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Controls on Arctic glacier-fed river water temperature

Christopher J. Mellor[1], Stephen J. Dugdale[1], Grace Garner[1], Alexander M. Milner[1,2] and David M. Hannah[1,*]

[1]School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK
[2]Institute of Arctic Biology, University of Alaska, Fairbanks, AK 99775, USA

[*]Corresponding author: d.m.hannah@bham.ac.uk

ABSTRACT

The impact of climate change on arctic rivers is expected to be severe. There is therefore a need for greater understanding of arctic river temperature processes. This study quantifies spatio-temporal variability of water temperatures in the Kårsa River, Sweden. Water temperature was monitored over two summers within the main proglacial channel and within braids fed by different sources. Longitudinal and lateral temperature patterns were assessed in relation to prevailing hydrometeorology. Temperature metrics in the main channel increased with distance downstream but were moderated by a large lake, while temperatures in the braids were dependent upon channel source. The high temperature standard deviation and inter-site differences within the braids highlights the importance of braided channels for creating thermal habitat heterogeneity. Temperatures were dependent on hydrometeorological conditions, with sensitivity to air temperature maximised during cooler, rainy conditions. These results shed new light on arctic river temperature patterns and their controlling processes.

KEYWORDS: River temperature; spatio-temporal variability; glacier; Arctic; lake; hydrometeorology

1. INTRODUCTION

Glaciated regions are among the most sensitive to climate change due to the dominance of snowpack and glaciers in such environments (Hannah *et al.* 2007). Surface temperatures in the arctic have warmed by approximately 2.9 °C since the beginning of the 20th century (Overland *et al*. 2015), over three times the global average (~0.8 °C; Comiso & Hall, 2014), and this trend is anticipated to continue in the future (Holland and Bitz 2003, Serreze and Francis, 2006, Schiermeier, 2006, Anisimov *et al.* 2013). Such a warming will likely have significant consequences for watersheds within arctic regions, modifying both hydrological regimes and river temperature processes (van Vliet *et al.*, 2013). River temperature is a major controller of the biological, chemical and physical properties of rivers and streams (Caissie 2006, Webb *et al.* 2008). Consequently, any changes to river temperature regimes in arctic environments could have far-reaching consequences for fluvial organisms in these regions. An understanding of arctic river temperature patterns and their drivers is therefore key to understanding how hydroecological processes in these regions may respond to climate change (Brown *et al.* 2005, Cadbury *et al.* 2008, Blaen *et al.* 2014a, 2014b).

A river's temperature is initially determined by its source and subsequently modified by energy exchange processes acting at the channel surface and bed as the river flows downstream (Blaen *et al.* 2013, Hannah and Garner, 2015). Heat gain and loss is controlled by a number of factors, including prevailing atmospheric conditions (e.g. Brown and Hannah, 2007, Garner *et al.* 2015, Khamis *et al.* 2015), advective inputs (e.g. Garner *et al.* 2014b), aspect (e.g. Brown and Hannah 2008), land use (e.g. Arscott *et al.* 2001, Garner *et al.* 2014b, Hannah *et al.* 2008) and discharge regime (e.g. Webb *et al.* 2003). Spatial and temporal variability in these controls thus drives heterogeneity in river temperature regimes across multiple scales (e.g. Mosley 1983, Imholt *et al.* 2013). In alpine environments, research has documented how these processes interact with glacial phenomena (ie. proglacial lakes, meltwater braids) to create unique longitudinal and lateral water temperature patterns in proglacial streams (e.g. Uehlinger *et al.* 2003, Robinson and Matthaei, 2007, Blaen *et al.* 2013, Ward *et al.* 1999, Uehlinger *et al.* 2003, Brown *et al.* 2006b, Hannah *et al.* 2006, Cadbury *et al.* 2008, Cardenas *et al.*, 2014). Such thermal habitat heterogeneity is now known to be highly important to species diversity at the basin-scale (Castella et al. 2001, Milner et al. 2001, Brown et al. 2006a, Milner et al. 2006, Robinson and Kawecka 2007, Blaen et al. 2014b).

