Wood River and Togiak System Water Temperatures

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Climate change is expected to affect the thermal regimes of streams and other freshwater ecosystems (Schindler 2001, Malmqvist and Rundle 2002, Poff et al. 2002). While increased air temperatures will have direct effects on water temperature, indirect effects due to changes in precipitation patterns, groundwater characteristics, and flow regimes (Perkins et al. 2010) may have much larger effects. We explored 1) how variation in hydrological characteristics of streams mediate their thermal regimes, 2) how geomorphic features of watersheds regulated stream water sources and, therefore, thermal characteristics, and 3) whether patterns of thermal variation among streams correlate with the life-history characteristics of Pacific salmon that spawn in these aquatic ecosystems.

Variation in spawn-timing among salmon populations is influenced by stream temperature and therefore might also be influenced by hydrological differences related to the relative contributions of snowmelt versus rainfall delivered to streams during spawning and egg incubation periods. We expected that streams receiving more snow sources will be cooler while rain dominated streams will be warmer. Coastal watersheds in Western Alaska, where the majority of world's wild sockeye salmon spawn, are expected to receive 25-50% more snow and 18-25% more rain in the next century (Maurer et al. 2007). Future "climate warming" may actually cool streams if the ratio of snow to rain increases for coastal watersheds. Salmon may have to spawn earlier in many streams to adapt to the cooler temperatures regimes. However, the magnitude of the temperature and hydrologic impact will depend on geomorphology and landscape features (slope, elevation, area, presence of lakes) specific to each stream. Watersheds of a certain size and shape may be able to buffer stream temperatures against expected changes in air temperature while other watersheds may have geomorphic characteristics that make them more sensitive to climate change.

We used stable isotopes of oxygen and hydrogen in water to assess the relative contributions of rain and snow to stream flows across a gradient of watershed characteristics in the Wood-Tikchik State Park and the Togiak National Wildlife Refuge in southwest Alaska. We also developed statistical models to quantify the effects of watershed characteristics on water sources and thermal regimes across the Western Alaska. This work is intended to lay the foundation to support future efforts to link forecasts of climate conditions (rainfall, snowfall, and air temperature) to the thermal conditions that will be experienced by aquatic organisms across this landscape.

Given the cultural, economic and ecological importance of aquatic resources in Western Alaska, there is pressing need to develop scenarios of the trajectories and magnitude of climate driven changes to aquatic ecosystems in this region. This research will inform efforts to develop management strategies for adapting to future warmer climates and to protect the aquatic resources of the region. Because so many terrestrial species are dependent on salmon-derived resources in this region, our work will also be important for understanding the future impacts of climate change on species and habitats dependent on the annual influx of marine-derived resources.

This study was conducted in southwestern Alaska in the neighboring river basins of the Wood, upper Nushagak, and Togiak river basins, which all drain south into Bristol

Bay. These rivers are either contained within the Togiak National Wildlife Refuge or the Wood-Tikchik State Park. The river basins and the surrounding region are characterized by large, deep, oligotrophic lakes which are fed by numerous tributaries and connected by short rivers. Each of these rivers has distinct geomorphic features. Lakes within these drainages annually stratify within a couple weeks following spring break-up (typically the last week of May to the first week in June; Schindler et al. 2005). Our goal was to monitor summer temperatures in >50 sub-watersheds within the three river basins (Figure 4.8), but the majority of the streams were surveyed in the Wood River Watershed.

Salmon return annually to streams, rivers, and beaches throughout the entire system and spawn between mid-July through late October (Schindler et al. 2010). From 2009-2012, the date of sockeye salmon (*Oncorhynchus nerka*) entry to their spawning ground was recorded after repeat visitations to each stream in the Wood River drainage until we confirmed that salmon were actively spawning. In these systems, sockeye salmon generally initiate spawning within two days of entering the stream; and salmon entry to the streams is typically predictable within 2-5 days each year (Moore and

