Project Title: *Interdisciplinary Study of How Climate Change May Affect Wetland Habitats, Invertebrates and the Shorebirds*

Suggested Short Title: *Climate Change Effects on Wetlands, Invertebrates and Shorebirds (CEWISH)*

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Total Funding Requested from Arctic LCC: $437,235 (Y1), $463,637 (Y2), $472,901 (Y3)
Total 3 year budget: $1,373,773
Total Leveraged Contributions during study: $477,359 (Y1), $287,583 (Y2), $256,274 (Y3)
Total 3 year match $1,021,216
Total Leveraged Contributions prior to start of this study: $3,836,934

Project Summary: Arctic wetlands, where millions of local and migratory birds nest, are composed of a mosaic of ice wedge polygons, non-patterned tundra, and large vegetated drained thaw lake basins. Regional climate projections suggest that evapotranspiration, rainfall, and snowfall will increase, making it difficult to predict how surface water distribution might change and how habitats for the invertebrate resources used by waterbirds will be impacted. This study will focus on evaluating how climate change will affect the invertebrate community, and whether the change in climate (through changes in hydrology and surface energy balance) could induce a trophic mismatch that might alter the growth and survival of shorebird young. Our interdisciplinary team will focus on understanding these relationships on wetland areas around Barrow, Alaska, where collaborators have on-going studies investigating snow cover, hydrology, invertebrate ecology, and nesting and brood-rearing shorebirds. Our Cryosphere and Hydrology team will use observations and physically-based modeling to assess and model the controls of climate on the thermal and hydrologic regime of terrestrial landforms and ponds of the Arctic Coastal Plain. Using the tuned model, they will then project how future changes in climate might affect physical conditions in both terrestrial and aquatic habitats. Our Invertebrate team will use experimental trials to evaluate how predicted changes in pond melt-off dates and thermal dynamics affect the timing, growth and development (and thus emergence and abundance) of the predominant invertebrate taxa that serve as primary food resources for migrant waterbirds. Our Shorebird team will evaluate whether a mismatch between invertebrate emergence and shorebird egg-laying and hatch currently exists, and experimentally enhance or create a mismatch so as to be able to evaluate how the growth and survival of young hatching in and out of sync with the invertebrates are impacted. Results from the Invertebrate team will indicate how much of a mismatch may occur in the future based on changes in invertebrate growth and development, as predicted by the cryosphere-hydrology model. Our Modeling team will evaluate the overall potential effects of trophic mismatch on the relevant shorebird populations by linking results from the shorebird growth and survival study to a set of shorebird population models. These analyses will inform management authorities about impacts climate change may have on a variety of shorebird species, and if impacts are found, which factors may predispose shorebird species to be more or less tolerant of climate change. Such knowledge will ultimately allow managers to make strategic decisions that incorporate climate change effects in planning efforts.

XX	I intend to comply with the Data Sharing Policy for the Arctic LCC should this proposal be selected for funding.
	I do not intend to comply with the Data Sharing Policy for the Arctic LCC should this proposal be selected for funding.

Background and Justification:

The effects of climate change on aquatic and terrestrial habitats are expected to be most severe on the Arctic Coastal Plain (ACP, Martin et al. 2009). The two climate-related changes generally thought to affect the terrestrial and aquatic habitats of the ACP the most are changes in precipitation and warming of air and water temperatures. However, the simplicity of these metrics belies a much greater complexity because it is the inter-relationship of seasonal temperature patterns and precipitation (i.e., snow vs. rain) that control terrestrial and aquatic habitats. In short, making the jump from climatic parameters (e.g., air temperature and snowfall) to relevant biophysical metrics that affect living organisms (invertebrates, birds) is one of the key elements of the work proposed here. To bridge from one area of science (geophysics) to another (biology) is difficult, requires an extensive team, and is therefore expensive. However it is both novel and necessary. Below, we trace the steps required to do this, followed by a plan by which we believe we can achieve our goals.

Warming patterns now seem to be well established (http://www.arctic.noaa.gov/reportcard/temperature_clouds.html), but how precipitation may change is difficult to predict. Recent modeling studies (Hosaka et al. 2005, Christiansen et al. 2007, Räisänen 2008, Deser et al. 2009) suggest that one outcome of continued arctic warming will be increased winter precipitation. The increase is explained by a reduced sea ice cover yielding greater moisture fluxes from the Arctic Ocean to the atmosphere and by warmer air holding and transporting more moisture. What is less clear from these studies is whether increased arctic winter precipitation will result in more or less snow (versus rain), deeper or shallower snow packs, or a shorter or longer snow-cover season (Figure 1). As Räisänen (2008) summarized:

> *"An increase in precipitation, if acting alone, would lead to an increase in snowfall and consequently to an increased amount of snow on the ground. On the other hand, an increase in temperature will act to reduce the fraction of precipitation that falls as snow and to increase the melting of snow. Whether snow will be actually reduced or increased depends on the balance between these competing processes."*

The warmer climate is also likely to increase summer precipitation (Walsh 2008), evapotranspiration (Woo 1990, Hinzman and Kane 1992, Rouse et al. 1992), and runoff (Rawlins et al. 2010). The expectation that both precipitation and evapotranspiration will increase in a warmer climate has led to the hypothesis of an intensified (accelerated) water cycle (Loaciaga et al. 1996, Trenberth 1999, Huntington 2006), which has been supported by large-scale modeling analyses (Rawlins et al. 2010). The projected increases in winter precipitation could

offset any increases in evapotranspiration resulting in a limited soil water reduction. Further, present evapotranspiration rates from the Arctic Coastal Plain experience multiple non-linear controls that will likely prevent extensive future soil drying and hence maintain the presence of coastal wetlands (Liljedahl et al. 2011). Therefore, surface water distributions may not be consistent across seasons or space, but changes could nonetheless have severe effects on the habitats and invertebrates used by local and migratory bird species.

The indirect effects of deeper winter snow cover but also warmer, earlier springs are hard to predict, particularly on the ponds of the ACP. The movement of increased melt water to low-lying wetland ponds and basins could lead to earlier thaw dates for these areas, with earlier pond melt and warmer water temperatures. These changes may affect the abundance, diversity, and timing of seasonal activity of invertebrate communities, notably the emergence of adult insects (Hodkinson et al. 1998; Tulp and Schekkerman 2008; Butler, unpubl. data; Figure 1). Warmer temperatures (both atmospheric and water) may speed development of insect larvae, which could lead to earlier emergence and shortening of the already brief period of adult insect abundance (MacLean and Pitelka 1971, MacLean 1973, Butler 1980a). Indeed, earlier thaw dates and warmer water at Barrow during recent years are associated with earlier emergence of aquatic insects that is evident when current patterns are compared to information collected in the mid-1970s (Butler 1980a, Braegelman and Butler unpubl. data). Miller et al. (1980) also found a strong correlation between pond thaw dates and annual snow melt, suggesting that what happens in the winter/spring months may influence the summer breeding season. Unfortunately, little is known about how invertebrates are distributed or regulated in the terrestrial environment (MacLean 1980). Water flow and the temporary inundation within the polygonal landforms suggest these areas could also be important reservoirs of food for invertebrate consumers.

Changes in the phenology and biomass of invertebrates are important to consumers, especially migratory birds, in the context of the climate match/mismatch hypothesis (Figure 1). This hypothesis suggests that survival and recruitment of consumer populations decline when they and their prey become temporally decoupled during key life cycle events (Durant et al. 2007, Saino et al. 2012). Indeed, trophic mismatches during the breeding season have been proposed as a mechanism linking climate change to declining populations across diverse animal taxa (Donnelly et al. 2011). Negative effects of trophic mismatch during the breeding period may be particularly severe for species that migrate long distances to breed, use cues outside of the breeding grounds to time migration, and depend on resources available on the breeding grounds to reproduce (Both et al. 2010, Miller-Rushing et al. 2010).

Shorebirds are one group of birds that meet the criteria above. Shorebirds that breed on the ACP migrate long distances, traveling to nonbreeding areas predominantly in the continental U.S., Central and South America, as well as Asia (Alaska Shorebird Group 2008). The timing of shorebird migration is likely triggered by photoperiod cues (Gwinner 1996, Gwiner and Brandstätter 2001) on their southern wintering areas, and as such, is independent of changes occurring in the Arctic. Arctic shorebirds are income breeders (Klaassen et al. 2001, Morrison and Hobson 2004), being completely dependent on invertebrates consumed on the breeding

grounds for maintenance, egg-laying, and successful fledging of young (Meltofte et al. 2007, Tulp and Schekkerman 2008, Jamieson 2009, Hill 2012). In addition, juvenile shorebirds in the Arctic are reliant on highly seasonal food resources to maintain higher growth rates than their temperate counterparts (Schekkerman et al. 2003). Such traits indicate that breeding in shorebirds may be timed to maximize temporal overlap between chicks and their critical food resources. These facts suggest shorebirds are an ideal group of birds for investigating climate-change impacts under the climate match/mismatch hypothesis. Perhaps more importantly, shorebirds are the predominant invertebrate consumer on the ACP, with at least 29 species and as many as six million birds estimated to occur on the National Petroleum Reserve-Alaska alone (King 1979, Bart et al. 2012).

A few studies on temperate-breeding passerine insectivores have showed that mismatches associated with climate change have led to negative fitness benefits and population declines (Both and Visser 2001, 2005, Both et al. 2005). Less information is available from arctic-breeding insectivores. Seasonal variation in food resources has been shown to influence both inter-annual variation in breeding phenology (Meltofte et al. 2007, Schekkerman et al. 2003) and chick growth (Ruthrauff and McCaffery 2005) and survival (Hill 2012) in shorebirds. McKinnon et al. (2012) found a lack of synchrony between the hatch of four shorebird species and the emergence of dominant prey during her study at Bylot Island in the 2000s. She also found that Baird's Sandpipers that hatched out of synchrony with the emergence of Tipulidae had reduced growth rates. However, there have been no studies that experimentally tested whether shorebird young mismatched with their prey had reduced growth and survival rates.

To address the relationships between climate-mediated changes in wetland habitat, invertebrate prey, and shorebirds, we formed an interdisciplinary team that will address the following objectives (see also red areas in Figure 1).

Project Objectives:

1) Understand through field observation and modeling how present-day climate affects the biophysical environment (e.g., water and sediment temperature) of ACP ponds and adjacent tundra, and project through heat and mass transfer modeling how a changing climate might alter the timing (with a focus on snowmelt) and nature of these biophysical conditions year-round.
2) Experimentally relate the growth, development and emergence timing of dominant insect taxa used by shorebirds to spring tundra and pond conditions (date snow- or ice-free, depth, stratification, water and sediment temperature, in-flow and outflow, and seasonal drying).
3) Use gut analysis and DNA sequencing to document diet of shorebird adults and chicks.
4) Assess whether a trophic mismatch currently exists by relating shorebird egg-laying and hatching date phenology to invertebrate emergence patterns in aquatic and terrestrial habitats.
5) Experimentally create or enhance the existing trophic mismatch between when two species of shorebirds hatch their young and when the insects emerge. This will entail

creating artificially early and late hatching broods, assessing whether a mismatch was created, and the degree to which the mismatch affects the growth and survival of shorebird young that hatch out of sync with their invertebrate prey.

6) Model observed effects of a trophic mismatch on two species of shorebirds at local level (i.e., Barrow) to a population level, and assess which shorebird features make species more tolerant to climate change.

Understanding how climate change may affect wetland habitats, invertebrates and ultimately the waterbird community is important to management authorities for several reasons. First, of all the factors influencing shorebird populations (see Sutherland et al. 2012), climate change is the least understood (Meltofte et al. 2007). Questions remain about whether altered climates and the associated changes to the physical environment will affect shorebirds, and if so, whether the effect might be positive or negative, since it remains to be shown whether these animals can adapt and take advantage of potentially beneficial consequences of this phenomenon. Experimental tests are a rigorous empirical approach to assess this possibility without waiting to see what happens. Second, obtaining insights into what predisposes species to be sensitive to changes in climate will allow managers to make conservation decisions in light of climate change and not in spite of climate change. Today, climate change is not addressed from a management perspective. Rather, it is treated like an elephant in the room – something that is either ignored or considered to override other conservation actions. Conducting insightful studies to unravel the mechanisms of climate change and the associated impacts on the natural environment will help place climate change in the management dialogue. Third, only by evaluating causes and effects of climate change with carefully planned and executed experiments, and then extrapolating detected effects on species at a population level, will managers finally be able to evaluate climate change on an equal playing field with the many other factors that regulate wildlife populations. Finally, it is rare to have an opportunity to evaluate, in a succinct and practical fashion, a set of issues as large as the cascading consequences of climate change through an ecosystem. We believe the circumstances at Barrow (see below), and the group of scientists participating in this team, present one of the best opportunities to finally begin to understand this global issue that is altering the Arctic ecosystem in profound ways.

Technical Approach/Methods:

Why Study at Barrow?

Our study will focus on tundra areas near Barrow, Alaska, where all collaborators have on-going research studies (Figure 2). The tundra around Barrow is a mosaic of low- and high-centered polygons, non-patterned tundra, and large vegetated drained thaw lake basins. These landform types are the predominant cover classes in much of the ACP of Alaska (Brown et al. 1980, Walker et al. 2004), providing habitat for millions of individuals of waterbirds. Our focus for evaluating the climate match/mismatch hypothesis will be on shorebirds – the predominant and most diverse bird taxon on the ACP (Johnson et al. 2007, Bart and Smith 2012) – and the invertebrate prey they depend upon. The timing of invertebrate emergence, which makes the

prey available, in turn is dependent on the seasonal timing of pond ice break-up and warming of the water.

Temperature and precipitation, the two main drivers of climate change, have changed dramatically at Barrow and are projected to continue to change (Figure 3). For example, temperature has and is predicted to increase during every month of the year with exceptional increases in Sept-Nov, while precipitation has and will likely increase more during the winter months than in the summer months. Changes in these parameters have led to a change in the date the tundra becomes snow free each spring, and the number of snow-free days present at Barrow (Figure 4). Spring snow melt has advanced about 10 days over the 72-year period, with the biggest advance since the mid-1970s (Stone et al. 2002, 2005; R. Stone, pers. comm.). The summer is also getting longer, with the date of the first snow becoming later each year. The number of snow-free days has increased about 18 days between 1975 and 2010 (R. Stone, pers. comm.). In addition, measured and simulated soil temperature profiles near Barrow, which may be less biased from city infrastructure, show increased permafrost temperatures since the early and mid-century (Romanovsky et al., 1997, Osterkamp and Romanovsky, 1999, Romanovsky and Osterkamp, 2001, Romanovsky et al 2002). Tundra vegetation measurements conducted at Barrow in the 1970s and the 2000s indicate a slight drying trend is occurring but the climatic factors and hydrologic processes related to this are unclear (Villareal et al. 2012). These cumulative changes have undoubtedly changed melt-off of terrestrial and aquatic habitats, which in turn likely have influenced invertebrate growth and development (see below).

Besides the documented climatic changes at Barrow, there are also long-term data sets on many factors that help us design, carry out, and interpret our experimental manipulations. Snow and hydrological studies have been conducted sporadically at Barrow since 1967 (Dingman et al. 1980) and consistently since 2006 (SnowNet site), allowing us to forecast and therefore include snow conditions in our surface water models. Similarly, the invertebrate fauna at Barrow is better known than in almost any other location in the North American Arctic, with studies dating back to the 1960s, 70s and 80s (Holmes 1966a, Holmes and Pitelka 1968, MacLean and Pitelka 1971, MacLean 1980, Butler et al. 1980, Butler 1980a&b, Butler 1982 a&b, Lougheed et al. 2011). These long-term data provide information on shorebird invertebrate prey, and have allowed Butler and colleagues to document changes in insect emergence phenology and pond thermal regimes (see below). Finally, shorebird studies at Barrow date back to the 1950s (see e.g., Pitelka 1959; Holmes 1966a, b, c; MacLean 1969; Norton 1973; Pitelka et al. 1974), allowing us to document changes in shorebird phenology, diversity and abundance (Taylor et al. in prep).

Barrow is also an exceptionally good place to conduct this study because of the high shorebird breeding densities, with about 150 to 180 nests/km^2 compared to ca. 21 to 50 in other locations in Alaska (Liebezeit et al. 2011; Andres et al. 2012; Saalfeld, et al. in prep). Indeed, in any given year, we find suitable numbers of at least six species of shorebirds for conducting the egg-laying and brood survival component of this study (Table 1). Dunlin (*Calidris alpina*) and American Golden-Plover (*Pluvialis dominica*) are considered species of high concern (U.S. Shorebird

Conservation Plan 2004, Alaska Shorebird Conservation Plan 2008) and large declines have recently been documented in Semipalmated Sandpipers (*Calidris pusilla*), raising concerns for that species as well (Andres et al. 2012). Some of these species nest early and others nest later, some prefer wet and others prefer dry habitats, and all migrate to different portions of the world to winter (Table 1). These factors, and the fact that none of the shorebird species are threatened, will allow us to obtain adequate sample sizes and conduct experimental manipulations to test major predictions of the climate match/mismatch hypothesis.