However, while the processes driving river temperature heterogeneity in alpine glaciated regions are now reasonably well understood, river temperature dynamics in arctic regions remain poorly documented (Blaen et al. 2013). Because energy fluxes in the arctic can differ substantially from those of alpine regions (eg. Lammers et al., 2007), it is possible that river temperature dynamics in arctic regions will contrast significantly to those in lower latitude environments. As such, research is needed in order to develop hypotheses regarding the processes responsible for river temperature regimes in arctic environments. Furthermore, given the high sensitivity of arctic watersheds to future climate change and that the consequences of climate changes to thermal regimes and aquatic biodiversity within arctic river basins may be severe (Milner et al. 2009), a better understanding of the processes responsible for longitudinal and lateral temperature patterns in arctic river basins is of great importance for protecting these delicate environments.

This paper therefore documents the results of a study carried out in Swedish Lappland with a view to elucidating the drivers of spatio-temporal variability in proglacial river temperature within an arctic river basin. Using river temperature and meteorological data acquired during two summer field seasons, we aimed to highlight the processes driving longitudinal and lateral water temperature patterns within the river. First, we examine longitudinal temperature patterns in a proglacial river, testing the hypothesis that the presence of lakes along the proglacial channel moderates the sensitivity of the river to meteorological trends. Second, we examine lateral temperature heterogeneity within a braided section of the river, testing the hypothesis that the sensitivity of the braided channel to air temperatures is dependent on the channel's source. Finally, we examine how water temperature variability at given locations within the river varies in response to prevailing hydrometeorological conditions, with a view to understanding the potential impact of climate change on temperature patterns in arctic rivers.

2. METHODOLOGY

2.1 Study area

The Kårsa River basin covers 83.7 km^2 within a steep, U-shaped valley in the Abisko National Park, Swedish Lappland (approximately 68° 20' N, 18° 23' W; 200 km north of the Arctic Circle, Figure 1a). The valley floor ranges in altitude from 500 m to 1000 m above sea level (ASL) and surrounding peaks rise to 1550 m ASL. Bedrock of the valley floor and walls is dominated by schist; surface geology comprises exposed bedrock overlain by a thin layer of glacial and glaciofluvial sand. Soils are poorly developed above 820 m, meaning that vegetation above this altitude is sparse with the exception of localised patches of hardy pines. Mosses, sedges and grasses typically grow below 820 m.

The Kårsa River is sourced from a small (1.1 km^2, ~1.3% of total basin area) temperate glacier. The basin experiences polar summer and winter: sunlight is continuous from 17 June until 19 July but between 18 December and 11 January the sun does not rise above the horizon. Mean monthly air temperature ranges from -10.9 °C in January to 11.4 °C in July. Annual absolute minimum can reach -38.9 °C and maximum can reach 29.5 °C (ANS, 2009). The Abisko Mountains cast a rain shadow and the region is therefore one of the driest in Sweden; average rainfall is 300 mm (ANS, 2009).

The valley floor of the Kårsa River is stepped. On the highest plateau, glacial meltwater forms a proglacial stream (900 m ASL). From the glacial snout, the river flows for around 0.3 km over gently sloping rocky moraine prior to descending to the second plateau at approximately 800 m ASL via a series of small waterfalls. The river then spreads laterally across the floodplain and braids (at approximately 720 m ASL). On emerging from this section, the river flows into a marshy valley prior to entering Bajimous Gorsajavri, the largest of two ribbon lakes located ~3.8 km from the glacier snout. Downstream of Bajimous Gorsajavri the valley widens before the river enters a shallower lake, Vuolimus Gorsajavri (~ 6 km downstream of the glacier snout). Approximately 20 km downstream of the glacier snout the river joins the main Abisko River. Here, the river is characterised by steep rapids, large calibre bed material and high discharge (>10 m^{3}s^{-1} during spring freshet).

2.2 Data collection

Hydrometeorological data were collected during the summers of 2008 and 2009. Air temperature, precipitation and river discharge were monitored in order to characterise hydrometeorological conditions and thus infer key drivers of water temperature variability. An automatic weather station (AWS; Campbell Scientific HMP34AC/CS700) located at K1 (Figure 1b) recorded air temperature and precipitation at 15 minute intervals. River stage was monitored using Druck PDCR-1830 pressure transducers installed at sites K1, K2 and K6, also recording at a timestep of 15 minutes. Stage-discharge curves for these sites were established using salt dilution gauging and subsequently applied to the stage observations to provide discharge.