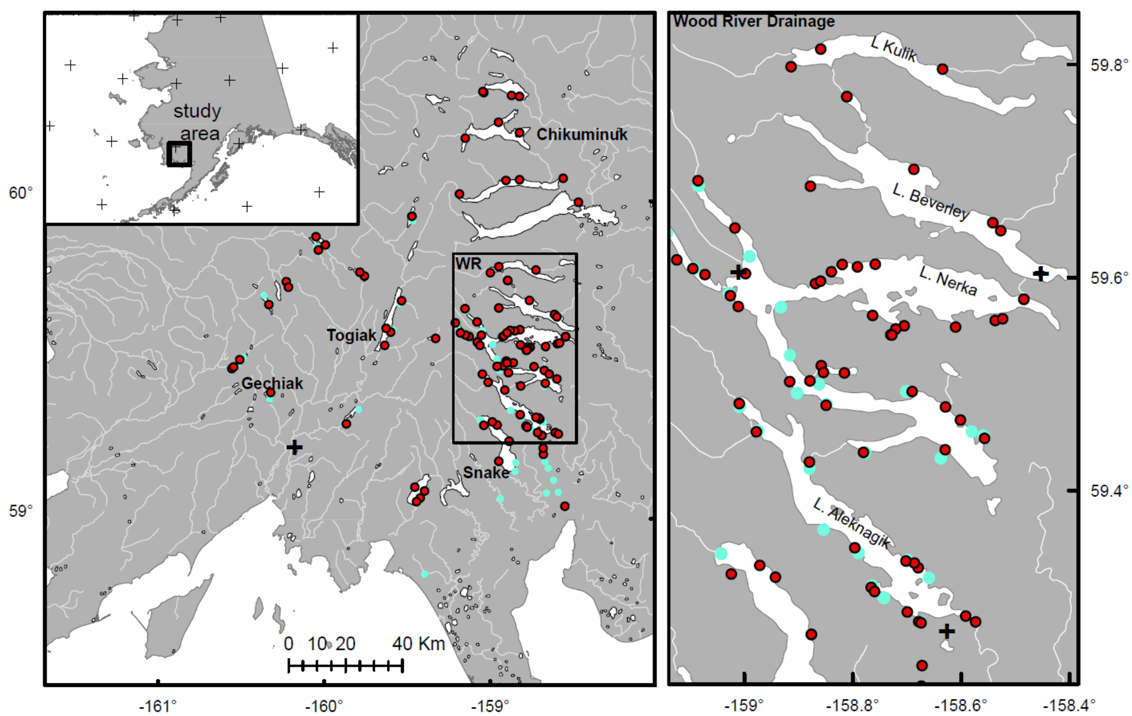

Figure 4.8: Study region in southwest Alaska (upper left), in the Togiak, upper Nushagak and Wood River drainages (center). Right map is enlarged version of the Wood River drainage (right). Red points indicate locations of stream mouths where water isotopes were sampled and continuous temperature loggers were deployed. Blue dots indicate locations of snow samples taken during March 2012.

Water source: Oxygen and hydrogen stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) in water were used to trace the relative contributions of rain and snow to surface discharge (Clark and Fritz 1997). Tributaries across the WTSP and TNWR were surveyed to characterize the spatial variation of $\delta^{18}O$ and $\delta^{2}H$ in streams during the open water season. Duplicate samples were taken once per month at each site, although some remote locations were only sampled once, to coincide with the salmon spawning season in late August. Water samples were collected from surface discharge at stream mouths using gastight 8ml Nalgene bottles and frozen for later analysis. Samples were run at the University of Washington's Isolab facilities to determine the $\delta^{18}O$ and $\delta^{2}H$ of water with a Micromass Isoprime dual inlet based instrument. Ratios of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ are expressed in delta units, per mil, defined in relation to V-SMOW (Vienna standard mean ocean water). These data will be submitted to IAEA online data depository, Global Network for Isotopes in Rivers (GNIR www.IAEA.org)

Snow and rain were sampled across the watersheds to estimate rain and snow end-members and their contribution to stream discharge. Depth-integrated samples of the snow pack were collected in late March 2012 using snow cores. These samples were collected by snowmobile and small aircrafts across a representative spatial extent of the study area. Snow samples were melted under refrigeration and subsamples were decanted as soon as the entire sample had melted. Rainfall was collected during the summer open water season with rain gages at the UW research station on Lake Nerka and Lake Aleknagik. WTSP volunteers collected rain samples at the Agulukpak River on Lake Beverley. FWS technicians collected rain opportunistically on the lower Togiak River. Rain samples were generally only collected during larger rainstorms that accumulated > 0.5 inches of rainfall. All samples were collected as duplicates, using 8ml Nalgene bottles and frozen for later analysis. Data will be made publically available on the Global Network for Isotopes in Precipitation (GNIP www.IAEA.org).