Finally, a study in Barrow is also ideal because Arctic Foxes (*Vulpes lagopus*) are culled annually to benefit Steller's Eider (*Polysticta stelleri*) nest and brood survival, leading to unusually high shorebird nest success (Figures 5, 6; Lanctot et al. in prep) and likely higher brood survival. High nest and brood success is essential for obtaining sufficient sample sizes of hatching chicks and the ability to relocate and capture chicks to assess growth rates. Despite the presumed inflated chick survival rates, we will still be able to compare growth and survival rates of chicks hatching at different times of the breeding season, including the experimentally induced early and late-hatching broods (see below).

Methods for Each Objective

<u>Objective 1</u>: Understand through field observation and modeling how present-day climate affects the biophysical environment (e.g., soil, water and sediment temperatures) of ACP ponds and tundra, and project through heat and mass transfer modeling how a changing climate might alter the timing (with a focus on snowmelt) and nature of these biophysical conditions year-round. (conducted by Liljedahl, Daanen and Sturm)

NOTE: The effort necessary to address Objective 1 includes developing measurements and models that can take standard climatological parameters (air temperature, precipitation) and detailed data layers (topography and vegetation) and from these produce reliable estimates of the biophysical conditions on the tundra and in water bodies of the ACP, including specificity where favorable and unfavorable conditions exist for living things in this ecosystem. While the work described here is tailored to producing these estimates for invertebrates for terrestrial areas and small ponds in the ACP, it is in fact, much more widely applicable to abiotic and biotic systems on the ACP. Other studies that would benefit from the proposed efforts include a multitude of ecosystem analyses of the past, present, and future that depend upon reliable hydrologic information. The proposed field measurements and model applications targets the ACP terrestrial landscape, which includes shallow ponds. Lakes are not the focus of this proposal. Nevertheless, the computational infrastructure that this proposal will deliver serves as the necessary platform to implement further refinements of the computational code (such as lake thermal regime). A separate ADDENDUM describing this work in more detail is attached.

Methods

The hydrothermal character of the tundra ecosystem is driven by snow ablation and active layer thermal regime during a short summer season of massive biological productivity in shallow ponds. Understanding the coupling between air, surface, ground and water temperatures is crucial for predictions of the effects of climate change on terrestrial and freshwater habitat. In this proposal, we will make a series of target observations to guide and tune a physically based numerical model that calculates the temperatures in critical habits of the tundra ecosystem, and then use this model to examine how these temperatures might change under different climate regimes. The Hydrology team will build upon two on-going studies at Barrow. The first on-going study relies on hydrologic field studies conducted by Liljedahl at Barrow in the mid-2000s; she showed that ice wedge polygon type affected watershed-scale hydrology with low centered polygons promoting soil and surface water storage (Liljedahl 2011, Liljedahl et al. 2012). Her findings have been incorporated into a larger study, called the Next Generation Ecosystem Experiments (NGEE-Arctic), which is a new, multi-institutional effort, aimed at improving and informing climate model predictions through advanced understanding of coupled processes in Arctic terrestrial ecosystems. Initial research through NGEE, which includes geophysics, hydrology, near-surface soil thermal regime and plant ecology, focuses on drained thaw lake basins and ice wedge polygon tundra for field measurements and numerical modeling.

The work will also build on a snow observation project run by Matthew Sturm, who has been conducting snow studies in Barrow and the ACP since the 1990s. In Barrow, Sturm currently heads a project called SnowNet, a comprehensive snow observatory funded by NSF, designed to test and improve the latest technology related to measuring snow depth, density, water equivalent and melt. Studies at this and other ACP sites have led to the development of "standard" snow measurement protocols (Sturm 2009), innovative techniques for mapping snow (König and Sturm 1998, Sturm et al. 2010), and snow-ecology studies (Sturm et al. 2005). These winter snow studies will be augmented by extending the measurements into the melt season, and by linking the work to the modeling.

The proposed hydrologic studies include field measurements, which are mainly supported by NGEE, and a physically-based and spatially-distributed modeling component. The hydrologic field campaign that is supported through the NGEE project presents an important dataset to inform and validate the modeling on the <u>terrestrial environment</u> (i.e., seasonally inundated areas). The measurements supported by NGEE include a spatially extensive network of continuous water level monitors among groups of neighboring polygons; continuous point-measurements of snow accumulation and snow ablation at individual ice wedge polygon features (trough, rim, center), which affect habitat selection; maps of thaw depth and frost table elevation, end-of-winter snow accumulation, and continuous soil moisture, soil temperature and runoff. Basic meteorological data is also measured by NGEE, including air temperature, relative humidity, wind speed, incoming solar radiation, and liquid precipitation. However, there are <u>no existing monitoring efforts</u> within the NGEE project or by others in Barrow that focuses <u>on the thermal and hydrologic regime of ponds</u> (i.e., water bodies that

freeze to the bottom in the winter or "ice wedge ponds" that have small area (<50m^2) but that have a floating ice coverage throughout the winter). Therefore, we propose to intensively instrument two ponds (bedfast ice ponds and deep ice wedge ponds) to continuously monitor the hydrologic and thermal regime in the air, snow, ice, water and soil continuum.

In order to develop a robust and trust-worthy model, it is necessary to observe in detail the processes that control the thermal structure of ponds and adjacent tundra in spring. The latter is straight-forward and is largely controlled by snow thermal insulation and melt sequence. The former is more difficult and requires understanding and modeling the coupled flow of heat and water on pond stratification, melt, and basal heating. To this end, we need to instrument two representative ponds, one that freezes to the bottom and one that does not. We then have to observe the ponds through at least two break-ups, recording water in- and out-flow, basal temperatures, and snow melt (for albedo effects). Water temperature, depth, flow, and pond condition will be recorded using capacitance probes, thermistor strings and time-lapse cameras. This work is described in more detail in an addendum called "The Cryo-Hydro Component".

The field observations, coupled with existing SnowNet and NGEE measurements will inform and serve as validation and calibration data to a physically-based hydrologic model that couples mass and heat transfer. Hydrologic simulations will be performed at selected sites (the intensive NGEE study sites) in a geographical resolution of 0.5 m or less in order to resolve ice wedge polygon features. Future hydrologic simulations will be forced by downscaled climate projections, which have already been provided by Jing Zhang, North Carolina State University. Apart from preparing and performing field measurements, significant time will be invested in model calibration and validation.

Effective projections of how the anticipated changes in climate may affect shorebird habitats require a tool that (a) represents important physical processes and feedbacks at the appropriate scales and (b) is extensively validated. Leveraging upon the field and modeling development efforts from the NGEE allows us to partially meet those criteria. The proposed activities would allow additional module implementation into WaSiM (surface water and lake thermal regime), which are critical in the interpretation of wetland habitat response to climate change, as well as model applications focusing on surface water thermal regimes. Field measurements of water and sediment temperature profiles and ice- and snow thickness above selected water bodies would need to be supported by this effort as NGEE is not monitoring lake/pond thermal regimes. Terrestrial and aquatic model simulations will be performed at the NGEE study sites due to the extensive availability of terrestrial data, including a fine resolution digital elevation model that resolves ice wedge polygons, to inform and validate the model. The monitoring program at the NGEE sites would need to be expanded to include ice- and snow thickness as well as temperatures throughout the water column and in the upper sediment. Ultimately, we would co-locate cryospheric/hydrologic monitoring and simulations with invertebrate studies. However, we do not have the necessary topographic information available at the long-term invertebrate study sites to inform a 3-D hydrological model for applications in low-gradient, ice wedge polygon tundra. Therefore, we propose to install

smaller satellite stations (continuous water and sediment temperature, manually measured ice and snow thickness) where Butler's team has ongoing studies.

Due to computational intensity of solving temperature distribution in moving water we need to develop a new thermal module in WaSiM based on a set of simplified physically-based equations and then ensure that these match the observed field data. The equation set will include natural stratification according to density, solar radiation throughout the water column (limited by turbidity), neighboring temperatures (advection/diffusion), air temperature and relative humidity, and the water velocity as a mixing factor. Snow melt can be assumed to have a temperature very close to the melting temperatures of ice, but newly exposed soil surface will warm runoff. We will include the separation between floating and ground fast ice in ponds. If pond ice remains ground-fast it is likely that the mixing in the pond increases the melting process, compared to floating ice, which will slow the warming of the pond.

The key output from the Cryo-Hydro modeling and measurements will be estimates of environmental variables that have a functional connection with invertebrate emergence. The model domain will be local enough to be accurate at a micro-topographic scale, but will be applied to an ensemble of ponds and terrains so that we can ultimately model the landscape that is of the scale of the feeding radii of the birds.

<u>Objective 2.</u> Experimentally relate the growth, development and emergence timing of dominant insect taxa used by shorebirds to spring pond conditions (depth, stratification, water and sediment temperature, in-flow and outflow, and seasonal drying). (conducted by Butler and McEwen)

NOTE: Understanding how invertebrates are likely to respond to climate change affects many invertebrate consumers besides shorebirds, including threatened Steller's and Spectacled Eiders (Somateria fischeri). Invertebrates, in turn, are predators of smaller fauna and thus help shape the ecosystem both top down and bottom up. The proposed experimental manipulations will allow a cause and effect relationship to be developed, and ultimately projections on how insect emergence is likely to change into the future.

Initial research on tundra ponds and their associated invertebrates was conducted at Barrow during 1971-1973 as part of the IBP Tundra Biome project (Hobbie 1980, Butler et al. 1980) with additional studies in 1975-1977 (Butler 1980a,b; Butler 1982a,b). That work provided baseline data on pond temperatures, invertebrate diversity and abundance, and insect emergence phenologies. Between 2007 and 2012, thermal data and benthic invertebrate samples were collected from several Barrow ponds. During 2009-2011, insect emergence phenologies were monitored with dip-net sweeps along pond leeward margins at 2-3 day intervals. McEwen & Butler (in review) compared historic (1971-73) and recent (2007-09) pond temperature data, finding warmer daily mean, minimum, and maximum temperatures in the recent years. Coupled with a growing season about two weeks longer than in the 1970s, these thermal changes produce a 30% increase in growing degree days, and suggest that pond invertebrates may now grow and develop faster than in the past.

There has been little to no change in the composition of the invertebrate community in tundra ponds at Barrow (Lougheed et al. 2011), and limited information suggests biomass has also not changed appreciably (Peterson and Butler, in prep). The great majority of insects reported from tundra ponds at Barrow (Butler et al. 1980, Lougheed et al. 2011) are chironomid dipterans, including 22 of 27 insect genera, and at least 32 chironomid species. The five non-chironomid species (one stonefly, two caddis flies, and two beetles) are larger than most chironomids, but are relatively sparse. During 2009-2011, the fifteen most-abundant chironomid species accounted for 98% of the total abundance of emerging insects.

There is some indication of increased growth rates for chironomid larvae, resulting in a shortening of life cycle duration for longer-lived species (Butler 2011). Although such changes will alter larval population structures and could potentially influence the magnitude and dynamics of prey biomass, the most notable change to the pond invertebrate fauna has been in the timing of adult insect emergence. As in the 1970s, most pond insect species showed highly synchronous emergence, with the majority of individuals in a population emerging in <5 days. The general sequence of insect species' emergence is conserved between years and across the decades. Emergence timing for a given species varies from pond to pond and from year to year, depending primarily on snow-melt timing and the subsequent accumulation of degree-days.

Braegelman, Butler, and McEwen (in prep) have analyzed chironomid emergence in Barrow ponds for change over the last 3.5 decades using mixed-effects Cox proportional hazard models. In these models, the probability that a pupa will emerge on a particular day is a function of an unspecified baseline hazard multiplied by a set of explanatory variables. Thus, the date of emergence for a chironomid of a given species depends on a baseline hazard modified by both a decade effect and a pond effect. Statistical significance was tested with likelihood ratio tests. Of 16 midge species emerging from 5 Barrow ponds, 14 showed significantly earlier emergence timing in the recent decade relative to what Butler (1980a) observed in the 1970s. Effect sizes varied among species. The increased likelihood of emerging on a particular day in the current decade ranged from 1.3X for *Constempellina* sp. and up to 15.6X for *Procladius vesus*. Additionally, the entire chironomid community showed a 4-day earlier median emergence date during 2009-11, relative to the 1975-77 data.

Having documented these climate-related changes in the seasonal timing of insect emergence over an interval of 3.5 decades, we are now in a position to address the potential significance of further phenological shifts for the availability of adult insects as a food resource for shorebirds. Here, we propose to build on our recent findings at Barrow by developing and testing a model of how insect emergence may respond to further warming of tundra ponds at Barrow. We will conduct simple rearing experiments on key species to test and quantify hypothesized thermal controls over the seasonal timing of insect emergence.

We know that adults of each insect species emerge from a given pond with high synchrony (spanning <1 week), and that all pond insect species emerge in a generally consistent seasonal

sequence. This sequence of species-specific emergence pulses defines the overall period of adult insect availability for foraging shorebirds. Our current hypotheses about how pond insect emergence is regulated by climate will be tested in 2013 with pending support from the National Fish and Wildlife Foundation. CEWISH funding in 2013 will allow us to make more rapid progress in testing our current ideas, and calibrating models to predict emergence timing of important species under different thermal conditions. Simultaneously, we will coordinate our work with other CEWISH researchers measuring thermal characteristics of various tundra habitats, monitoring insect emergence on shorebird study plots, and identifying the most important prey taxa used by shorebirds. The rationale for our experimental work is described below.

We propose that the timing of insect emergence for any species is determined by (a) the starting point, at pond thaw, for remaining growth and development, and (b) two thermal variables that govern those processes. These variables are (1) a species-specific base temperature (T_b) below which no growth or development will occur and (2) a temperature-dependent rate for final-season growth and development that culminates in adult emergence. Under this conceptual model, differences among species in developmental starting point, in T_b, or in rate of developmental response to temperature, may explain species differences in emergence timing. The latter two variables are combined as "thermal time" (degree-days above T_b), a concept that is well-supported in the literature (Charnov & Gillooly 2003, Trudgill et al. 2005).

Thus, we propose to determine values for each of these three variables for important insect prey species at Barrow. Knowing the developmental starting point (the overwintering stage for each species) and the cumulative heat sum (above T_b) that an organism experiences (i.e., the growing degree days), we can build predictive models about how changes in pond melt-off date and environmental temperatures should influence when insects emerge. If emergence schedules are indeed governed by this thermal time concept, then we expect to find (a) early-emerging species will have lower thermal requirements (fewer degree-days above T_b) for adult emergence than later-emerging species, due to different temperature-specific rates of larval and pupal development, (b) early-emerging species may have a lower threshold temperature (T_b) for late-larval and pupal development than do later-emerging species, and (c) different developmental starting points (developmental stage at pond thaw) may contribute to variation in seasonal emergence timing.

For our experiments, we will collect overwintering larvae of a range of insect species (both major chironomid species and the few other insect taxa: two caddis flies, two beetles, and one stonefly) from common source ponds. Some of these taxa were identified as prey of shorebird young during studies in the 1960s (Holmes 1966, Holmes and Pitelka 1968). Selection of species tested in years 2 and 3 will focus on prey identified in the DNA barcoding portion of the study (see objective 3). We will divide these larvae into treatment groups to be reared in containers that will be incubated in local ponds offering different thermal conditions. Natural tundra ponds at Barrow vary in their thermal characteristics due to pond type, size, depth, and setting. In addition, we can use landscape features such as proximity to late-melting snow

accumulations along fences to provide additional variability among rearing treatments. Hobo loggers will track hourly temperatures in each treatment. Thermal conditions used in years 2 and 3 will be based on projected temperature conditions determined by the cryosphere / hydrology portion of the study (see objective 1). By monitoring these rearings daily, we can collect high-resolution data on the time required for these insects to complete larval/pupal development and emerge as adults under a range of thermal conditions.

We also will collect overwintering insect larvae from study ponds (at least 3 ponds of two differing types: shallow, bedfast ice ponds and deeper ice-wedge ponds) at the time of spring thaw to determine the developmental starting point for target species each year. Larvae will be fixed immediately in Kahle's fluid, which highlights primordial pupal and adult tissues and permit high-resolution scoring of developmental state within the final instar (Butler 1982a).