River temperature was recorded at twelve sites using Gemini TinyTag TG-4100 temperature loggers (accuracy +/- 0.2 °C). Six loggers were installed within the glacier-fed main channel of the Kårsa River (K1-K6; Figure 1b) and six in channels within the upper braided section (B1-B6; Figure 1c). Loggers installed within the main Kårsa River recorded data between 1st July and 31st August; loggers in the braided section were operational between 15th July and 31st August. Field constraints (site access difficulties owing to ice cover) limited the collection of data outside of these periods. Loggers K1-K6 were located approximately 0.1, 2.0, 2.3, 7.5, 14.1 and 18.3 km downstream of the glacier snout in the main channel of the Kårsa River. Loggers within the braids were strategically placed to assess the thermal regime of water deriving from different sources. The source of each braid was established by assessing the geochemical signature of water samples taken from each site (see Mellor (2012) for further details), and used to separate the braids into three classes: glacial melt-sourced, groundwater-sourced and snowmelt-sourced. Loggers B1 and B2 were installed in glacial meltwater braids, B3 and B4 in groundwater-sourced braids and B5 and B6 in snowmelt-driven braids. Snowmelt at site B5 was sourced from a southerly facing slope whereas B6 derived from a northerly facing slope. All loggers were housed within radiation shields to prevent solar heating and programmed to record temperature at 15 minute intervals. Loggers were cross-calibrated before and after field deployment to ensure comparability of records; correction factors were applied where necessary following the method of Evans and Petts (1997).

The volume of the upstream-most lake (Bajimus Gorsajavri) was established from a bathymetric survey conducted using a Humminbird 587ci HD GPS-sonar attached to a rowing boat. Lake depth was recorded at 30 m intervals during longitudinal and lateral transects of the lake. Recorded depths were interpolated using Surfer 8 (Golden Software, 2008) in order to estimate lake volume (0.018 km^3). Maximum lake depth was 32 m. Lake residence time was estimated by dividing lake volume by discharge measured at the lake outflow (using velocity-area flow gauging) and was estimated to be 130 days.

2.3 Data analysis

2.3.1 Longitudinal and lateral temperature variability

Longitudinal and lateral temperature patterns within the Kårsa River and the braids were quantified from descriptive statistics of water temperature at each site. Longitudinal and lateral temperature variability was characterised by examining inter-site differences in the mean, minimum, maximum and standard deviation of water temperature. Increased longitudinal/lateral variability was defined as an increase in the magnitude of differences between sites. The sensitivity of water temperature to air temperature was quantified at each site and across each field season using the slope of the regression equation between air and water temperature (after Kelleher et al. 2012). Exploratory analysis (ordinary least squares regression, autocorrelation analyses and Durbin-Watson statistics, after Dickson et al. 2012) identified significant serial autocorrelation of residuals for all timeseries. Autoregressive integrated moving average (ARIMA) models (eg. Gurnell et al. 1992) were therefore used to fit air-water temperature relationships between daily mean water temperature at each site and air temperature recorded by the AWS at site K1. Models were fitted in the 'forecast' package (Athanasopoulos et al. 2014) for R (R Group for Statistical Computing; version 3.0.2). Because standard R^2 statistics are not applicable to non-ordinary least squares regression models, model strength was assessed using Efron's pseudo R^2 analogue (R^2_E):

$$R^2{}_E = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{\sum_{i=1}^{n}(y_i - \bar{y})}$$

where y and $\hat{y}$ are the observed and predicted water temperatures at time i and $\bar{y}$ is the mean water temperature for the entire time series (Menard, 2000). However, it should be noted that this metric describes the combined ability of the air temperature covariate *and* the ARIMA autoregressive structure to explain variability in the observed water temperature data; it cannot therefore be used as an independent measure of the relative strength of the air-water temperature relationship between 2008 and 2009. However, the *p*-value of the air temperature covariate can give an indication as to whether or not the correlation is significant. Following the application of the ARIMA models, modified Tukey-Kramer multiple comparison tests (Hochberg & Tamhane, 2008) were applied to the model fits to identify sites that yielded statistically dissimilar means, allowing for the determination of discontinuities in longitudinal and lateral temperature.