Estimating snow contribution to streams

We assume that phase changes within the hydrologic cycle create measurable differences in the isotopic composition of hydrogen and oxygen in water of precipitation, because the fractionation of isotopes in water vapor to precipitation is temperature dependent. Here, lighter oxygen isotope ratios in stream water suggest a snow-melt source, while streams with enriched oxygen isotope ratios reflect the rain contribution to stream discharge (Clark and Fritz 1997, Henderson and Shuman 2010). Given a known isotopic composition of rain and snow for a particular watershed, we used a simple two source mixing model to estimate proportion of rain or snow in a stream. A two end-member linear mixing model can be formulated from the mass balance equations where the mean proportion of rain in a stream (*fr*) is:

$$fr = \frac{\bar{\delta}_{stream} - \delta_{snow}}{\delta_{rain} - \delta_{snow}}$$

Several processes can affect stable isotope ratios in water vapor during evaporation and condensation phases that make estimating end members of snow and rain difficult (Gat 1996). For instance, continental effects are usually evident in precipitation because heavier molecules containing isotopes ^{18}O or ^{2}H preferentially condense in water vapor, leaving precipitation depleted in ^{18}O or ^{2}H that falls further inland. To account for continental effects, we developed a locally derived meteorological water line (MWL) for both rain and snow end-members. A MWL is the relationship between $\delta^{18}O$‰ and $\delta^{2}H$‰. We compared the slope of the local MWL to the that of Vienna standard meteoric ocean water or VSMOW $\delta D = 8.17\ \delta^{18}O‰ + 11.27$ (Rozanski et al. 1993). MWL slopes between 3.7 and 5 usually indicate water that has undergone substantial evaporation on land (Henderson and Shuman 2009). We do not expect significant evaporative processes in streams or lakes within the study system due to relatively high summer humidity and short surface residence times (see results).

Stream temperature and hydrology: We characterized stream temperatures to define thermal characteristics of individual tributaries relevant to salmon and capture the wide range in topography. The majority of stream thermal regimes were monitored with I-button temperature recorders (Maxim Integrated Products, Sunnyvale, CA) programmed to log at 60 to 90 minute intervals (0.125 to 0.5°C resolution) during the summer. Temperature loggers were placed within 5 cm the streambed by attaching them to steel rebar and tied to features along the river bank or fixed to the river bottom. Togiak FWS had an existing stream temperature network on several monitoring locations for hydrology and temperature. Stream temperature associated meta-data have been made publically available through the Alaska Online Aquatic Temperature Site (AKOATS).

ArcGIS (v10.0, Environmental Systems Research Institute, Redlands, CA, USA) was used to identify the location of the center of each stream's watershed (centroid) by latitude and longitude, and to estimate total watershed area, average elevation, average watershed slope (degrees) from a digital elevation model, and total area of lakes in each watershed. Large lakes were identified with polygon areas > 80,900 m^2 and small lakes and ponds > 800 m^2 at 50 m^2 resolution. Last, we used stream particle size from Wolman pebble counts (Wolman, 1954) in the upper, middle, and lower segments of the main stem of each stream where salmon spawn in several tributaries in the Wood River watershed. The particle size was summarized by a common metric for scaling pebble counts with the 84^{th} percentile (D84) of the cumulative particle size distribution.

We hypothesized that watershed area likely controls the heating capacity of the stream; average watershed slope effects the hydrologic residence time; and watershed elevation influences whether precipitation is captured as rain or snow. We presume that watersheds with lakes in their headwaters provide warm surface water during the summer months through the effects of lakes have on residence time in watersheds (Jones 2010) and possibly evaporative effects on water isotopes (Clark and Fritz 1997). While particle size may not be directly associated with stream temperature, it is correlated with several stream characteristics including sediment transport and supply, stream power, and channel gradient (DeVries and Asce 2002, Buffington 2004), Furthermore, particle size can characterize suitable salmon spawning habitat where salmon usually require smaller gravel to dig and incubate their eggs (Buffington 2004).