Pre-emergent insect larvae of a given species, reared under varying temperatures, should require similar total degree-days above T_b. For example, we have previously assessed thermal requirements of the abundant, early-emerging midge *Trichotanypus alaskensis* in a series of pilot experiments conducted both in the field at Barrow and in laboratory incubators. These studies produced a mean value of 1550 degree-hours for pupal duration. Different rearing conditions (cooler vs warmer, constant vs oscillating temperatures) did not influence the thermal requirement for pupation by this species. Plotting rate of pupal development (inverse of pupation time) against mean rearing temperature, we can make a linear extrapolation to zero development to estimate the base temperature (T_b). For this highly cold-adapted midge, T_b appears to be effectively 0°C. By rearing other insect taxa under a range of temperature treatments, we can quantify both T_b and development rate for other taxa we know to emerge at different times of the season. Once we determine T_b and degree-day requirements for the important shorebird invertebrate prey, we can incorporate projected changes in water temperature and melt-off dates (see objective 1) and predict how seasonal availability of these invertebrates may change in the future.

Objective 3. Use gut analysis and DNA sequencing to document diet of shorebird adults and chicks*. (conducted by Gurney, López, Butler, Lanctot and Saalfeld)*

NOTE: Obtaining an accurate assessment of the food consumed by shorebirds is a necessary first step in determining whether a trophic mismatch is present and whether shorebirds can adjust their foraging according to what invertebrates are emerging.

General Approach

To document the presence or absence of a trophic mismatch requires accurate data on the invertebrates eaten by shorebirds and the emergence patterns of the relevant invertebrates. Unfortunately, the relative importance of specific food items for many shorebird species breeding in Alaska is poorly known. Existing information comes from morphological identification of invertebrate parts found in the upper gastrointestinal tract (UGT) contents of collected birds in the mid-20th century (Bent 1927, Holmes 1966, Holmes and Pitelka 1968,

MacLean 1969, Baker 1977), and such analyses are likely biased toward identification of hard-bodied prey (Tollit et al. 2003, Purcell et al. 2004). Historic studies are also limited by low taxonomic resolution and the failure to report life history stages of prey items (e.g., larvae, pupae, adults) in many cases. It is also possible that shorebird diets have changed and that shorebird adults and young switch their diet to other invertebrate taxa if their historic prey emerges earlier (*diet-switching hypothesis*, see Hipfner 2009, García-Navas and Sanz 2011). Thus, obtaining accurate diet information from shorebird adults and young, and understanding current and seasonal trends in their diets, is essential for evaluating objectives 4 and 5 in this study.

Recent advances in DNA sequencing techniques offer a powerful new tool (i.e. DNA barcoding, Figure 7) for studying food resources and diet without sacrificing the lives of shorebird young. Species-specific gene sequences are first isolated and identified from the complex mixture of DNA found in fecal samples, using the polymerase chain reaction (PCR). Primers (i.e. the strands of nucleic acid required for DNA synthesis) that are required to target key taxonomic groups in the sample during this step have been well-studied and previously identified (Folmer et al. 1994, King et al. 2008, Zeale et al. 2011). Once prey DNA is isolated from samples, sequences are compared with a reference DNA barcode library (see below). Such libraries generate fine-scale taxonomic identifications very effectively; more than 95% of species in test assemblages of varied animal groups have been shown to possess distinctive genetic sequences (Ratnasingham & Hebert 2007). Further, customized libraries allow the diet samples to be analyzed with reference to what food items are actually available and provide more accurate taxonomic assignation than what might be available from publicly available libraries (Pompanon et al. 2012). DNA barcoding thus represents a unique opportunity to determine the exact invertebrate taxa that should be tracked to investigate trophic mismatch potential in shorebirds.

Generating a Reference Library

Invertebrate adults and larvae will be collected in terrestrial and aquatic habitats using protocols established by the Arctic Shorebird Demographics Network (Gates et al. 2012). Terrestrial sampling will include installation of modified Malaise pitfall traps placed in linear transects of 5 pitfall traps each spaced 15 m apart (Figure 8). Two transects will be established, with one trap line in xeric (e.g., high-centered polygon) and the other in wet habitat-types (e.g., pond edges and rims of low-centered polygons). Core samples (n = 5) will also be collected along each trap line transect to sample larval or subterranean insects, such as beetles and spiders, that may be important food items. Invertebrates will be removed from cores back in the laboratory using a modified funnel type extractor. Aquatic invertebrates will be sampled by towing a D-frame net through the water for five 1-meter distances along unique sections of the downwind edge of five ponds, as well as by deploying pop-bottle activity traps in each pond to capture free-swimming invertebrates in the water column (Arctic Shorebird Demographic Network Protocol Subcommittee 2010, Gates et al. 2012). Butler will also provide rare and unique invertebrate samples collected during his studies (see objective 3) for development of the DNA reference library. He has worked in Barrow for many years and is the most familiar

with all the taxa available. The DNA reference library will serve as a legacy database of invertebrates present on the ACP, and will also be useful for researchers studying other invertivores, such as threatened Steller's and Spectacled eiders on the ACP of Alaska (USFWS 1993, 1997).

Trapping will commence shortly after snow melt and stop at the end of brood-rearing (approximately 1 June to 15 August). Samples will be collected every 3 days and all samples will be labeled and stored in 95% un-denatured ethanol, which preserves DNA most effectively for molecular analyses (King et al. 2008). These samples will also be used to look at patterns of invertebrate emergence and biomass (see objective 4), and for a gut microbiota study (Kirsten Grond, PhD student, Kansas State University).

Invertebrate samples will be sorted, with specimens identified to the lowest taxonomic level possible (likely family using common references such as Thorp and Covich 2001, Merritt et al. 2008) in the laboratory in Barrow or at the University of Alaska Fairbanks. Based on results from field work in 2010, we anticipate 30 – 35 unique families will be identified. For each potential prey family, genomic DNA will be extracted from 25 individuals, then sections of the cytochrome c oxidase subunit I (COI) and of the 16S ribosomal RNA (16S) genes will be amplified and sequenced at htSEQ (Seattle, WA), following standard protocols (Ivanova et al. 2006, Baird et al. 2011). Once the raw sequence data is edited and aligned, we will use clustering algorithms (jMOTU) to describe groups of specimens within each family, and these molecular operational taxonomic units (MOTU) will be associated with known organismal taxonomies using Taxonerator, a well-established bioinformatics program (Jones et al. 2011). This approach produces sequence data with up to 90% efficiency, and is particularly effective for samples preserved in ethanol (King et al. 2008, Baird et al. 2011). Specimens from which DNA is extracted will be retained to form a voucher collection that will be used to identify samples taxonomically if sequence data for the specimen is not available in public databases (GenBank, Barcode of Life Data Systems; Ratnasingham & Hebert 2007).

Characterize diet and seasonal variation in the diets of adult and juvenile shorebirds

Adult diet will be assessed at Barrow for Dunlin, Semipalmated Sandpiper, Red Phalarope (*Phalaropus fulicarius*), Pectoral Sandpiper (*Calidris melanotos*), American Golden-Plover and Long-billed Dowitcher (*Limnodromus scolopaceus*) through collections and fecal sampling. A limited number of adults (3 individuals for each species) will be lethally collected at Barrow during the pre-breeding period, and the UGT contents will be washed out with 95% denatured ethanol and food items will be assessed by (1) identifying invertebrate parts with a dissecting microscope to the finest taxon possible and (2) extracting DNA from the unidentifiable parts and relating this to the reference DNA barcode library. We will also capture adults during incubation using bownets (Naves et al. 2008). Between 10 and 20 individuals of each species will be captured between 5 June and 1 August (samples will be spaced out as much as possible).

We will track 30 broods each of two shorebird species during each of the three years of this study. We propose to follow Dunlin during all three years; the second species will be either Red

Phalarope or Pectoral Sandpipers depending on their abundance. Dunlin tend to prefer drier habitats and both Red Phalarope and Pectoral Sandpipers prefer wetter habitats. Broods will be followed for up to 3 weeks after hatching from nests previously located on study plots (see objectives 4 and 5 for details on shorebird tracking and capture). Efforts will be made to sample at least one chick from each brood once every 3 days until they fledge (about 18 days).

Feces will be collected from captured adults and chicks by placing them in holding boxes (small animal aquariums with vented lids, 30cm x 30cm) until they defecate. The bottom of the container will be cleaned with ethanol and lined with clean waxed paper to avoid sample cross-contamination from other birds. Birds usually defecate within 5 to 10 min. of capture, and if a sample is not collected within this time frame, the bird will be measured and released. Following best practices (Frantz et al. 2003), fecal samples will be placed in 2 ml tubes or small sterile bags, immersed in 95% un-denatured ethanol, labeled and stored in a freezer to keep them cold until they are transported to the University of Alaska Fairbanks (UAF), where they will be stored at −20°C.

Total DNA will be extracted from fecal samples at UAF, using standard protocols (Ivanova et al. 2006) and materials (QIAamp DNA Stool Mini Kit, QIAGEN). To assess success of DNA isolation and test for presence of PCR inhibitors, we will screen all samples by PCR targeting a short conserved segment of the bird mitochondrial genome. Total DNA isolates will be enriched for COI and 16S through amplification using universal primers that target major invertebrate groups (Folmer et al. 1994, King et al. 2008, Zeale et al. 2011). All target enrichment assays will include redundancy and controls (positive and negative) to ensure amplification products are generated from the intended templates. The molecules in each enriched DNA preparation will receive a unique sequence tag that identifies its sample of origin. The tagged and amplified DNA libraries will be sequenced on an Illumina HiSeq instrument at the Georgia Genomics Facility, University of Georgia (Athens, GA). The sequencing assay output will be sorted computationally by sample of origin using the unique tags. MEGAN 4 (Huson et al. 2007) will be used to characterize prey species identity based matching components in the sequence output to our reference DNA barcode library and to the most relevant publicly available databases.

The DNA bar code analysis will indicate whether a particular invertebrate taxa is present in a feces sample but the analysis does not indicate its relative abundance (e.g., a positive detection could mean a bird ate one or a dozen Chironomid larvae). Accordingly, analyses are limited to determining (1) the percentage of shorebird chicks within a brood or across a species that had a positive detection of a given invertebrate prey taxa during a given sampling period, (2) a seasonal assessment of changes in the invertebrate prey taxa consumed by a given brood or species, and (3) the overall representation of each prey species across all samples (Murray et al. 2011). We will also use a Principal Components Analysis to generate factor loadings and test for differences in diet composition through the season (Rayé et al. 2011). We will then use an information-theoretic approach (Burnham and Anderson 2002) to model a suite of *a priori* candidate models for each species that represent the PCR-based diet weighting factor as a function of additive or multiplicative combinations of hatch date, temperature, and other environmental factors. Inference concerning the specific effects of hatch date will be based on

regression coefficients estimated by the maximum likelihood method (Littell et al. 2006). In the likely case of model selection uncertainty, a model-averaged parameter estimate and predictions will be calculated as per Anderson (2008).

Objective 4. Assess whether a trophic mismatch currently exists by relating shorebird egg-laying and hatching date phenology to invertebrate emergence patterns in aquatic and terrestrial habitats. (conducted by Saalfeld, Lanctot and Kesler).

NOTE: This objective tests a fundamental assumption of the climate match/mismatch hypothesis, i.e., whether shorebird young and their prey are linked in terms of hatching and emergence, respectively.

Background

Our experience with monitoring arctic-breeding shorebirds dates back to 1991 when Lanctot began his PhD at Prudhoe Bay, Alaska (Lanctot 1994, Lanctot and Laredo 1994, Lanctot and Weatherhead 1997, Lanctot et al. 1997). He subsequently worked on Western Sandpipers near Nome, Alaska (Lanctot et al. 2000, Blomqvist et al. 2002), and began his work at Barrow in 2003 when he established six long-term study plots along the road system (Figure 2). During the intervening 10 years, Lanctot and colleagues have established standard protocols for locating nests (Smith et al. 2009, Gates et al. 2013), gathered data on renesting (Naves et al. 2008, Gates et al. 2012), monitored nests to measure nest survival (Saalfeld et al. submitted, Lanctot et al, in prep), captured and marked adults and young (Hill 2012), and radio-tracked broods to monitor survival (Hill 2012). In 2010, the Barrow field site became part of the newly created Arctic Shorebird Demographics Network, whose goal was to collect demographic data on shorebirds. Much of this work has laid the groundwork for this study, enabling us to accurately monitor nest initiation dates of shorebirds (needed for this objective), and create an experimental, or amplify an existing, mismatch of shorebird hatch and invertebrate emergence (needed for objective 5).

At Barrow, we have been collecting invertebrate emergence data for the past five years (2008-2009 as part of Brooke Hill's MS thesis, and 2010-2012 as part of the Arctic Shorebird Demographics Network). Figure 9 shows emergence/hatch dates for the predominant invertebrate orders and common shorebirds breeding in the area between 2008 and 2010; data are not yet available for invertebrates in 2011 and 2012. These results illustrate the considerable variation that occurs across taxa, both within the invertebrates and the shorebirds. Unfortunately, we do not have any data on exactly what invertebrates were consumed by shorebirds during these years so we cannot accurately assess whether mismatches in shorebird and invertebrate phenology exist. Nor do we have information on shorebird growth rates, which is the response variable thought to be most affected by a mismatch. These results do show, however, that there are some years where a mismatch appears evident (see 2010, Figure 9). These data highlight the need to continue to gather phenology data in the coming years, while simultaneously evaluating shorebird diet and chick growth and survival rates. Without this information, we cannot assess the presence of a

mismatch, nor evaluate how the timing of shorebird hatch affects shorebird growth and survival – two of the ultimate goals of this study.

Shorebird hatching date phenology

Shorebirds will be monitored on six 36-ha study plots (Figure 2). Each plot is divided into 144 quadrats with wooden stakes placed every 50 m to facilitate orientation and marking of nests within the plots. One of the plots surrounds the Barrow landfill, whose fence and road system affects snow, allowing habitats to become snow-free sooner and shorebirds to nest earlier (Saalfeld et al. submitted). The landfill portion of this plot will be instrumental in creating our experimental "early" broods (see objective 5).

Nests will be located using single-person area searches and two-person rope drags (Naves et al. 2008). During area searches, surveyors will systematically search plots by walking "w" patterns within each 50 x 50 m quadrat. Nests will be found primarily by following individual birds displaying nest attendance behaviors, or occasionally by flushing an incubating bird. Area searches will be conducted 4 hrs per day by one person, six days per week, between early June and early July each year. Daily plot maps will be made so surveyors can share information on potential nest locations and facilitate equal coverage of the entire study plot. Each plot will be rope dragged near the end of June, typically over one and a half to two days per plot. During rope dragging, two people will pull a 35 m rope systematically through the study plot to flush incubating birds from their nests. In addition to the daily nest searchers, nests will also be located opportunistically by individuals capturing birds at nests.

Once a nest is found, we will record the location using a handheld global positioning system (GPS) unit, mark its location, and determine the status of the nest as either laying or incubating. We will visit nests found with fewer than four eggs (modal clutch size for all species in this study) daily until clutches are completed or until clutch size remains unchanged for two consecutive days. If clutch size remains unchanged from the day the nest was discovered, we will float eggs to determine incubation stage (Liebezeit et al. 2007). We will estimate clutch initiation dates of nests (i.e., date first egg laid) using (1) laying dates and assuming one egg laid per day if the nest is found during laying, (2) by subtracting a species' incubation period (based on the Birds of North America accounts, Poole 2005) from hatching dates if the nest is found during incubation and successfully hatches, or (3) based on estimates of embryo development using egg flotation (Liebezeit et al. 2007) if the nest is found during incubation but is unsuccessful. Once nests are found, we will check them every three to five days until three to four days prior to the estimated hatch date; at which time we will check nests every two days until eggs begin to hatch (i.e., are starred), and daily thereafter. Clutches will be considered hatched when at least one chick is present. Nests that fail to hatch will be included in our species-specific hatch date phenologies by adding the normal incubation period for the species to the date the nest was initiated.

Invertebrate emergence patterns

As discussed in objective 2, invertebrates will be collected in terrestrial areas using modified Malaise pitfall traps and core samples at five xeric and five mesic sites, and in five ponds by deploying pop-bottle activity traps and by towing D-frame nets for five 1-meter distances along the downwind side (see Figure 2 for locations). Trapping will take place prior to nest initiation and throughout brood-rearing (approximately 1 June to 15 August), with samples collected every 3 days. Invertebrate samples will be sorted, with specimens identified to genus if possible, and then counted. For each taxonomic grouping, biomass will be estimated for each organism using established length/width – weight regressions (see e.g., Sage 1982, Rogers et al. 1977). Abundances and biomass of each invertebrate taxonomic grouping will be summed across the five sampling sites and three habitat types during each 3-day sampling period to provide a general index of seasonal availability for the entire study area.

