyl Hg analyses, zooplankton analyses, conference travel, and collaborative travel.

Budget

FY2014

Description	Scenario 1 U Waterloo	Scenario 1 USGS	Scenario 2 USGS	Scenario 3 U Waterloo	Scenario 3 USGS	Matching
Student salary	20,000			20,000		
Christian Zimmerman (2 Months)						25,267
Michael Carey (6 Months)						47,908
Heidi Swanson (2 Months)						18,750
Josh Koch		21,312	21,312		21,312	
Travel to Anchorage for UW (3 person-trips)	7,500			7,500		
AirTransportion to/from field (4 people)	3,610	3,610	3,610	3,610	3,610	
Sample freight	5,000			5,000		
Accommodation ($150/night*2 rooms*8 nights)	2,400			2,400		
Equipment and supplies		7,500	7,500		7,500	4,500
Food in Field ($30/person/day)		5,550	5,550		5,550	
Contract to University of Waterloo (Scenario 2)			50,795			
Net	38,510	37,972	88,767	38,510	37,972	
Indirect (UW-31.9%;USGS-30.127%)	12,285	11,440	26,743	6,547	11,440	
Gross	**50,795**	**49,412**	**115,509**	**45,057**	**49,412**	96,425
Charter Aircraft (Contracted by ALCC)	105,000		105,000	105,000		
Total Project Cost to ALCC	**205,207**		**220,509**	**199,469**		

FY2015

Description	Scenario 1 U Waterloo	Scenario 1 USGS	Scenario 2 USGS	Scenario 3 U Waterloo	Scenario 3 USGS	Matching
Student salary	20,000			20,000		
Christian Zimmerman (2 Months)						25,267
Michael Carey (6 Months)						47,908
Heidi Swanson (2 Months)						18,750
Josh Koch (3 Months)		21,312	21,312		21,312	
Travel to Anchorage for UW (2 person-trips)	5,000			5,000		
Per diem for UW 2-person trips (50*10)	500			500		
Accommodations in Field	2,400			2,400		
Analytical (SI + Total Hg)	27,720			27,720		
Water chemistry analysis	3,240	7,500	7,500	3,240	7,500	
Commercial from ANC to ATQ (2 people)	1,805	1,805	1,805	1,805	1,805	
Food for field season ($30/day/person)		1,320	1,320		1,320	
Accommodation (1 room*$150/night*5 nights)		750	750		750	
Zooplankton Abundance	6,750			6,750		
Contract to University of Waterloo (Scenario 2)			88,920			
Net	67,415	32,687	121,607	67,415	32,687	
Indirect (UW-31.9%;USGS-30.127%)	21,505	9,848	36,637	11,461	9,848	
Gross	**88,920**	**42,535**	**158,244**	**78,876**	**42,535**	91,925
Charter Aircraft (Contracted by ALCC)	**42,000**		**42,000**	**42,000**		
Total Project Cost to ALCC	**173,455**		**200,244**	**163,410**		

FY2016

Description	Scenario 1 U Waterloo	Scenario 1 USGS	Scenario 2 USGS	Scenario 3 U Waterloo	Scenario 3 USGS	Matching
Student salary	20,000			20,000		
Christian Zimmerman (2 Months)						25,267
Michael Carey (6 Months)						47,908
Heidi Swanson (2 Months)						18,750
Josh Koch		21,312	21,312		21,312	
Travel to ANC for UW (2 person-trips)	5,000			5,000		
Accommodation	2,400			2,400		
Per diem for UW 2-person trips	500			500		
Analytical (speciation analysis)	35,775			35,775		
Conference Travel	5,000	5,000	5,000	5,000	5,000	
Contract to University of Waterloo (Scenario 2)			90,582			
Net	68,675	26,312	116,894	68,675	26,312	
Indirect (UW-31.9%;USGS-30.127%)	21,907	7,927	35,217	11,675	7,927	
Gross	90,582	34,239	152,111	80,350	34,239	91,925
Total Project Cost to ALCC	124,821		152,111	114,589		

Products

Project results will be presented in manuscripts submitted to peer-reviewed journals. We expect one manuscript will be prepared for each objective (see above).

Data Management Plan and Dissemination Strategies

Prior to data collection, the research team will develop a data management plan and data base structure in consultation with data base managers at the U.S. Geological Survey Alaska Science Center. Where appropriate, water-related data will be uploaded, archived, and served through the National Water Information System (http://waterdata.usgs.gov/nwis). All other raw data will be archived at USGS Alaska Science Center and otolith chronologies will be archived in publically accessible databases (such as the NOAA Paleoclimate Database). We will work with ALCC staff to ensure that data management and dissemination plans are consistent with ALCC protocols.