First, we assessed the associations between stream temperature and broad-scale geomorphic characteristics of watersheds such as average watershed slope, average elevation, watershed area, total lake area, and particle size (D84) for each stream. Multivariate statistical analyses were then performed to determine controls on patterns of rain and snow contribution to stream discharge or temperature. All habitat variables were log-transformed prior to analysis to control for differences in scale among descriptor variables. Principal components analysis (PCA) on the correlation matrix was used to summarize dominant gradients of environmental variability among streams. Stream scores on principal component axis 1 and 2 were regressed (using ordinary least-squares linear regression) against stream temperature and rain-snow contribution to streams. We used Akaike's information criterion (AIC; Burnham 2004)Burnham and Anderson, 2002) to compare correlations with temperature and spawning date against three linear models according to the equation: $y = \beta_{0+} \beta_{1*}X1 + \beta_{2*}X2 + \varepsilon$, where β_0 = the intercept, β_1 and β_2= the slopes, and ε = the residual error.

Estimating water source contribution to streams.

The relationship between $\delta^{18}O$ and δ^2H for water in study streams, snow and rain tended to parallel VSMOW (VSMOW slope = 8.17, snow = 8.14, rain = 7.9, streams = 7.2, Figure 4.9). This suggests that isotopic change in stream water due to evaporation is negligible across our study system (Gat 1996). Second, we found that multiple linear regression on snow and rain isotopes suggested that the best candidate model (determined via AIC) had linear predictors with the same slope but different intercepts for snow and rain. We used the hydrogen isotope from stream water samples to predict their corresponding oxygen snow or rain end-member according to the snow or rain MWL regressions ($\delta^2H_{rain} = 8.02 * \delta^{18}O_{rain} + 10.94$ and $\delta^2H_{snow} = 8.02 * \delta^{18}O_{snow} + 3.9$). Then we estimated the mean contribution of rain or snow in a particular stream with the two source linear mixing model with the $\delta^{18}O_{stream}$, $\delta^{18}O_{snow}$ and $\delta^{18}O_{rain}$ end-members (Figure 4.10). The vast majority of our samples had isotopic ratios of $\delta^{18}O$ and δ^2H that fell between the MWL of snow and rain. Many of the streams fell closer to the MWL of snow, suggesting snow dominance to summer discharge in the river basin.

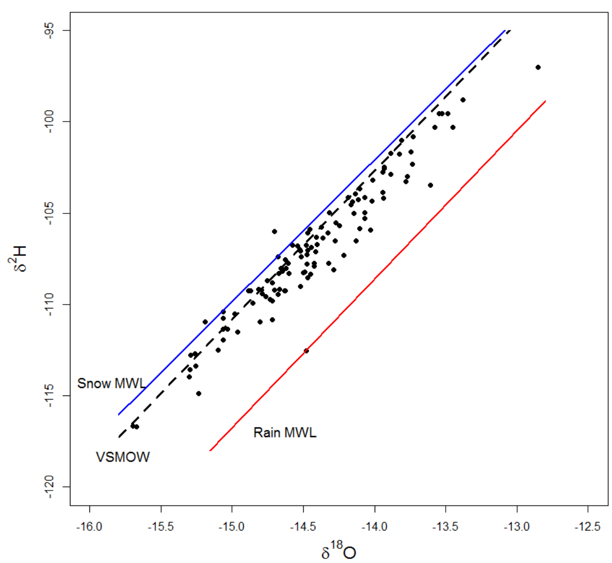

Figure 4.9: Relationship between $\delta^{18}O$ and δ^2H from streams in August 2011 (points). Dashed line indicates the standard of VSMOW (Vienna standard meteorologic ocean water) compared to the locally derived snow MLW in blue and rain LMWL in red plotted with a common slope 8 but different intercept. Streams with more snowmelt are likely closer to the Snow MWL and streams containing mostly rain are located closer to the Rain MWL.