Assessing the presence of a trophic mismatch

We will generate invertebrate biomass availability plots throughout the breeding season (every 3 days) for each shorebird species by summing biomass data for all invertebrate taxonomic groupings that are found in at least 10% of the gut/fecal samples for that shorebird species, as indicated by the gut content and DNA barcoding study results. We will repeat this process with the abundance data. We will then identify an *ideal laying date* and an *ideal hatch date* based on both invertebrate biomass and abundance for each shorebird species. Because food availability may vary a lot due to daily weather variation, we will determine an early and a late date that begins a period that is followed by 4 (laying) and 18 days (chick growth), respectively, where the cumulative invertebrate biomass (4- and 18-day running biomass total) was in the top 10th percentile of all 4- and 18-day running biomass totals throughout the summer (after McKinnon et al. 2012). These intervals were chosen because 4 days are required for females to develop a full clutch and we plan to measure chick growth for 18 days (see objectives 3 and 5). We have chosen several different approaches to determine invertebrate availability because it is not clear whether shorebirds are limited by biomass or abundance.

Next, we will compare when shorebird nests are laid and clutches are hatched (or should have hatched for those that failed early) to the ideal laying and hatching dates defined above. To generate an index of trophic mismatch for laying, we will determine the number of days from the ideal laying date each nest was laid and then sum the absolute value of these numbers. A similar approach will be used to generate an index of trophic mismatch for hatching. In the end, we will have an index of trophic mismatch for laying and hatching for the six most common shorebird species breeding at Barrow for both biomass and abundance invertebrate data using the ideal lay and hatch dates described above for the three years of the proposed study. This will allow us to evaluate the extent to which a trophic mismatch exists across species and years using two measures of invertebrate availability known to be consumed by the birds during the year of study.

Objective 5. Experimentally create or enhance the existing trophic mismatch between when two species of shorebirds hatch their young and when the insects emerge. This will entail creating artificially early and late hatching broods, assessing whether a mismatch was

created, and the degree to which the mismatch affects the growth and survival of shorebird young that hatch out of sync with their invertebrate prey. (conducted by Saalfeld, Lanctot and Kesler)

NOTE: Experimental adjustments in when shorebird young hatch is the only way to determine a cause and effect relationship between shorebird growth and survival, and hatching out of sync with insect emergence.

Creating an experimental mismatch between insect emergence and shorebird hatching

Data collected at our six long-term study plots show the natural variability in nest initiation dates for these species, allowing us to determine dates of a natural "early" and "late" laid nest. Based on this information, we propose creating mismatches in two species of shorebirds each year, including Dunlin in all years, and either Red Phalarope or Pectoral Sandpiper, depending on which is most numerous. We propose using the same species during each year of the study because many other factors influence chick growth rates and survival, and collecting data over three years will help us to unravel the importance of prey availability relative to temperature, date clutches were laid, chick age, and other factors previously found to be important (Hill 2012).

We will rely on two methods to have young hatch earlier and later than what is observed naturally. The first method will rely on the presence of structures that reduce snow levels to create an "early" brood treatment. Structures such as roads and fences reduce snow on their leeward sides, which results in earlier snow melt-off and ultimately earlier nesting. Evidence for this exists from our work at the Barrow landfill that has a fence surrounding the facility. Snow measurements during the first week of June between 2005 – 2012 indicated significantly lower snow levels inside the landfill than out (24.6 ± 8.8% inside compared 71.9 ± 11.2% outside, Saalfeld et al. submitted). Nest initiation dates were also earlier inside the landfill by 2 (Pectoral Sandpiper), 3 (Red Phalarope), 5 (Semipalmated Sandpiper) and 6 (Dunlin) days on average (Saalfeld et al. submitted). To further expedite snow melt in this area and other areas where our 10-year dataset indicates birds nest regularly, we will mechanically place black shade fabric on the snow that will increase the albedo effect and cause even earlier melting of snow. Experimental work with this fabric has shown it can increase melt-off by up to 15 days if put over the tundra 3-4 weeks prior to normal snow melt (Steltzer et al. 2012, M. Weintraub, pers. comm.). Once areas become snow free, we anticipate shorebirds that have arrived in Barrow will begin initiating nests in these areas, resulting in very early nest initiation dates.

The second method will entail manipulation of shorebird clutches to create a "late" brood treatment. During the past 10 years, we and others have perfected techniques to remove eggs from nests so they can be artificially incubated to enhance hatching success (Blomqvist et al. 2002, Lesku et al. 2012). This work has shown that shorebirds, in general, are incapable of differentiating between their own eggs and artificial eggs placed in their nest, and will incubate eggs many days beyond their normal incubation period. We will take advantage of this fact by removing eggs found during laying (on the day the 4th egg is laid) and replacing them with

artificial eggs of a similar color, size, and weight. The removed eggs will be refrigerated for 10 days and then placed back in the nest for normal incubation to occur. Refrigeration of eggs will delay development of embryos without harming them, as long as eggs are removed prior to incubation occurring (Buse et al. 1999). Thus, this procedure will be limited to nests found during egg laying (<4 eggs in nest cup at discovery). We selected the 10-day period because it represents approximately two standard deviations in the timing of lay, and such a delay would place most nests well outside the normal laying range. Data from our ongoing work illustrates that the standard deviations about the mean lay date range from 4.6 to 6.0 days for all of the included species. Using this approach, we will delay hatch by 10 days and create artificially late hatching broods that are outside the observed range of laying. Creating artificially late hatching broods is superior to simply observing nests naturally laid late in the breeding season because these nests often represent replacements for nests depredated earlier (i.e., the 2nd nest laid by the same bird; Naves et al. 2008, Gates et al. 2012), and thus can be of lower quality, or are from lower quality parents (e.g., first year birds laying their first nests; Hill 2012). Anecdotal data on brood growth rates collected by Hill (2012) indicated young of replacement broods grew much slower despite hatching on similar dates as young from initial broods.

In addition to the experimentally created mismatched broods, we will rely on naturally early broods, as well as broods hatched in the middle of the season (i.e., average hatching broods) to evaluate how differences in hatch date influence growth and survival of young. We will monitor 30 broods of each species (2 species/year), including 10 artificially initiated or naturally found early, 10 artificially initiated late, and 10 naturally initiated within 3 days of the peak initiation date for that year and species. We will avoid using naturally found late broods for the reasons mentioned above.

The extent to which we create a mismatch between invertebrate abundance and biomass, and shorebird hatch dates will be assessed using methods described in objective 4. The invertebrate data used in this assessment will be refined further by using DNA barcode information on the prey being eaten by the broods in question.

Do mismatches affect the growth and survival of shorebird young that hatch out of sync with their invertebrate prey?

To assess the growth and survival of shorebird young, individual broods will need to be tracked after hatch. Because shorebird chicks are precocial (i.e., leave the nest with 24 hours and feed on their own) and difficult to relocate in the tundra, we will need to mark and track adult parents tending broods. To do this, adults will be captured on the nest during incubation using a bow-net (Bub 1995). Each adult will be marked uniquely with a U.S. Geological Survey (USGS) metal leg band and engraved flag and color band combinations (Figure 10). We will use morphological measurements and plumage to sex adults in the field, and if necessary, confirm sex with genetic testing. We will catch chicks by hand at or near the nest within 24 hours of hatch. Chicks will be marked with a single USGS metal leg band for individual identification within a brood. Chicks will be measured (wing, tarsus, culmen) to the nearest 0.5 mm, and weighed to the nearest 0.1 g with an electronic scale (Ohaus®, Pine Brook, NJ) at hatch and

during subsequent recaptures. We have refined these techniques over the past 10 years and routinely capture and band >300 adults and >800 chicks per year.

To track broods, we will use radio transmitters to locate adults attending broods. We will place radio transmitters (model A1020 [1.5 g], Advanced Telemetry Systems, Isanti, Minnesota) on the attending adult of each species (males for Dunlin and Red Phalarope, females for Pectoral Sandpiper). Transmitters will be attached by clipping feathers on their backs about 1 cm above the uropygial gland and then gluing the radio to the skin (Warnock and Warnock 1993). We will track individual birds using conventional VHF radio tracking techniques (Fuller et al. 2005) and after visually locating the attending adult, we will retreat until they stop alarm calling and resume contact calling with their chicks (Johnson et al. 2008). This distance typically varies from 20 – 40 m, depending on the individual adult and age of the chicks. This will allow us to either visually locate the chicks or determine the approximate area of the brood. If chicks are not observed, we will use a FLIR P640 Thermal Imaging camera (FLIR Systems Inc. 2011) to detect them hidden in the grass. This approach was used successfully to locate shorebird chicks on the Seward Peninsula (Johnson and Brusseau 2012). We suspect the method will work even better at Barrow due to the inherently colder temperatures, paucity of sunny days, and lack of heat absorbing rocks that can hinder animal detections. Broods will be monitored every three days until death or 18 days of age (hatch day = age 0). During each visit, we will attempt to capture at least 1 chick, but preferably 2-3, of each brood and measure and weigh them as described above. Feces samples will also be collected from chicks, so as to ascertain invertebrate prey being eaten and how prey selection may be changing as the season progresses (see objective 3). Once chicks are at least 10 g in weight, we will attach a transmitter to one individual per brood (Model A2414, 0.3 g, Advanced Telemetry Systems, Isanti, Minnesota) using methods described above to enhance subsequent detections in case adults desert their young and cannot be used to relocate broods. Ten grams is a minimal weight chicks should be to assure growth and survival is not affected by the radio transmitter weight (Fair et al. 2010). These smaller transmitters (0.3 g compared to 1.5 g in adults) were used successfully to track Dunlin young during studies at Barrow in 2008 and 2009 (Hill 2012) and are an acceptable approach for tracking shorebirds (Warnock and Takekawa 2003).

An index of body size for each bird captured will be generated using the first factor loading from a Principal Component Analysis that summarizes variation in culmen, tarsus, and wing length. An index of body condition will then be determined by dividing this first factor loading score by the body weight of the bird. These two types of information will be combined across all chicks within each brood to generate body size and body condition growth curves using the package “drc” in R (Ritz and Streibig 2005). The growth rate, generated from the slope of the line reflecting the change in body size or condition during the maximum growth period will serve as the response variable in a subsequent analysis that assesses growth rate as a function of additive or multiplicative combinations of hatch date, estimated invertebrate biomass during the brood growing period, deviance from ideal hatch dates, summed daily temperature values during the chick-rearing period, and other environmental factors. We will not test for a categorical effect of hatch treatment (i.e., experimental early, normal or experimental late) because these effects will be evaluated by hatch date and the deviance from ideal hatch dates.

Inference concerning the specific effects of these variables on growth rate will be based on regression coefficients estimated by the maximum likelihood method (Littell et al. 2006). In the likely case of model selection uncertainty, a model-averaged parameter estimate and predictions will be calculated as per Anderson (2008).

Survival of young will be assessed by first evaluating the behavior of adults. Adults tending broods typically give alarm calls or perform a "rodent run" distraction display when a human approaches their brood (Brown 1962). They follow this with contact calling with chicks when the perception of "danger" abates. Non-broody adult behavior includes foraging rapidly, preening diligently, roosting, and allowing humans to approach without alarm calling. If adult behavior indicates their broods have failed prior to reaching 10 days of age, we will presume chicks have died. The exception to this will be in cases where chicks have been equipped with radio transmitters. Here, we will make an effort to locate radio-equipped chicks throughout the study area and season to determine their fate. Chicks will be classified as alive if visually observed, if a strong radio signal was detected near their parent, or, in the case of chicks without radio transmitters, if the attending adult demonstrated broody behavior. Chicks will be classified as dead if a carcass is found, if their radio signal is missing and the attending adult does not exhibit broody behavior for two consecutive visits, or if the radio signals for both the adult and chick are missing for the remainder of the season. For retrieved carcasses, we will assign cause of death to determine if chicks died from starvation (presumably due to the mismatch with invertebrate prey) using the following criteria: chicks found intact on the surface of the tundra with no apparent flesh wounds will be presumed to have died of exposure, and chicks found in burrows with bite marks or in owl pellets will be presumed to be depredated by weasels and avian predators, respectively. We realize that it will be impossible to determine whether a chick died from exposure before being depredated. Finally, we will conduct an aerial telemetry flight in late July or early August to locate missing adults and chicks.

We will use logistic regression analysis to evaluate how a brood's survival (yes, no) relates to hatch date, invertebrate availability, deviance from ideal hatch dates, summed daily temperature values during the chick-rearing period, and other environmental factors as described for the growth portion of the study. Based on prior work, we anticipate being able to reliably track at least 80% of the broods (about 50 of 60) so should have adequate sample size for this analysis.

The resulting metrics developed in Objective 5 will be used as the τ_{chick} and τ_{egg} input variable in the population modeling described in objective 6.

Objective 6. Model observed effects of a trophic mismatch on two species of shorebirds at local level (i.e., Barrow) to a population level, and assess which shorebird features make species more tolerant to climate change. (conducted by Kesler and Saalfeld)

NOTE: This last objective uses information obtained in prior objectives to estimate how climate change will likely affect entire shorebird populations using state-of-the-art population models.

Background

In the final phase of the study, we will evaluate the potential effects of tropic mismatch on localized and ACP region shorebird populations by linking results from previous project phases to a set of shorebird population models. Population projection models can be designed using a variety of structures and they can incorporate a range of intrinsic and extrinsic factors with the potential to influence population processes (e.g., Kesler and Haig 2007, Kesler et al. 2012, McNew et al. 2012). Simplistic models with fixed deterministic effects can be solved analytically, thus readily providing insights into factors with the potential to drive population changes. More sophisticated models can incorporate numerous demographic and environmental factors, some correlated and many stochastic in nature, but computational approaches to solving larger models are burdensome or infeasible. As an alternative, Monte Carlo simulations will be used to identify model outcomes, and to address a variety of research questions (Caswell 2000). In this proposal, we aim to develop models that evaluate the influence of trophic mismatch driven alterations to laying and chick development, and subsequent post fledging survival on population processes. Further, we will attempt to identify the magnitude of mismatch driven shifts needed to exert substantial influence on population changes. Below, we outline a conceptual structure for a population model, and outline the development and a fundamental model structure for a quantitative representation. We discuss from where base parameter estimates will be drawn to make the model functional. Finally, we detail how we will use simulations to evaluate the effects of model parameters, including those associated with trophic mismatch, on shorebird population processes.

Model design

We will use results from the previous project phases to develop a series of Lefkovitch population projection matrix models for each of three shorebird species investigated during this study. These models will then be used to evaluate the relative effects of altered climate, hydrologic function, and trophic mismatch in food resources on shorebird population processes. Initially, we will develop a first-stage model to evaluate the localized effects of perturbed climate and resources on shorebirds by incorporating information from physical and biological process described in the objectives above (Figure 1). Here we will use our data and those from the literature.

The Lefkovitch matrix model will be composed to replicate the form of the conceptual model (Figure 11) with a superstructure based on females, and with an annual time step immediately prior to nesting:

$$\begin{matrix} f_j & f_a \\ S_j & S_a \end{matrix},$$

where f_j and f_a are stage specific fecundity values for hatch year birds and after hatch year birds and S_j and S_a are stage specific survival rates for hatch year and after hatch year birds.