Permit Requirements

Known permit requirements include: BLM Research Permit for conducting activities on the National Petroleum Reserve – Alaska, Fish Resource Permit (Scientific Collecting Permit) from Alaska Department of Fish and Game, and Institutional Animal Care and Use Permit (USGS). Initially, we will consult with other agencies with management responsibilities in the study area to ensure that all permit requirements are met prior to conducting any project activities.

Education and Outreach

The research team will work with Outreach staff from the USGS Alaska Science Center to develop appropriate outreach and education materials in consultation with ALCC staff and other agencies.

Research Team Roles and Responsibilities

Christian E. Zimmerman – Zimmerman will serve as the project leader and lead researcher for Objective 2. As Project Leader, he will provide administrative oversight for the project and serve as the primary contact and facilitator. Dr. Zimmerman has over 20 years experience conducting field and laboratory research in aquatic biology, limnology, ecology of fishes, and genetics. Zimmerman has conducted research across a broad range of habitats and locations from the arid streams of southern California and high desert of central Oregon to the tundra and interior rivers of Alaska.

Dr. Heidi Swanson – Heidi is the lead researcher for Objective 4. She will supervise a Ph.D. student for this research. The student will be involved from the beginning of the project, and will complete their degree approximately one year after field and laboratory activities have finished. Heidi has over ten years of experience conducting stable isotope and Hg research in northern lakes. Her expertise lies at the interface between fish ecology and contaminant bioaccumulation, and much of her recent research has focused on coastal lake ecosystems in Nunavut, Canada. Over the last several years, she has conducted over 12 months of remote field research in Alaska, Nunavut, and the Northwest Territories, and her current research in ALCC areas of interest in Canada will allow us to compare our results with those found in other Arctic ecosystems.

Dr. Michael Carey – Mike is a research fish biologist at USGS ASC and lead researcher for Objective 3. Dr. Carey has over 10 years of experience conducting research in both lab and field environments studying community-level fish productivity and dynamics and bioenergetics modeling. He has conducted research in a variety of habitats including temperate lakes, large rivers, alpine streams, and nearshore marine environments. Carey will oversee all bioenergetics components of the proposed study plan to predict fish growth and performance relative to water temperature and primary and secondary productivity.

Dr. Joshua Koch – Josh is the lead researcher for Objective 1. He will compile the meteorological and lake temperature data and work with model developers as necessary to develop, run, calibrate, and verify lake temperature simulations. He will also direct hydrologic field data collection, to ensure that potential lateral fluxes are accurately quantified. Josh has seven years of experience working in Arctic and Antarctic hydrology, and has used multiple water flow and coupled water and heat flow models to address research questions in high-latitude environments.

Dr. Joel Schmutz - Joel has conducted field studies in the Arctic for more than 20 years, with the last 10 years focused on lake ecosystems such as these. He will principally serve in an advisory role.

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Appendix 1. Data types and sources

Table 1: Type and Source of Information needed for Water Temperature Simulations

Data Needs (preferably at 2m)	Source
Present	
Air temperature	CALON
Precipitation	CALON
Specific humidity	CALON
Wind speed	CALON
Atmospheric longwave radiation	CALON
Incident shortwave radiation	CALON
Lake temperature depth profile	This study
Depth	CALON
Turbidity	CALON
Lateral heat fluxes	This study
Future	
Air temperature	SNAP
Precipitation	SNAP
Specific humidity	ƒ(surface pressure & dew point)
Wind speed	IPCC, adjust to 2m height
Atmospheric longwave radiation	ƒ(vapor pressure & air temperature)
Incident shortwave radiation	IPCC

Table 2: Type and Source of Information needed for Fish Bioenergetics Simulations

Data Needs	Source
Present	
Water temperature	CALON; This study - Objective #1
Zooplankton composition	This study
Zoobenthos composition	This study
Prey energy density	Rudstam et al. 1994; Madenjian et al. 2006; This study
Predator energy density	Rudstam et al. 1994; This study
Fish diet	This study
Fish growth	This study - Objective #4
Fish Physiological parameters	Rudstam et al. 1994
Future	
Water temperature	This study - Objective #1

Table 3. Type and Source of Information needed for Fish Growth Analyses

Data Needs	Source
Present	
Lake temperature	CALON/This study
Growing degree days	CALON/This study
Ice-out date	CALON/This study
Fish lengths and weights	This study
Otolith increment width measures	This study
Future	
Water temperature	This study - Objective #1

Table 4. Type and Source of Information needed for Food Web and Hg Analyses

Data Needs	Source
Present	
Zooplankton composition and abundance	This study
Water chemistry	CALON/This study
Hg concentrations in water	This study
Hg concentrations in biota	This study
Lake temperature	CALON/This study
Stable isotope ratios in biota	This study
Climate variables	See Table 1
Fish size, age, and growth rates	This study
Future	
Water temperature	This study - Objective #1