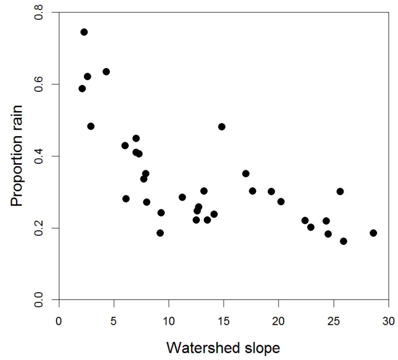

Figure 4.10: Estimated proportion rain for streams as a function of their watershed slope.

Flatter watershed (< 5 degrees) areas tended to have enriched oxygen isotope values with ~50 to 80% rain derived surface discharge. Higher elevation drainages, such as those in much of the TNWR, Upper Nushagak and northwestern edge of Wood River drainage, had discharge composed of ~80 to 85% snow in August. Point measurements from 1st order ground water streams and springs also suggested majority of snow dominance. Surface water collected in peat lands and wetlands showed nearly identical isotopes as those collected in rain water.

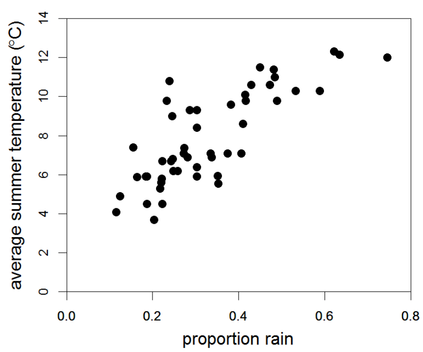

Figure 4.11: Streams summer temperature as a function of the proportion rain.

How do temperature regimes of streams relate to the inputs of snow and rain in this region?

We observed stream temperatures as high as 26°C in streams and others as cool as 2°C within the same week. Average summer temperatures (June to September) varied by 10°C among study streams. Warmer streams were strongly associated with rain dominated watersheds, while cooler streams were associated with snow dominated watersheds. In fact, the proportion rain explained ~70% of the average temperature variation among the study streams ($P < 0.01$ Figure 4.11). Sockeye salmon spawning date was positively correlated with summer stream temperature ($r^2 = 0.42$, $P < 0.01$; Fig. 4.12). Later spawning salmon populations were found in warmer streams, while earlier spawning populations were found in cooler streams.

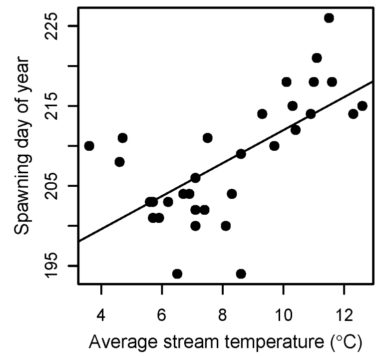

Figure 4.12: Salmon spawn timing as a function of average summer stream temperature (r^2 = 0.42, p < 0.001, n = 33), Lisi et al. 2013.

How do watershed features relate to the sources (rain vs. snow) of water to streams?

Principal components analysis summarized a large proportion of the variance in watershed characteristic in the first two components (~85%). PC1 was largely driven by elevation and watershed slope. PC2 tended to be driven by watershed area and lake area. These environmental characteristics predicted associations with variation in water source, where 76% of the variation observed among stream source conditions (proportion of rain) was explained from multiple linear association between PC1 ($r^2 = 0.50$, $P < 0.01$) and PC2 ($r^2 = 0.29$, $P < 0.01$) (Figure 4.13E). This suggests that most of the variation in snow or rain contribution to streams can be explained by elevation and slope gradients (Lisi et al. 2013).

How does the hydrologic source determine how sensitive these streams are to changes in air temperature?