The dominant eigenvalue (λ) for the matrix represents the asymptotic finite rate of population change (Williams et al. 2001, Morris and Doak 2002). Values for λ > 1 represent populations that are increasing in size, whereas those with λ < 1 indicate declining populations (Caswell 2001). The stage-based population projection matrix will include nested variables associated with vital rate subcomponents including nestling survival, fledgling survival, post-fledge first year survival, and after hatch year life stages:

$$\begin{matrix} \phi_{HY} \times f_{HY} \times \phi_{egg} \times \phi_{chick} & \phi_{AHY} \times f_{AHY} \times \phi_{egg} \times \phi_{chick} \\ \phi_{egg} \times \phi_{chick} \times \phi_{HY} & \phi_{AHY} \end{matrix}$$

where Φ_{AHY} represents annual survival of birds after hatch year, Φ_{egg} is nest survival, Φ_{chick} represents chick survival, and Φ_{HY} represents survival of birds from fledge through the first breeding attempt. Respectively, f_{HY} and f_{AHY} represent the fecundity in first year and after first year birds. The model will incorporate the effects of trophic mismatch on population processes with the inclusion of variables that adjust Φ_{chick} and Φ_{AHY} across a range of values that represent what would be expected under trophic mismatch scenarios:

$$\phi_{chick} = S_{chick} \times \tau_{chick}$$

where S_{chick} is chick survival and τ_{chick} is the predicted proportional effect of trophic mismatch on chick survival. As we described above, the lingering effects of mismatched shorebird hatch and forage availability are likely to be exhibited in reduced chick growth which will likely transfer to degraded survival during the post-fledge phase of the first year (Φ_{HY}). Thus, the model will also include subcomponents associated with mismatch effects on Φ_{HY}:

$$\phi_{HY} = S_{HY} \times \tau_{HY}$$

where S_{HY} is estimated survival from fledge through the first breeding attempt and τ_{HY} is the predicted proportional effect of trophic mismatch on that survival. Parameters based on trophic mismatch (τ_{chick} and τ_{HY}) may be broken into further climate subcomponents, depending on the eventual outcomes of previous project phases associated with temperature, hydrology, and foraging (objectives 1-4). Those subcomponents and the associated functions would then be substituted for (τ_{chick} and τ_{HY}) in the model structure. The effect of nest predators will similarly be included in the model to allow adjustment for the fact that Barrow sites occur in areas under fox control and to evaluate the potential population performance under scenarios that included elevated predation

$$\phi_{egg} = S_{egg} \times \rho_{egg} \times \tau_{egg}$$

where S_{egg} is estimated egg survival from egg laying through hatch and ρ_{egg} is the predicted proportional effect of predation, lemming and predation interactions, and other external factors on nest survival. The effects of invertebrate biomass on laying will be included with the τ_{egg} parameter. Therefore, the adjusted matrix that matches the conceptual model presented above is

$$S_{HY} \times \tau_{HY} \quad \times f_{HY} \times (S_{egg} \times \rho_{egg} \times \tau_{egg}) \times \ S_{chick} \times \tau_{chick} \qquad \phi_{AHY} \times f_{AHY} \times (S_{egg} \times \rho_{egg} \times \tau_{egg}) \times \ S_{chick} \times \tau_{chick}$$
$$(S_{egg} \times \rho_{egg} \times \tau_{egg}) \times \ S_{chick} \times \tau_{chick} \ \times \ S_{HY} \times \tau_{HY} \qquad \phi_{AHY}$$

Model parameterization

Models like the one included herein are notoriously difficult to populate with precise and accurate parameter estimates, because of scant or missing information about some life history stages (Sandercock 2003, Kesler and Haig 2007, Kesler et al. 2012, McNew et al. 2012). For these reasons, the resulting λ values are rarely considered to be particularly meaningful. Our model is similarly challenged, in that only crude estimates are available for some parameters, and because fox control at the Barrow site likely substantially reduces predation to shorebirds. Nonetheless, models that are populated with reasonable ranges of parameter estimates can provide insights into the relative influences of each parameter on the direction and magnitude of shifts in λ. Associated research questions are typically aimed at understanding how much and in which direction λ might change if single or multiple parameters are perturbed. The approach fits soundly with work described herein, as we ask how shorebird populations might change with altered food, hydrology, and temperatures brought on by climate driven trophic mismatch. Further, the relationships between variables and population processes can be quantified and compared. Sensitivity and elasticity analyses, coupled with life table response analyses in a full version of our model will thus provide meaningful measures of the relative influence of trophic mismatch on shorebird population processes.

We will identify realistic values and ranges of plausible values for each parameter with which to test the model. Parameters associated with trophic mismatch will be drawn from the objectives outlined above. Objectives 1-5 provide the links between climate driven changes in hydrology and temperature, the potential effects of those changes on invertebrate food items, and the potential effects of mismatched food and hatch dates on shorebird chick survival and growth/body condition. Results from these objectives will be used to directly inform the range of values that could be expected for τ_{egg}, τ_{HY} and τ_{chick}. If deeper functional links between hydrology, temperature, and foraging resources can be drawn, those subcomponents will be used in the models rather than τ_{egg}, τ_{HY} and τ_{chick}. Ranges of realistic values for Φ_{AHY}, f_{HY}, f_{AHY}, S_{egg}, and S_{chick} in each species will be drawn from the literature, from our past work in Barrow, and from the Arctic Shorebirds Demographic Network. Similarly, ρ_{egg} will be drawn from the fox control conditions in Barrow and from other sites without control in the Arctic Shorebird Demographics Network (ASDN).

The S_{HY} parameter is particularly challenging for all migratory shorebird species because juvenile birds often disperse from sites and are thus extremely difficult to detect in mark-resight studies. Previous investigations have used a value of $0.5*\Phi_{\mathrm{AHY}}$, a crude approach which has been somewhat supported in targeted studies across a range of species. A second approach to identifying a reasonable estimate of S_{HY} is to begin with the assumption that

populations are generally stable and then to fit the model so that S_{HY} causes a balance of λ=1. We will use both approaches to identify the potential range of S_{HY} parameters.

Model analysis

To evaluate the relative influence of each metric on shorebird population change, we will use life table response simulations, and sensitivity (*S*) and elasticity (*E*) analyses to identify parameters key to population dynamics and conservation (de Kroon et al. 2000, Wisdom et al. 2000, Caswell 2001, Williams et al. 2001, Morris and Doak 2002). Each of the three aforementioned focal species will be evaluated separately, and with separately parameterized matrixes that align with each unique natural history, and with differential outcomes from objectives 4 and 5. Each parameter in the model will be perturbed slightly and the response in λ will be analyzed. Sensitivity for each parameter represents the change in λ associated with small changes in θ, where θ was the demographic parameter of interest, or

$$S_\theta = \partial\lambda/\partial\theta$$

(Williams et al. 2001). Elasticity is a metric scaled to reflect the proportional change in λ realized by a similarly proportioned change in θ, thereby facilitating comparisons among θ (Williams et al. 2001)

$$E_\theta = \frac{\partial\lambda/\partial\theta}{\lambda/\theta}$$

Results from the analyses will provide quantitative metrics for comparing the change in shorebird populations that can be expected with changes in each matrix variable, including temperature, hydrology, and foraging resources.

Additionally, we will conduct a series of population simulations with values for each variable that are randomly selected from the reasonable value ranges described above, and which are normally distributed about the means. The distribution shapes and ranges for variables associated with trophic mismatch will be drawn from the observed distributions reported in objective 5 and from climate model predictions for the region as a whole; these values will be used in place of τ_{egg}, τ_{HY} and τ_{chick}. In the simulations, matrix elements and subelements will be populated from the random draws of variables 10,000 times, and the associated λ values will be estimated. Input variable values for each simulation will then be regressed against the resulting λ values to assess the strength (r^2) and the magnitude (slope) of association between input variable values and population change. To gather region-wide perspectives on the relative influence of climate-driven changes to shorebird population processes, a second set of model simulation analyses will be conducted with models populated to ASDN site-specific conditions of survival and predation (other variables will not change).

Results from the population modeling and simulation analyses will provide insights into what factors are limiting growth of shorebird populations, and how population growth is likely to be

altered under specific altered climate scenarios and from trophic mismatch. Insights will be species and location specific and will identify how climate driven trophic mismatch affects each species differently. We will thus report the results of analyses for each species, and then as a group. Species-specific differences will be emphasized and discussed. Further, climate-driven changes in populations will be compared to the potential population influences of normal perturbations that might be expected to occur during other life-history phases and at a metapopulation scale.

Deliverables and Timeline:
Planning is based on the premise that study teams will receive funds sufficiently early (or host agencies will front funds) to conduct field work in 2013. If funds are not provided in time, study accomplishments / deliverables may be offset a year.

Date	Accomplishment / Deliverable
Jan – April 2013	*Planning for Implementation of study plan*
May – Sept 2013	*1st field season for snow melt, hydrology, invertebrates and birds*
Sept – Dec 2013	*Data entry, quality control, archiving, analysis*
Oct – Apr 2014	*1st Hydrology modeling and code development efforts*
Jan 2014	*1st annual meeting*
Jan – April 2014	*Continued analysis and report writing*
April 2014	*1st annual report due*
May – Sept 2014	*2nd field season for snow melt, hydrology, invertebrates and birds*
Sept – Dec 2014	*Data entry, quality control, archiving, analysis*
Oct – Apr 2015	*2nd Hydrology modeling and code development efforts*
Jan 2015	*2nd annual meeting*
Jan – April 2015	*Continued analysis and report writing*
April 2015	*2nd annual report due*
May – Sept 2015	*3rd field season for snow melt, hydrology, invertebrates and birds*
Sept – Dec 2015	*Data entry, quality control, archiving, analysis*
Oct – Dec 2015	*3rd Hydrology modeling and code development efforts*
Jan 2016	*3rd and final annual meeting*
Jan – April 2016	*Continued analysis and report writing*
April 2016	*Final report due*
Sept –Dec 2016	*Publication of papers on cryohydrology, experimental manipulations of invertebrates, trophic mismatch between invertebrates and shorebirds, and shorebird population level impacts associated with climate change*

Education and Outreach Plan
Residents in local communities and schools on the North Slope will have opportunities to participate in this research and learn about the role of invertebrates and shorebirds in the

tundra food web. We will work with local teachers and with Barrow-based USFWS staff to identify students interested in helping on these studies. Outcomes of successful collaboration will include educational opportunities for North Slope residents, stronger ties between researchers and local communities, and expanded opportunities for data collection, both in the short and long term. We anticipate that this collaborative study, enhanced through daily communications in our proposed joint housing unit, will lead to continued collaboration among our disciplines, resulting in continued local and regional monitoring of cryohydrology, invertebrates and shorebird populations, information important in documenting longer-term ecological effects of climate change. Success in these goals will be evident through rates of participation in public outreach presentations and student internships, and by following the progress of student participants who continue with education or professional employment.

Post-doctoral Research Associates, Graduate students, undergraduates, volunteers

This project will depend on a variety of people with different levels of biological and physical science knowledge to accomplish the proposed objectives. Funding requests will include 1 post-doctoral research associate, 2 graduate students, and many undergraduates and volunteers. The shorebird study alone has six full-time people for 3 months each summer, with plans to bring on additional support during hatch and brood-rearing. Supporting letters are appended from the following (to be included in final submission):

Manomet Center for Conservation Sciences
U.S. Geological Survey, Alaska Science Center
Oak Ridge National Laboratory, Department of Energy

Figures and Tables

Table 1. Characteristics of focal shorebird species proposed for trophic mismatch and dietary assessments. Nest data, forage habitat, and peak hatching based on data collected at Barrow between 2006 and 2012; nonbreeding areas and migration flyway from the Alaska Shorebird Group (2008).

Species	Nests found (mean, range)	Forage habitat	Peak Hatching Period	Nonbreeding Area	Migratory Flyway
Semipalmated Sandpiper (*Calidris pusilla*)	36 (17-53)	pond edges, moist sedge lowlands	late June	The Americas	Mississippi Americas
Red Phalarope (*Phalaropus fulicarius*)	92 (42-160)	shallow freshwater ponds	early July	The Americas	Pacific Americas
Dunlin (*Calidris alpina*)	35 (31-46)	pond edges, moist sedge lowlands	early July	East Asia	East Asian-Australasian
Pectoral Sandpiper (*Calidris melanotos*)	59 (15-108)	low-lying ponds, marshy ground	early to mid-July	South America	Mississippi Americas
American Golden-Plover (*Pluvialis dominica*)	12 (6-25)	more upland areas, dry lichen tundra	mid July	South America	Mississippi/Atlantic Americas
Long-billed Dowitcher (*Limnodromus scolopaceus*)	25 (14-48)	wet, grassy meadows, sedge marsh	mid July	The Americas	Mississippi/Pacific and Atlantic Americas

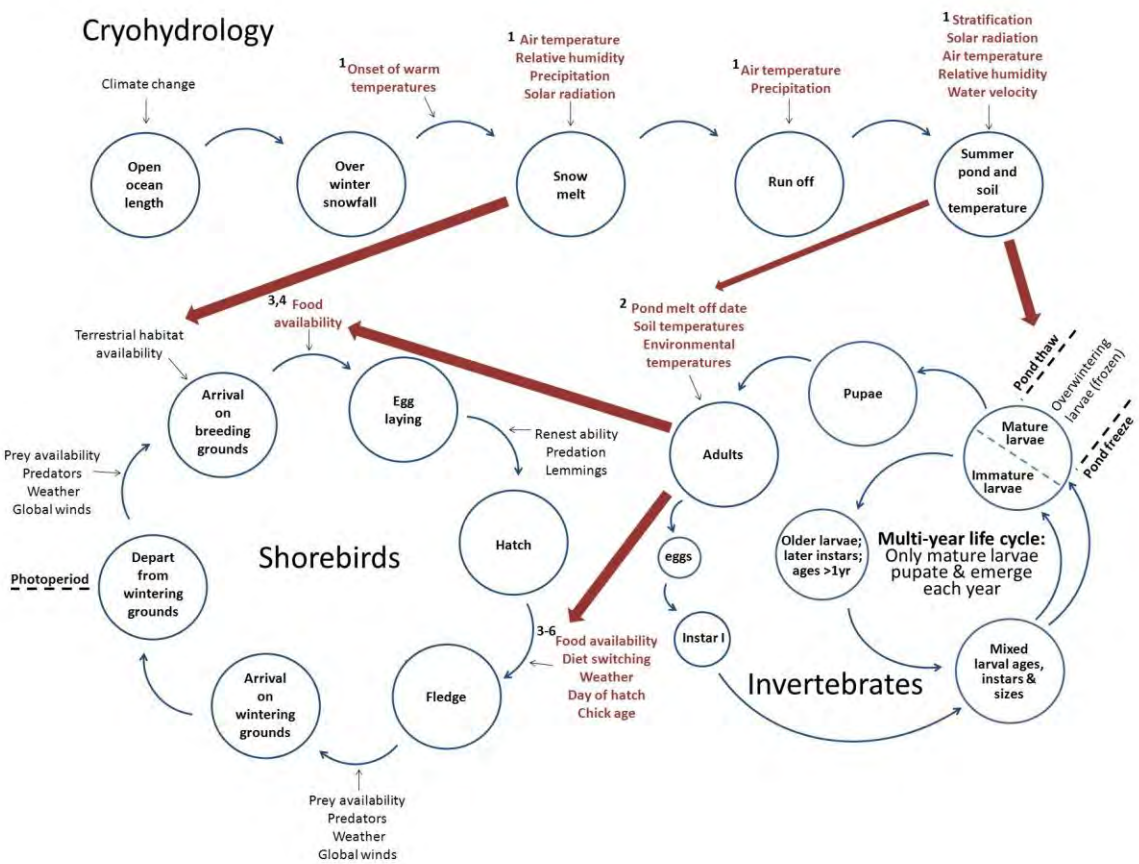

Figure 1. Schematic illustrating climate change effects on wetland habitat, invertebrates and shorebirds. Climate changes are shown linearly along the top of the graph, whereas typical shorebird and invertebrate life cycles are shown opposite one another below. Solid red lines show how the major factors link across the different portions of the study. Forcing factors that will be measured during this study are illustrated in red (appropriate objective #s are listed nearby), and other forcing factors are in black. The principal reason for an expected trophic mismatch is the fact that photoperiod length is thought to drive shorebird departure form wintering grounds (shown with dashed lines on far left), while pond thaw and water temperatures are thought to drive larval development (shown with dashed lines on far right).