One of our goals was to understand how sensitive these watersheds may be to changes in air temperature. We hypothesized that the stream temperature response to air temperature may depend on the water source conditions in each stream. To quantify this relationship, we compared the average daily stream temperatures with the average daily air temperature for all our study streams. The regression slope of the relationship between air and stream temperature has been traditionally used to describe stream temperature sensitivity to air temperature. As an example, Moose Creek, a stream draining a large flat watershed with rain dominated discharge, is much warmer than Joe Creek, a stream draining a steep watershed with snowmelt dominated discharge (Figure 4.13B). Moose has daily stream temperatures that are positive correlated with air temperature (regression slope= 0.46), while Joe is relatively uncorrelated with air temperature (regression slope = 0.007, Figure 4.13C). We found positive linear association between stream sensitivity and the proportion of rain in each watershed (Figure 4.13D, $r^2 = 0.72$, $P < 0.01$). A few snow dominated streams had negative sensitivity values, suggesting that they cool off during the warmest weather. We infer this cooling is related to snow melt during warmer weather. These results suggest that rain dominated streams respond quite quickly to air temperature changes, while snow dominated streams do not. The data also suggest a continuum of responses because the watersheds are mixtures of different physical characteristics (Figure 4.13E).

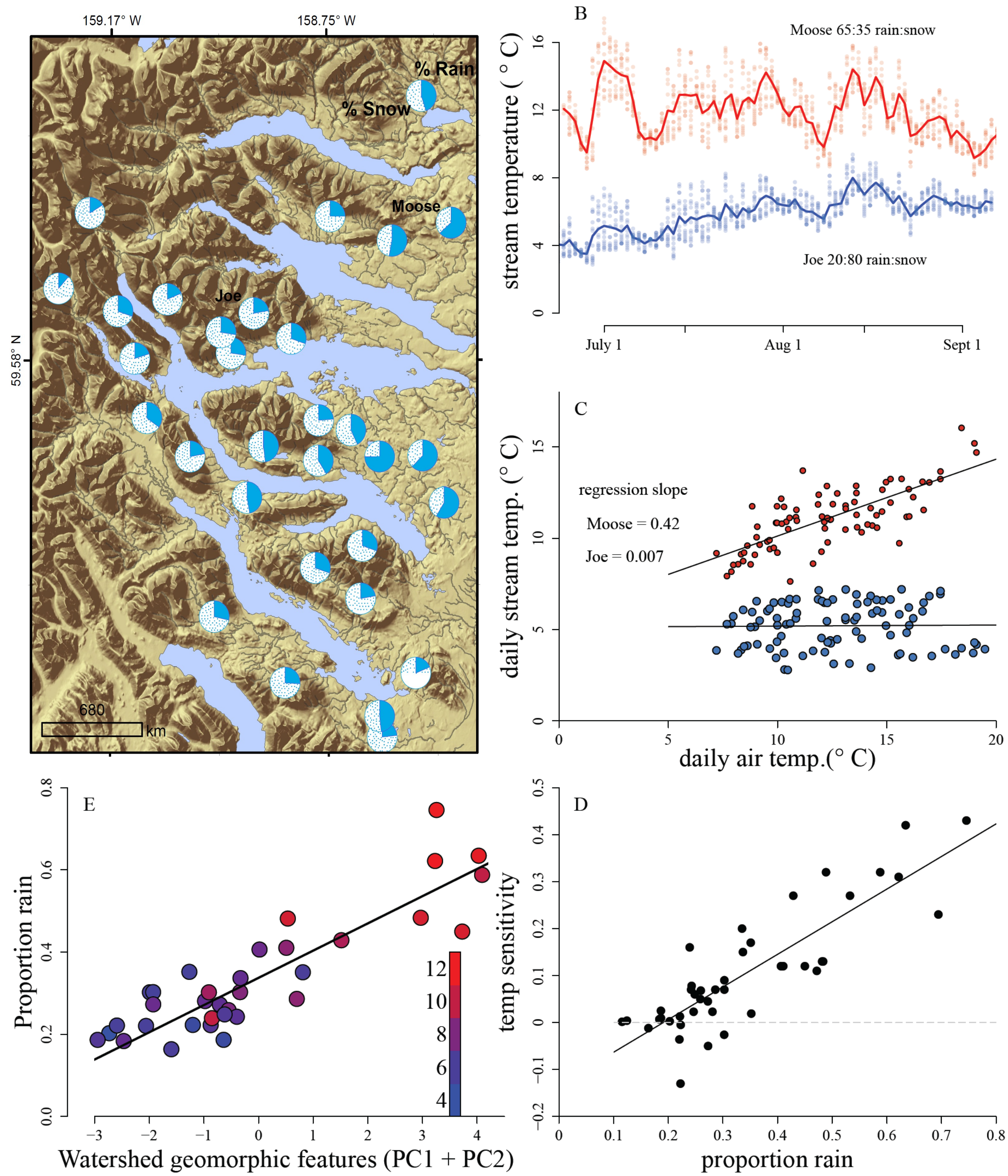

Figure 4.13: A) Map of streams in the Wood River system showing the relative contributions of rain (blue) and snow (white) to August stream flows, B) Stream temperature regimes of Moose Creek (rain dominated) and Joe Creek (snow dominated). C) Daily stream water temperature as a function of daily air temperature for Moose Creek and Joe Creek; the slope of the regression used as proxy for stream sensitivity to increases in air temperature. D) Relationship between proportion of rain for 45 study streams and temperature sensitivity for each stream. E) Proportion of rain as a function of watershed geomorphic features the principal component score for the first two axis (PC1,PC2), points colored by their average summer stream temperature.

The results of this study illustrate how differences in watershed topography translate into differences in water source among streams and, therefore, differences in summer stream temperature. Our results suggest that snow dominated streams have a much different response to air temperature compared to rain dominated streams; rain dominated streams tend to respond more quickly to increases in air temperature while snow dominated streams do not. Snow dominated drainages may be more buffered to increases in temperature by melting snow pack that keeps these streams cool during warmer summer weather. Such associations between geomorphic features and thermal regimes of streams provide a useful basis to evaluate how ongoing climate change may be expressed differently among watersheds at the basin scale depending on how landscape affects the thermal and water source of individual streams and, therefore, the susceptibility of salmon and other aquatic biota to changing climate conditions.