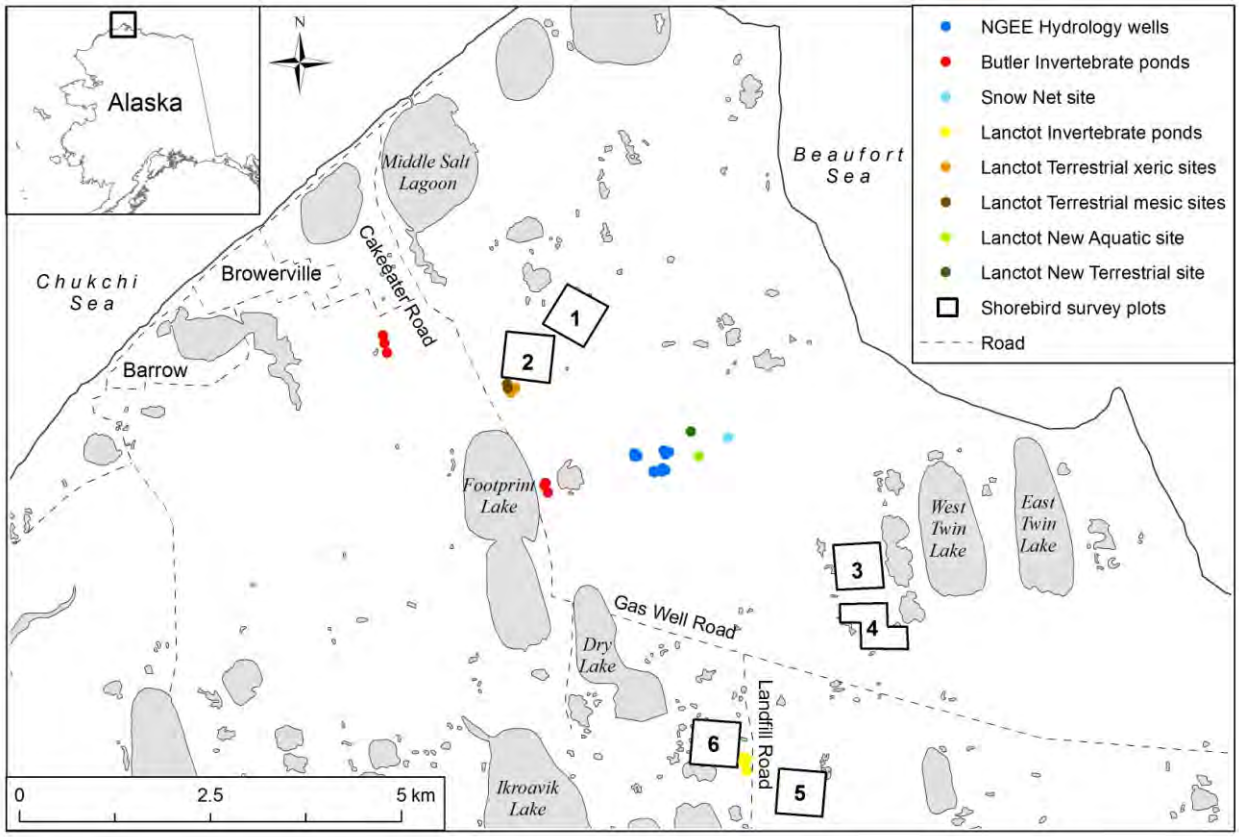

Figure 2. Schematic illustrating study sites at Barrow, Alaska, including SnowNet, NGGEE hydrology, invertebrate (both Butler and Lanctot), and shorebird survey plots. Shorebird survey plot 5 corresponds to the plot located over the landfill that will facilitate creation of "early" hatching broods.

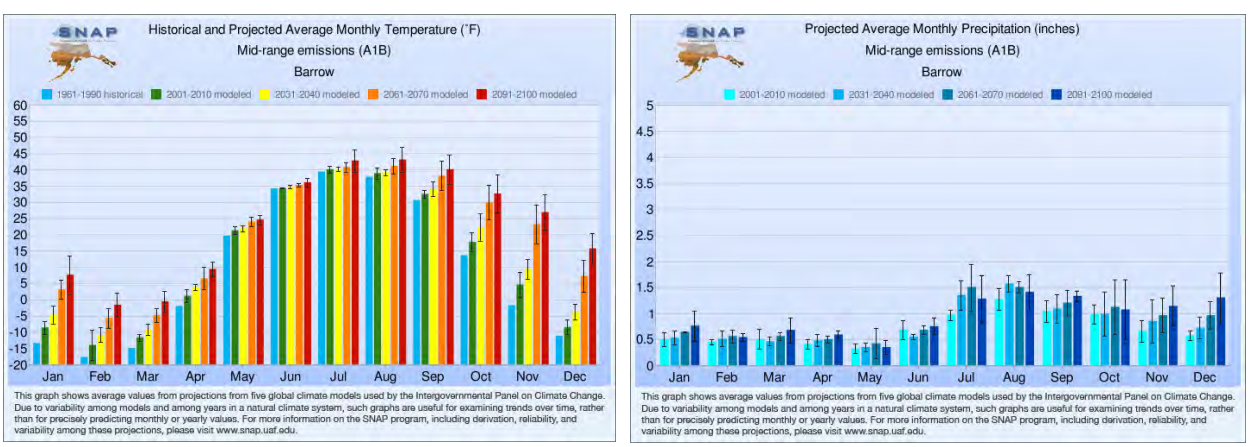

Figure 3. Scenarios Network for Alaska Planning (SNAP) models of mean monthly temperature and precipitation downscaled for Barrow using local weather station data, the PRISM model (accounts for land features such as slope, elevation, and proximity to coastlines) and the A1B1 Global Circulation Model (http://www.snap.uaf.edu/community-charts?c=barrow).

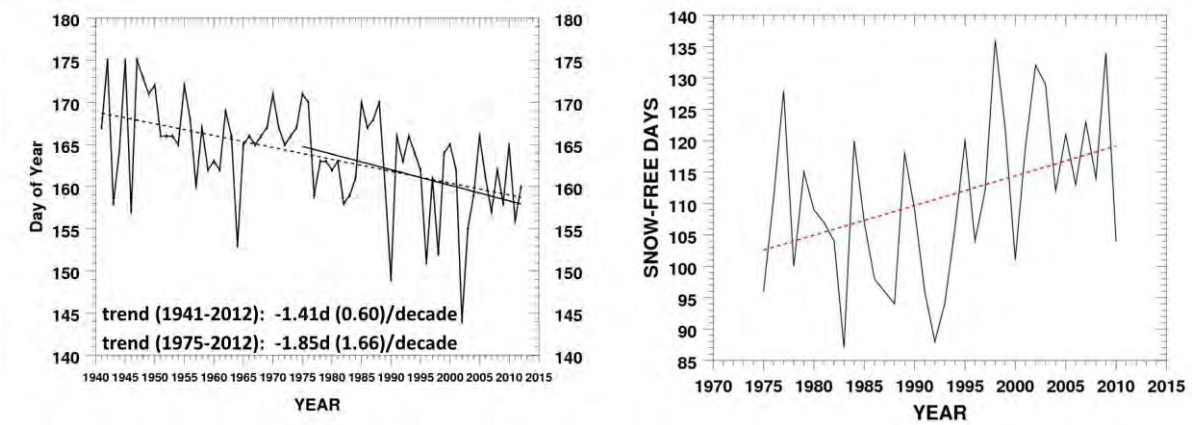

Figure 4. Date of first snow melt (left panel) and snow-free days (right panel) constructed for the NOAA/ESRL GMD Barrow Observatory from direct snow depth observations, proxy estimates using daily temperature records, and beginning in 1986 on the basis of surface albedo measurements. Earlier snow melt and later snow accretion is likely due to less than normal accumulation of snow throughout the winter months and/or warmer spring temperatures (see Stone et al. 2002, 2005, pers. comm.).

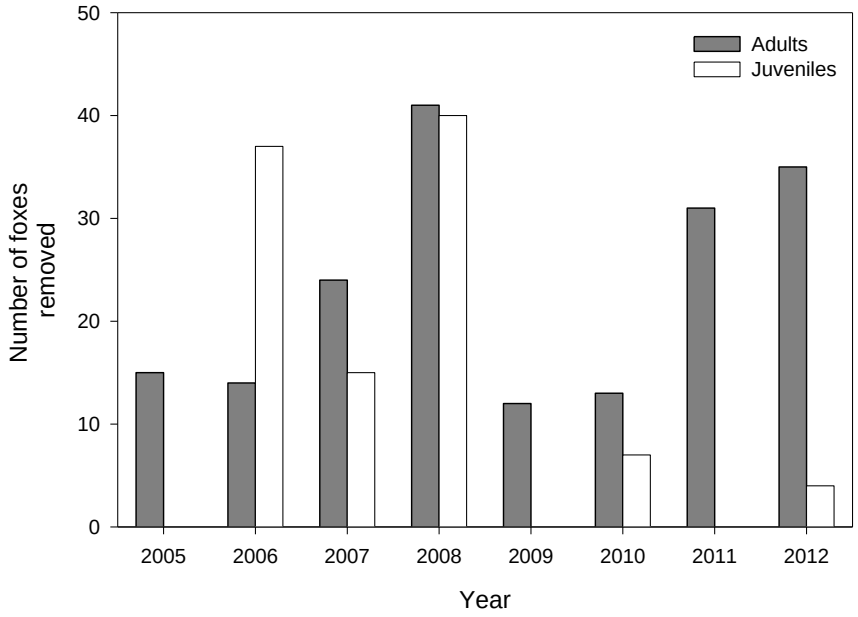

Figure 5. Number of Arctic Fox removed within 10 km of the shorebird study plots at Barrow, Alaska between 2005 and 2012.

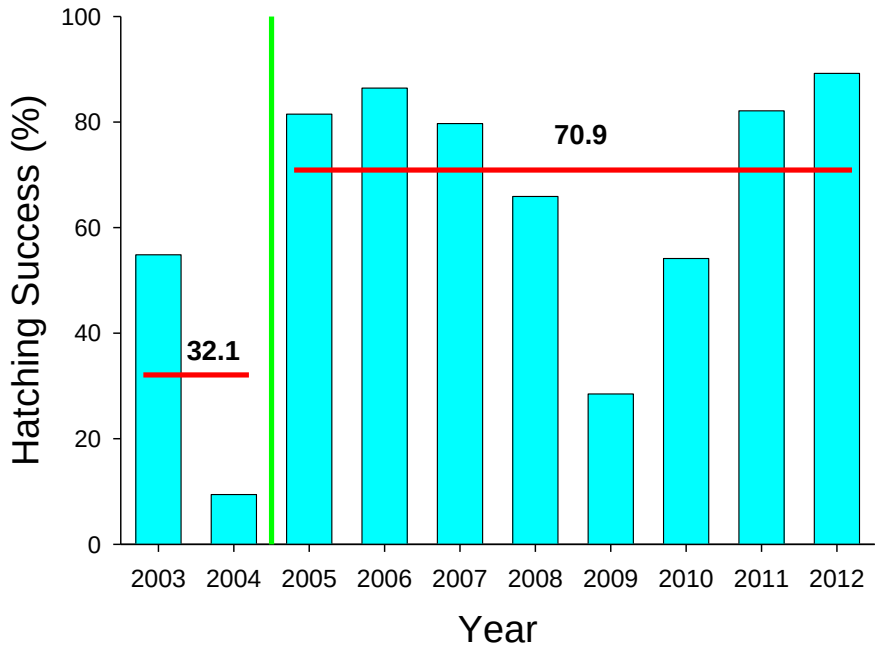

Figure 6. Shorebird apparent hatching success (i.e., at least one chick documented hatching from a nest) at Barrow, Alaska, between 2003 and 2012. Hatching success rates are illustrated when fox control was absent (2003 and 2004) and present (2005-2012).

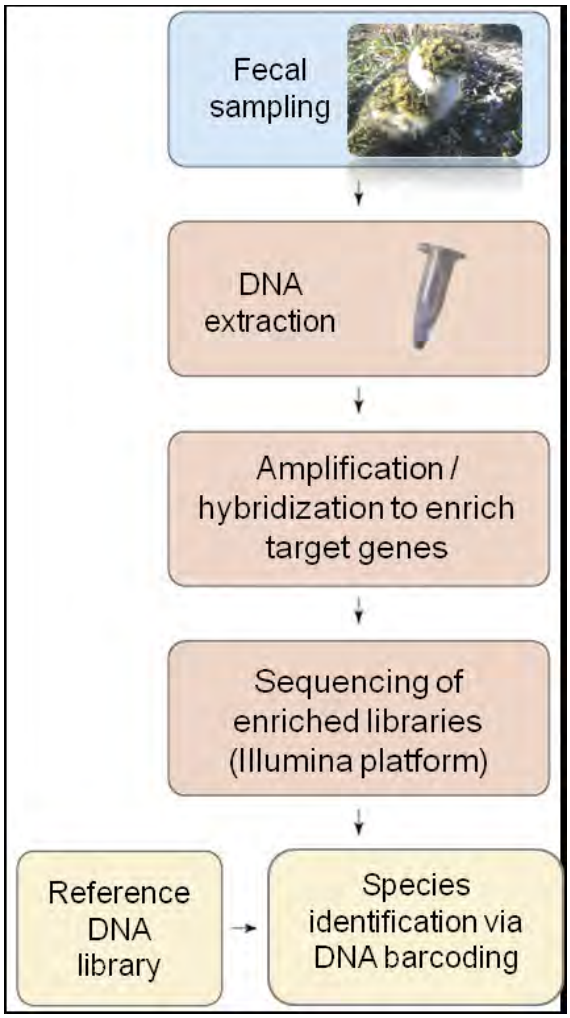

Figure 7. Generalized approach for assessing diet from fecal samples based on next-generation DNA sequencers (modified from Valentini et al. 2009).

Figure 8. Close up view of modified-malaise pitfall insect activity trap shown close up (left panel) and in a series within the terrestrial xeric habitat (right panel).

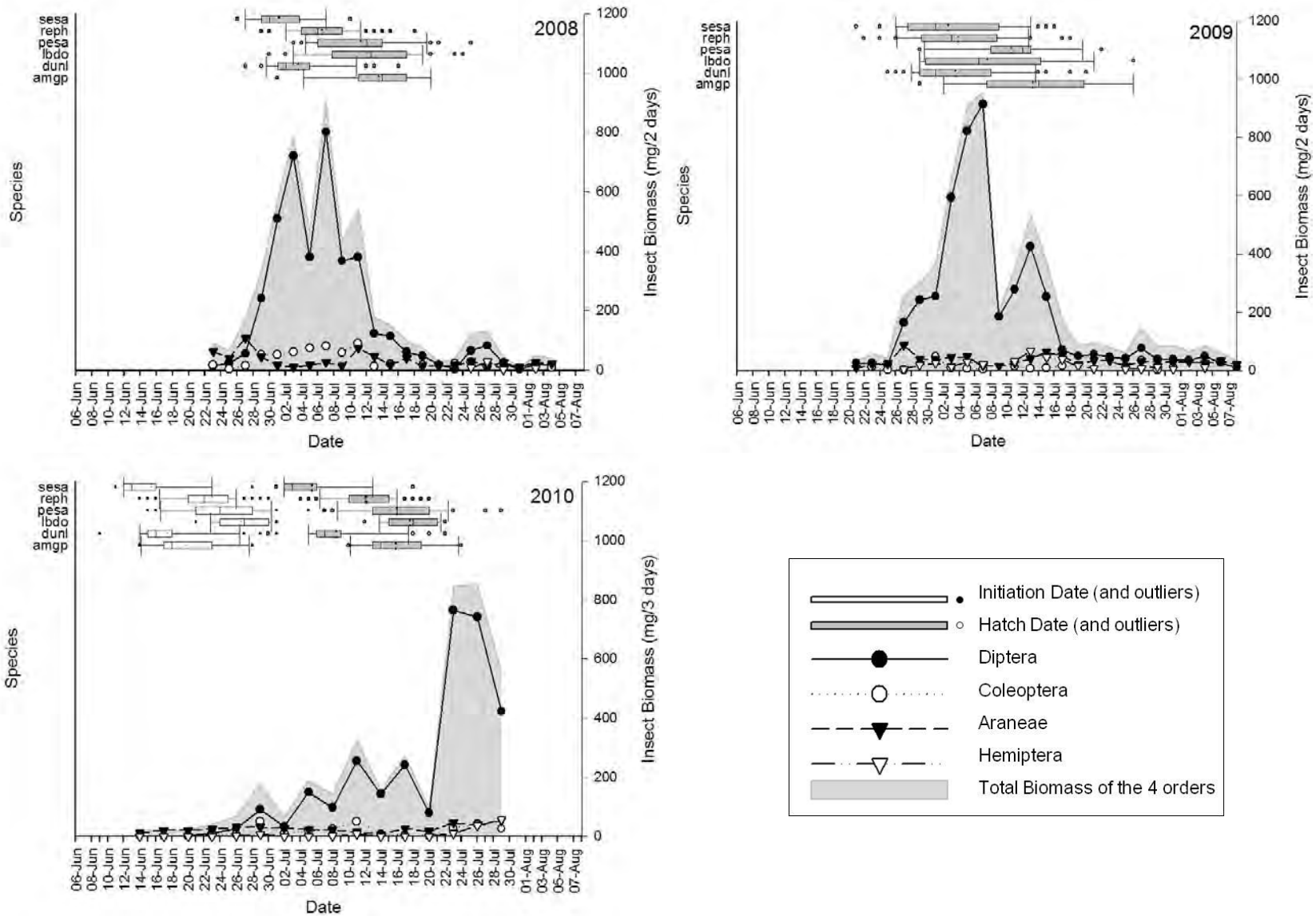

Figure 9. Phenology of shorebird egg-laying (2010) and hatch (2008-2010), and invertebrate emergence at Barrow, Alaska, between 2008 and 2010. See objectives 3 and 4 for methods. Biomass abundance is listed for four dominant invertebrate orders (all families combined) separately and together (gray shaded area). Box plots illustrate 25% and 75% quartiles, median (solid line), mean (dashed line), and outliers (dots outside of bars).