Our hope is that the empirical relationships and approaches developed in this study can better inform future downscaled climate predictions to stream temperatures at spatial scales that are relevant to stream ecology and salmon spawning. We expect rain dominated streams to be more sensitive to increasing air temperature than snow dominated streams. For instance, Scenarios for Arctic and Alaska Planning (SNAP) projections predict a 3.5^{o}C average summer increase in July and August by 2090-99. Already, we have observed temperatures above 25^{o}C in rain dominated streams during summer spawning periods. During these heat waves, salmon were able to avoid these potentially lethal conditions by delaying entry and spawning at a later date when temperatures had cooled down. It may be possible that behavioral, adaptive, or even evolutionary mechanisms by salmon can keep mitigate changes that are likely to occur in these watersheds (Reed et al 2012).

SNAP models also predict average monthly air temperatures above freezing one to two months earlier by 2090-99 (May vs April and March). We speculate that an earlier spring may reduce the buffering capacity of snow-melt dominated streams during the late summer when salmon currently spawn in these presently cooler streams. We may also expect a transition of many snow dominated streams to rain due to expected increase in summer precipitation. In this scenario, streams that are now marginally buffered by snowmelt may become increasingly sensitive to summer air temperatures if winter snowpack accumulation declines. Loss of glacial contribution may also accelerate for similar reasons (Walsh et al. in prep).

Our results also show how spatial heterogeneity in watershed attributes translates into temporal heterogeneity in salmon residence among streams. Water temperatures in adjacent streams can vary substantially (>8^{o}C). This produces a mosaic of available resources for mobile consumers such as bear, gulls, and resident fishes that are able to move across the landscape to exploit sequentially spawning salmon populations (Schindler et al. 2013). Thus, the landscape and hydrology that produce spatial variation in the salmon availability has created a dependable and extended schedule of salmon resources within any given season.

Products of this research:

Peer-reviewed publications: The results of this research have produced two peer-reviewed scientific publications (Schindler et al. 2013, Lisi et al. 2013). In Lisi et al. (2013), we sought to understand the association between geomorphic attributes of streams and their watersheds, stream water temperature, and the seasonal spawn timing of sockeye salmon. We asked: 1) what are the dominant habitat features associated with salmon spawn timing and 2) how does the spatial heterogeneity in watershed attributes translate into temporal heterogeneity in salmon residence among streams. In Schindler et al. (2013), we asked 1) how does the temporal heterogeneity in salmon spawning, generated by watershed temperature and geomorphology, create temporal opportunity for scavengers of salmon carcasses (e.g., bears and gulls).