Figure 10. Adult Dunlin marked with an engraved flag and unique color bands that allow it to be uniquely identified throughout the season and from year-to-year.

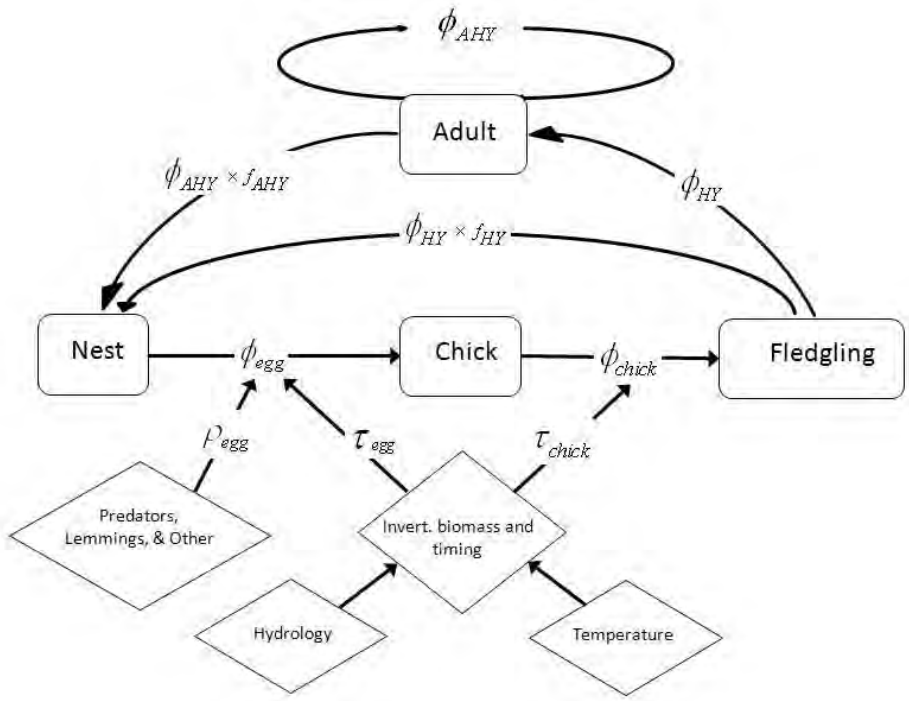

Figure 11. Conceptual representation of population model proposed for use in evaluating localized and regional effects of climate perturbations on ACP shorebirds. Quantitative development of the model will incorporate results from previous project phases in a series of linked Lefkovitch matrix models, which will be used in a prospective perturbation analysis. Φ_{AHY} represents annual survival of birds after hatch year; Φ_{egg} is nest survival; Φ_{chick} represents chick survival; Φ_{HY} represents survival of birds from fledge through the first breeding attempt; f_{HY} and f_{AHY} represent the fecundity in first year and after first year birds, respectively; τ_{chick} is the predicted proportional effect of trophic mismatch on chick survival; ρ_{egg} is the predicted proportional effect of predation, lemming and predation interactions, and other external factors on nest survival; and τ_{egg} is the predicted proportional effect of trophic mismatch on nest survival.

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Budget and Budget Narrative:
Below we present a budget to support five teams (Cryosphere, Hydrology and DNA bar coding – University of Alaska Fairbanks, Invertebrates – North Dakota State University and Minnesota State University Moorhead, Shorebird – FWS, and Shorebird / Modeling – University of Missouri Columbia) to conduct field and laboratory work for a 3-year period. All outside organizations have agreed to a 17.5% overhead rate and to use the CESU process for transferring funds. Substantial leveraging of funds has been obtained by members of each team and is also summarized in the budget below. We have tentatively planned for a start date of 1 May 2013 for our work. Host organizations are willing to front funds should the contract process go into the summer months. Thus our fiscal year for year 1 would be 1 May 2013 to 30 April 2014, etc. We are flexible on this of course.

Management Approach to Integration
Overall coordination of the study will be done by Richard Lanctot who will lead planning, day to day exchanges, and coordination among projects. Monthly, and if needed, weekly, planning and implementation teleconferences will be held to ensure the study plan is being conducted correctly and in a coordinated fashion, and that all team members are aware of the larger study goals and objectives. Regular meetings will be held by members present in Barrow during the summer months, and an annual meeting will be held by all team members in the winter months to assess study plan progress, make revisions in plans as needed, and to continue meeting the objectives of the study. A failure by a team or team member to meet their objectives in a timely manner will be grounds for losing funds and for the greater cross-discipline team to select a replacement team member.

Coordination with Existing Programs
Project personnel have agreed to (1) use information currently being collected during their field and laboratory studies and (2) to expand their field / laboratory work as needed to cover items identified in this study plan. All team members have existing programs in place that will have to be augmented to address issues in this proposal; team members have agreed to coordinate and implement these changes. Coordination will occur through teleconference calls, field meetings at Barrow, and an annual meeting of PIs as indicated above.

Among our team members, coordination is being done with the following larger projects:

1) Snow – NSF Collaborative Research-AON: A Snow Observing Network to Detect Arctic Climate Change – SnowNet II $1,102,060 (5 years)
2) Hydrology – Oak Ridge Laboratory, funded by Department of Energy study, entitled Next Generation Ecosystem Experiment (NGEE-Arctic), ~$10,000,000 project.
3) Invertebrates, experimental manipulations – an Arctic LCC and NFWF funded project that began in 2006, with funding for 2009 through 2013 field seasons.
4) Invertebrate DNA bar coding – This is a new study that will aid not only our work but also a trophic mismatch study being conducted at the Chipp River, NPR-A, by the U.S. Geological Survey's Changing Arctic Ecosystems Program. This study focuses on geese and waterfowl, although there is a smaller shorebird component. Synergistic

interactions between these projects will provide an expanded spatial inference on trophic mismatch not possible otherwise.

5) Shorebird – a primary USFWS funded project that began in 2003. In addition, this project benefits from and contributes to work being done by the Arctic Shorebirds Demographic Network. Shorebird and environmental data collected as part of the ASDN will help us put our laying and hatch dates, as well as chick survival rates, into perspective by providing a broad geographic interpretation of whether trophic mismatches are occurring over the 14 network sites. The fecal collections being done for the diet assessment portion of this study will also aid a PhD student, Kirsten Grond, on her studies of shorebird gut microbiota and immunity.

Data Management Plan and Dissemination Strategies

Please see Arctic LCC database questionnaire in the appendix. We have also provided basic information here.

Types of data. – *C*ore electronic datasets will include information on snow/hydrology, invertebrates, and shorebirds. Invertebrate specimens will also be collected and representative samples archived.

Snow and ice data will include depth, density, sow water equivalent and melt chronology across a nested series of areas including the ponds in which measurements of invertebrates is taking place. Data will also include ice thickness, melt rate, and percent pond coverage.

Hydrology information produced by this project will include a refined tool to simulate heat transfer in shallow water bodies, which includes ice formation and melt as well as water and sediment temperatures. The existing version of WaSiM includes coupled mass and heat transfer in soils, including phase change, which will be expanded to include coupled hydrologic and thermal regimes in smaller shallow water bodies (not lakes). Model outputs from the proposed efforts will include fluxes and storage of water and heat (temperature) under present and future climate forcing presented as time series of a specific site (a point location) or area (map). Hydrology measurements supported by the proposed activities will include continuous (hourly) pond and sediment temperature profiles and pond in- and out-flow.

Invertebrate data will include insect growth / development and emergence relationships under different experimental thermal regimes. We will also obtain taxon-specific estimates of emerging insect abundance and biomass under natural conditions throughout the breeding season. Aquatic and terrestrial invertebrate samples representing four distinct life-stages for each identified group (larvae, pupae, pupal exuviae, and adults) will be preserved in 80% ethanol for long-term storage.

Shorebird information will include dates of nest initiation and hatch, estimates of nest success and chick growth, as well as measurements of a suite of environmental variables (e.g., avian

predator surveys, lemming surveys, snow and surface water surveys) being collected as part of the ASDN.

We also anticipate geospatial data describing the latitudinal/longitudinal location of hydrology / snow measurements and modeling locations, invertebrate sampling and experimental locations, and shorebird study plots, nest sites and brood movements.

Data and metadata formats. -- Metadata from field and laboratory are currently managed in Microsoft Excel format, and will be ultimately archived in Microsoft Access databases. After taxonomic identification and biomass estimation, invertebrate samples will be archived by date x sampling station x taxon in separate glass vials with 80% ethanol as the preservative. Each vial will be assigned a unique reference number which links the specimen to measurement data.

Data preservation. – Metadata and individual data files will be archived in the location specified by the Arctic LCC Science Coordinator and his associates. Metadata have been prepared for some components of the shorebird work as part of the Arctic LCC funded ASDN project. The reference DNA barcode library meta-data will be registered in the Barcode of Life Data Systems (Ratnasingham and Hebert 2007) and in the International Nucleotide Sequence Database, maintained by GenBank (Benson et al. 2000). Invertebrate collections will be archived as voucher collections at the University of Alaska Fairbanks Museum of the North.

Data reuse. – The external research community can obtain access to the metadata given they meet four conditions: use of data will be restricted to research or educational purposes, data may not be redistributed without the conditions of use, access to data should be credited by appropriate citation and acknowledgement, and the Interdisciplinary team members are notified prior to preparation or publication of any work originating from data collected during this study. We anticipate wide use of the reference DNA barcoding library by other researchers studying invertivores in northern Alaska.

Data access and sharing. – The public will be able to access the metadata through the archives established by the Arctic LCC or from individual project team leaders. Results from this study will be presented at conferences and professional meetings, as well as published in peer-reviewed journals and annual and final reports to funding agencies. We anticipate that team members will present talks and publish papers on results originating from their component of this study, while working across teams to present and publish cross-discipline talks and papers, respectively. We plan to present our results to the Arctic LCC Steering Committee and other interested groups annually through meeting presentations and possibly webinars.

Permit Requirements

Permits are currently in hand to conduct all aspects of bird biology, including Master Banding Permit (R. Lanctot, Permit #23269), annual federal and state scientific plan permits (provided annually by USFWS Migratory Bird Management and State of Alaska permit offices). Fieldwork

in Barrow is also done through a formal consultation with the USFWS Endangered Species office; a Biological Opinion has been issued during 2011 and 2012 and will be issued in the coming years to cover shorebird, invertebrate and cryohydro related work. All activities will be conducted under a land permit through the North Slope Borough Planning Department, and each field worker will have an individual Ukpeagvik Iñupiat Corporation (UIC) Scientific Land Use permit to work on native lands. In addition, all field work within the Barrow Environmental Observatory will be coordinated through the Umiaq Corporation – a subsidiary of UIC that is now tasked with the management of these lands.

Suggested Implementation Team

Shorebird / Modeling Team

Dr. Richard Lanctot will coordinate the overall study. He will advise the shorebird post-doc research associate and team of technicians to implement the experimental shorebird mismatch study. He will help write the shorebird component of the interim and final reports, and take the overall lead on combining reporting across all teams. Dr. Lanctot has studied shorebirds at Barrow since 2003 where he and a number of graduate students have collected information on species abundance, diversity, phenology and demographic rates of shorebirds. He and his graduate students have developed methods for locating nests, manipulating nest contents, and following broods to assess growth and survival.

Dr. Sarah Saalfeld will serve as the shorebird post-doc research associate on this study. She studied the breeding ecology of Snowy Plovers for her PhD and has worked on shorebird habitat selection models on the Arctic Coastal Plain as part of an earlier Arctic LCC project. She has also conducted in-depth survival analyses on the long-term shorebird data collected at Barrow since 2003, and wrote papers related to the effects of fox removal and construction of the landfill on shorebirds. For this study, she will help design, implement, and analyze objectives 4-6, creating the experimental mismatches discussed above.

Dr. Dylan Kesler will co-advise the shorebird post-doc research associate, advise on the design and analysis of objectives 4-5, and together with the post-doc conduct modeling and simulations that are part of objective 6. Dr. Kesler has investigated and modeled relationships between birds and resources in highly dynamic systems, in areas prone to anthropogenic habitat modification, and locations likely to be affected by climate change. His current collaboration with Richard Lanctot is aimed at improving nest site resource selection functions for the range of shorebirds breeding on the Arctic tundra.

Cryo-Hydrology Team

Dr. Anna Liljedahl has studied the water balance and the controls on hydrologic fluxes and stores at the low-gradient tundra of Barrow, Alaska, since 2007. Her PhD dissertation described multiple non-linear controls of evapotranspiration and the importance of ice-wedge polygon type in controlling surface water distribution, evapotranspiration rates and runoff amounts. She is currently committed to continue her analyses of present and future hydrology in the ice-wedge polygon landscape near Barrow through the large, interdisciplinary Next Generation

Ecosystem Experiment (NGEE) project. For this study, she will utilize terrestrial field information received from the NGEE project to validate, parameterize and apply the revised version of WaSiM on the NGEE study sites in order to simulate soil and water temperatures and the storage and flow of water across differing ice wedge polygons and water bodies. She will provide the team with projected changes in hydrology, including water and sediment temperatures and she will work closely with Ronald Daanen in the development of the WaSiM numerical code.

Dr. Ronald Daanen did Snow hydrology modeling for his PhD in water resources from the University of Minnesota. He spent his postdoctoral career conducting research on permafrost at the Geophysical Institute of the University of Alaska Fairbanks. He currently holds the position of Assistant Research Professor in the Water and Environmental Research Center. For this study he will guide the ground based LIDAR aquisition and together with Dr Jörg Schulla (model developer and consultant) and Dr. Liljedahl develop a new module for WaSiM to simulate thermal regime in shallow ponds. Dr. Daanen will also oversee the proposed thermal-hydrological field measurements.

Dr. Matthew Sturm has conducted long-term snow cover measurements at Barrow since the 1990s and is recognized nationally as an expert on Arctic snow cover. For this study he will supervise and conduct the snow and ice measurements in spring, will develop an understanding of how the surface processes are linked, and how best to represent them in the modeling work, including how best to predict runoff and associated fields of soil, sediment and water temperature relevant to invertebrates.

Invertebrate Team

Dr. Malcolm Butler worked on aquatic invertebrates at Barrow for his PhD between 1975 and 1980, and returned in 2006 to investigate potential climatic effects on invertebrates. He has extensive knowledge about life history cycles and emergence patterns of arctic invertebrates. He will help design and implement the experiments to investigate how invertebrates respond to different water temperatures, and provide advice on invertebrates to be used in the reference DNA barcode library.

Dr. Dan McEwen will help in the design, implementation and analysis of the experiments and develop models that predict changes in invertebrate availability relative to predicted changes in water temperature.

Tundra Food Resources and Diet of Shorebirds

Dr. Kirsty Gurney works on the USGS Changing Arctic Ecosystems Program that has an intensive field effort near Chipp River (about 80 km southwest of Barrow) studying trophic mismatch in waterfowl, geese and shorebirds. For this project, she will supervise and work with lab technicians to identify collected invertebrates to be used in generating the reference DNA barcode library. She will also collaborate and work with Dr. López to prepare prey items for

inclusion in the reference DNA barcode library and prepare fecal samples for DNA-based identification of diet composition.

Dr. Andrés López is a specialist in genetics and molecular phylogeny. He will advise on the creation of the DNA barcode library and shorebird diet identification process. Along with Dr. Gurney, he will also orchestrate contracts with High Throughput Sequencing (htSEQ, Seattle, WA) and the Georgia Genomics Facility (University of Georgia, Athens, GA) to sequence the reference DNA barcode library and the fecal DNA extracts, respectively.

Cryo-Hydro Measurement and Modeling Component

Background

Climate change will affect all biota especially in the Arctic. Climate downscaling products are readily available and they use an increasing level of detail and feedback. However landscape response to climate change does not behave one dimensionally like typical downscaling models do. Hydrologic and snow drifting models are capable of simulating three dimensional processes of heat and mass transfer and typically use downscaled climate model products as their input variables. Snow drifting models deal with the winter months in the frozen tundra, where large quantities of snow distribute from exposed to sheltered areas. Hydrologic models like WaSiM can take snow distribution data and calculate snowmelt and runoff with a high degree of accuracy using physically based relationships. Incorporating additional thermal processes in WaSiM, allows for further downscaling of climate data to a level of interest for biologists. An example is small pond temperatures, a breeding ground for invertebrates; a key food source for many migratory shorebirds in the Arctic Coastal Plain (ACP). Another example is fish habitat evolution along the annual migration routes from wintering grounds to feeding grounds.

WaSiM is developed to simulate surface and groundwater flow and soil temperatures in watersheds on a scale from meters to tens of kilometers. The meter-scale is most relevant to flora and fauna living in the Arctic. WaSiM will become a key tool for the next level of climate change downscaling products. WaSiM development is now at a point where it becomes a useful tool for very specific climate downscaling. Development of individual physically based modules will enable it to be used in a variety of projects dealing with surface and subsurface water flow and temperatures. Future development of the model could include modules with: long-term (decadal) changes in vegetation, ice degradation and aggradation in the intermediate layer (upper layer of permafrost), ice wedge polygon growth, thermokarst, thermal erosion, aufeis formation, pingo formation and thermokarst lake and coastal erosion. Processes of landscape evolution in the Arctic need to be simulated on a physical basis rather than empirical in order to incorporate climate forcing as a driver. Remote sensing products are becoming available now at sub-meter resolutions that can be used to determine micro habitat characteristics and change in these habitats can be predicted using coupled heat and moisture transfer.

Climate Change Effects on Wetlands, Invertebrates and Shorebirds

In the context of the work proposed in *Climate Change Effects on Wetlands, Invertebrates and Shorebirds* the biggest question is whether there will be a trophic mismatch between feeding birds and emergence of invertebrates as the climate changes, but the issue of the modeling and predicting changes in the biophysical conditions in tundra and ponds of the ACP has a larger applicability (i.e, for fish, run-off, terrestrial invertebrates, etc.). In the context of the *Climate Change Effects on Wetlands, Invertebrates and Shorebirds* project we will address this question by modifying a state of the art physically based thermo-hydrological model, WaSiM, then using that model to understand the response of pond water temperatures to shifting climate variables. However, in order to do this, it is essential that we a) observe the processes that contribute to the thermo-hydrologic state of these features, and b) collect data that can be used to develop and then test the model. To our knowledge, such data do not currently exist. As part of this process, we will add algorithms to allow the model to solve the full surface energy exchange, including shallow pond temperatures. The model currently simulates the complete water balance and soil temperatures driven by air temperatures precipitation, solar radiation, relative humidity and wind speed. Components belonging to the surface energy balance equation that

WaSiM already include cover incoming short-wave radiation through a canopy (let it be tall grass or a spruce), reflected short-wave radiation, latent heat transfer (evaporation and transpiration, but not sublimation), ground heat transfer and, under development, snow heat transfer. Data collected during this study will be crucial for the development of the pond module, which must be able to effectively represent the formation and degradation of pond ice as well as sediment and water temperatures. During the final phase of the study we will use the model to predict how various ponds in the landscape will respond to climate change scenarios and therefore project the potential trophic mismatch. We will force the model with downscaled climate projections, which have already been provided by Jing Zhang, North Carolina State University.

To understand the process of developing a reliable model, it is necessary to see what controls the biophysical "world" of ponds on the ACP. Table 1 lists the main climate variables for the region and how they might change in the next 20 to 50 years. While the variables appear simple, each undergoes seasonal, synoptic and daily changes (i.e., each is a function of time, denoted in the table by (t)), all of which has an impact on when a pond will thaw and freeze, when pond water and sediment temperatures might rise above a level necessary for invertebrate response, and how much water and ice might be in a pond.

Table 1: Climate variables likely to change in the next 20 to 50 years

Variable	Meaning	Likely Change
$T_{air}(t)$	Air temperature (annual and seasonal)	Large increases in winter; more modest increases in summer
$P_s(t)$ and $P_r(t)$	Snowfall and rainfall	Projected to increase, but anybody's guess.
$W(t)$	Wind speeds and consistency	No clue
$R_h(t)$	Relative humidity	More humid?
Cloudiness (t)		Possibly more clouds

Pond module development

We hypothesize that pond water (T_w) and sediment temperature (T_s) are the main interests to the project. Therefore, the task before us is to develop an adequate ability to predict T_w and T_s, given the state of the surrounding landscape (due to the effect of lateral inflow/outflow of water and snow) and the weather. Figure 1 depicts a typical ACP pond. The climate variables in Table 1 appear in blue boxes. On a day-to-day basis these produce the weather. Rain (P_r) may saturate the surrounding terrestrial landscape and hence, resulting in runoff into the pond; rain may also recharge the pond directly or rain may fall on snow and makes it icy and more dense (or melts it). Snow (P_s) falls starting in October (perhaps) and builds up for the next 7 months, producing a snow pack of thickness h_s, but then begins to melt in the spring. Depending on the late summer and autumn rains, the pond will be deeper or shallower when entering the winter. More water in the pond promote as later freeze-up due to the large latent heat storage. The pond freezes, with air temperature a major driver at first, but with snow cover on the ice eventually becoming a more important control on ice thickness (h_i) than the air temperature (T_{air}). The temperature of the surrounding permafrost (T_p) is also a determinant in the process as the sediment cools from below.

Depending on the severity and length of winter, the depth of the pond, and the thermal conditions of the previous summer, the pond may or may not freeze to its bed, and therefore the bottom sediment in

which the larvae exist may stay at a higher or lower temperature throughout the winter. Come spring, the sun returns and the snow will start to melt. The air temperature, the pre-existing snow depth, the ice thickness, and the amount of exposed bare ground vs. snow cover (lower vs. higher solar reflectivity) all impact the surface energy balance at this crucial time. Water from the surrounding landscape begins to flow beneath the snow into the pond basin, bringing in heat to the pond ($F+$), but also flowing out and exporting heat (F-). The water also accelerates the rate that the snow melts, exposing more bare tundra to the sun's power, but not if it is consistently cloudy. At some point, all of these processes in combination produce a set of conditions more or less favorable to the invertebrate larvae in the pond, and they respond. Challenge #1 of the project is to at least understand the various interactions in the figure well enough to model them for a selection of pond geometries and sizes test the model against data, and then use the model to examine how changes in the climate drivers might alter the timing and nature of the physical conditions in the ACP ponds.

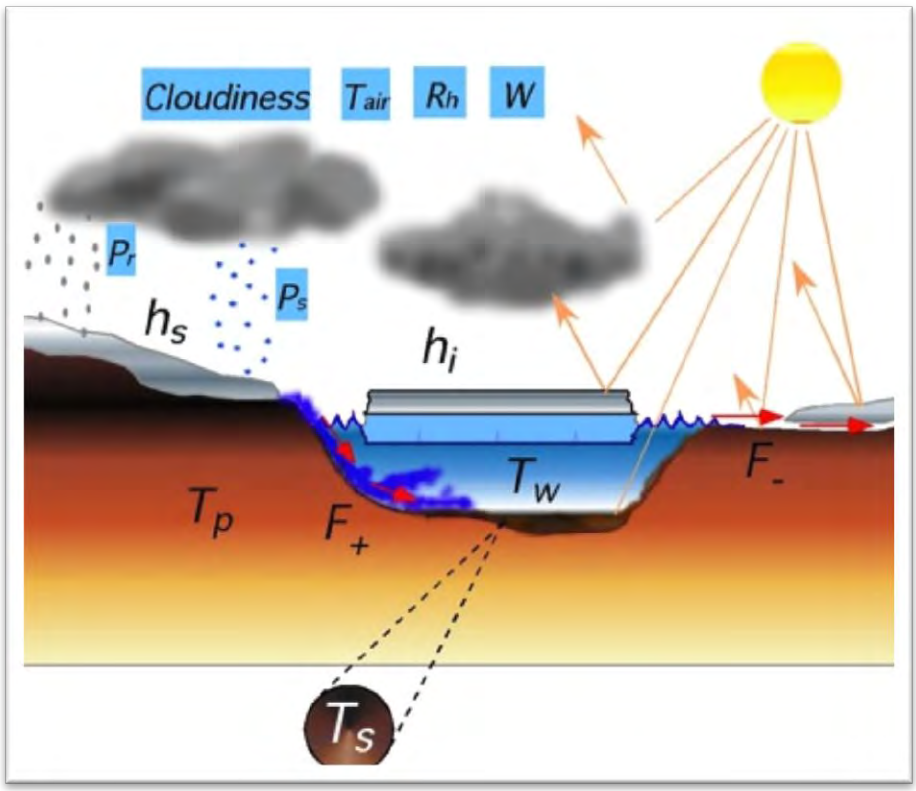

Figure 1: A typical pond on the ACP showing the various processes and agents that affect the pond environment and therefore the emergence timing and abundance of invertebrates in the pond (see above for details).

To our knowledge, the observations and data necessary to develop this model do not exist in together and/or under the necessary temporal and spatial resolution. The numerical and physical basis in WaSiM does exist. What is needed then is an integrated model development, model application and field measurement campaign. In Years 1 and 2 of the proposed project we plan to instrument two ponds typical of the ACP and which bracket what we hope will be the range of biophysical responses ponds might have to climate conditions. To this end, one pond will be deep and potentially will not freeze to the bottom in winter while the other one will.

Field measurements

Two ponds will be instrumented as indicated in Figure 2. The instrumentation essentially is designed to capture times series that mirror processes in Figure 1: snow-up and freeze-up, snow and ice thicknesses through the winter, snow melt and run-off including spatial distribution of high and low albedo surfaces, and the corresponding changes in temperature of sediment and water that reflect the climate forcing, and which are the metrics needed to link the physical modeling to the biologic response. Capacitance probes will be used to measure the water depth in the pond and in the in-flow and out-flow streams, a sonic sounder will be used to measure snow depth, two Go-Pro cameras will capture freeze-up and break-up processes and will allow us to map the snow depth distribution using stereo-image techniques, while a series of thermistors will record the temperature of the pond bottom (in order to identify where best to measure this critical metric). Most importantly, a human observer will be on scene during the two-week window of break-up when the thermal structure of the pond is probably most likely set. The observer will keep the instrumentation running and watch the processes occurring to ensure we have captured all the relevant biogeophysics. The observer will also make spot measurements in surrounding ponds to ensure the modeling is robust and can be used with confidence to extrapolate from the ponds on which it was developed.

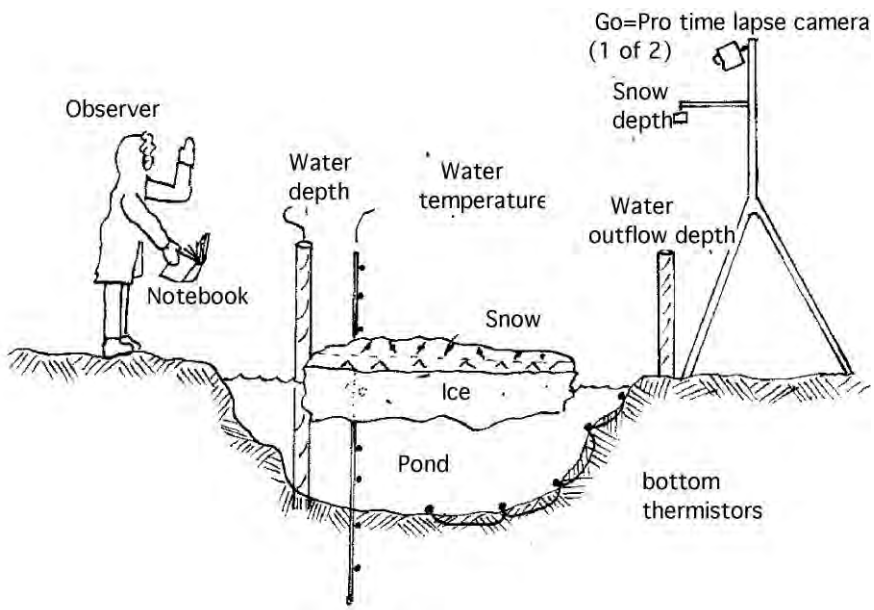

Figure 2: Instrumentation for two ponds (one shallow one deep) designed to elucidate the processes shown in Figure 1 and to allow development and testing of the numerical model.

Landscape integration

The ponds of the ACP vary greatly in size, depth, size of basin feeding the pond, bank height and steepness, and type of vegetation surrounding the pond. WaSiM is uniquely capable of accurately simulating this complex landscape. The model uses topography and hydrology to automatically outline ponds rather than requiring a pre-specified pond location. For this reason it is crucial to have accurate topographic input data for the model. The lack of relief in the ACP makes it harder to measure topography accurately to predict pond formation. In addition to the spatial challenge to the topography there is also a transient challenge in that topography changes over time as ground ice aggrades or degrades. An example is the low centered ice wedge polygon system. When ice wedges expand the ramparts rize above the surrounding tundra, causing pond formation in the center of the low centered

ice wedge polygon. Where ice wedges intersect and perhaps thaw, a deep narrow pond might develop, while where a former thaw lake has drained a shallow but broad pond might be found (Fig. 3). Given this variability, it is essential that we a) create a system to characterize the ponds in terms of variables that can be introduced into our model (area, depth), b) use remote sensing images to create a census of the ponds in feeding area surrounding the nesting birds, c) model the response of all the main classes of ponds for present day climate conditions, d) use simple instrumentation to verify that the model works satisfactorily for the full range of ponds present, and then (and only then) model the response of the ensemble of ponds to future climate conditions. This is the only way we can go from a specific pond and invertebrate response to a local feeding area response. Figure 3 suggests a simple dichotomous subdivision of ACP ponds that might be used in this work.

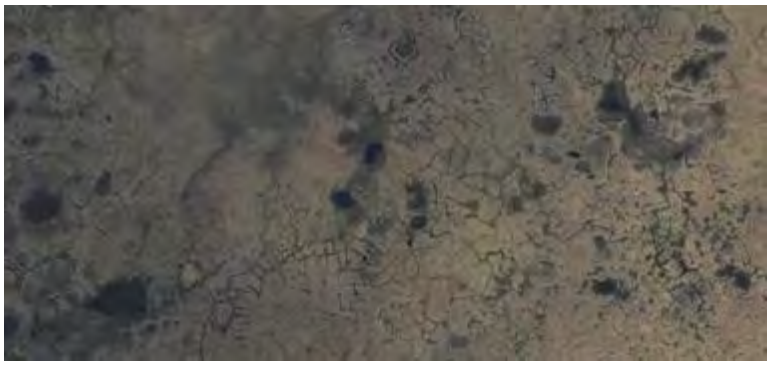

Figure 3: A selection of ponds on the ACP found near the SnowNet site. The largest pond in the picture is about 25-m across, the smallest a mere puddle, yet all could be sources for invertebrates that the birds feed on.

In order to characterize ponds in the field we will need to develop a system to base our categories on. This system will need to be developed based on aerial images and field work, to identify significant differences affecting pond temperatures and invertebrate emergence time. We will perform a multiple linear regression analysis on the variables to statistically determine the importance of those variables. A first cut system for characterizing ponds in given in Figure 4. Upslope contributing area characteristics will vary between ponds and is expected to be an important variable in pond temperature. WaSiM uses the pond location and the digital elevation model to determine where in the watershed the pond is placed and how snowmelt water and runoff temperature drive the particular pond temperature.

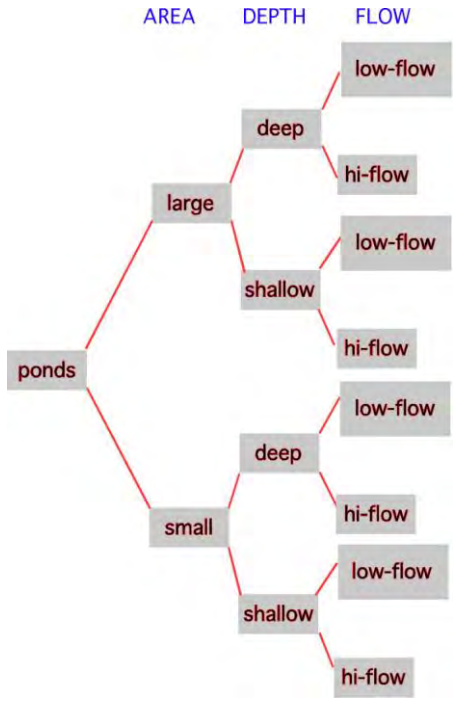

Figure 4: A key that could be used to conduct a census of ponds in the Barrow area or on the ACP.

Projections

When the model is completed and tested (Year 2 Q4), we will be in a position to examine the impact of changing climate variables on the thermal state of the ponds in Spring. By then, relationships between pond productivity and some metric related to pond temperature should have been developed. In combination, these two models will be able to be used to simulate productivity under changing conditions like earlier snow melt, greater run-off, increased cloudiness and so on. We will force the model with downscaled climate projections and run scenarios of individual drivers in order to better understand the sensitivity on the system to individual climate drivers.