2.3.2 Temporal variability and response to hydrometeorology

In order to understand how the observed water temperature dynamics responded to different prevailing hydrometeorological conditions, hierarchical clustering was used to group days exhibiting similar air temperature and precipitation characteristics. First, daily mean air temperature and daily total precipitation across both seasons were standardised (z-scores) to ensure comparability. Ward's algorithm was then applied to these data to identify days with similar air temperature/precipitation conditions. Ward's algorithm was chosen because it yielded the most robust and evenly sized classes (Kalkstein et al. 1987). Groups of similar days (in terms of air temperature and precipitation) were subsequently determined by inspecting the resulting cluster dendrogram/agglomeration schedules, and these groupings applied separate the water temperature data recorded at each site. Water temperature metrics describing each site under each cluster group were compared to highlight differences in longitudinal and lateral water temperature patterns under different prevailing hydrometeorological conditions. Composites of the diurnal temperature cycle (after Blaen et al., 2013) corresponding to each group were constructed for each site from the 15-minute water temperature series to assess the response of the diurnal temperature signal to different hydrometeorological trends. Finally, ARIMA models were re-fitted to the clustered data to quantify how the air temperature sensitivity of each site varied under the different groupings.

3. RESULTS

3.1 Hydrometeorological context

Average air temperature was warmer (+ 1.2 °C) in 2009 than in 2008 (Table 1) due to an extended period of high temperatures in early to mid-August (Figure 2), but maximum and minimum temperatures were almost identical during the two summers. Total precipitation was greater in 2009 than 2008 (+89.4 mm) (Table 1); an extended period during which no rain fell occurred in late July and early August 2008 (Figure 2). Discharge measured at K2 (where continuous observations throughout both seasons were available) was higher on average in 2009 (+0.9 m^3s^{-1}; Table 1).

3.2 Longitudinal temperature variability

Within the main Kårsa River, mean, minimum, maximum and standard deviation of water temperature typically increased in a downstream direction as a function of distance from the glacier snout (i.e. from K1 to K6; Table 2, Figure 3). Two-way analysis of variance (ANOVA) applied to the ARIMA fitted temperatures indicates that there was no significant difference (p>0.01) in overall water temperature between 2008 and 2009. However, modified Tukey-Kramer multiple comparison tests applied to the ARIMA fitted temperatures highlight the existence of inter-site differences between 2008 and 2009. Results show that in 2008, most sites were statistically dissimilar (p<0.01) from each other apart from K5 and K6, indicating that inter-site temperature variability was higher in the upstream reaches of the Kårsa River and decreased downstream. However, the same analysis applied to the 2009 temperature series reveals that all sites were statistically dissimilar (p<0.01). This indicates that variability in the downstream reaches increased in 2009 in comparison to 2008.

Results of the ARIMA models show that air temperature was found to be a significant (p<0.01) predictor of water temperature at all sites. Sensitivity of water temperature to air temperature (measured by the slope of the regression models; Table 2, Figure 4) increased non-monotonically in a downstream direction from K1 to K6. The downstream warming trend was interrupted temporarily at site K4 (located below Bajimus Gorsajavri lake), before re-establishing and continuing towards K6. Despite the fact that air temperature was higher in 2009, a two-sample t-test applied to the regression slopes did not reveal any significant difference in air temperature sensitivity between 2008 and 2009 (p>0.01), indicating that the sensitivity of the Kårsa River to changes in air temperature is stable over the two-year measurement period.

3.3 Lateral temperature variability

Water temperatures in the braided section of the Kårsa River varied substantially between sites, indicating high levels of lateral temperature variability (Figure 5). Stream temperature and temperature standard deviation was highest in the snowmelt channel that drained the southerly slope (B5), followed by the groundwater-fed channels (B3 and B4) and the snowmelt channel that drained the northerly slope (B6). Water temperatures and temperature standard deviation were lowest in the glacier-fed channels (B1 and B2; Table 2). Although two-way ANOVA indicates that there was no significant difference (p>0.01) in water temperature in the braids between 2008 and 2009, modified Tukey-Kramer multiple comparison tests reveals differences in inter-site variability between 2008 and 2009. While all sites recorded dissimilar temperatures (p<0.01) for the 2008 observation period, in 2009, sites B1 and B2 and B3, B4 and B5 were found to be statistically similar (p>0.01). This reduction in inter-site variability within the braids between 2008 and 2009 directly contrasts with observations from the main Kårsa River that suggested that inter-site variability increased in 2009 (see section 3.2).

ARIMA model results again show that air temperature was a significant (p<0.01) predictor of water temperature at all sites. In terms of sensitivity to air temperature, sites B5 and B6 (southerly and northerly-facing snowmelt-channels respectively) were found to be most sensitive, exhibiting relatively sleep regression slopes (~0.3 – 0.4; Table 2; Figure 6). Indeed, sensitivity of B5 and B6 was higher than any site in the main Kårsa River. Conversely, air temperature sensitivity was greatly reduced within the groundwater (B3 and B4) and glacier-fed (B1 and B2) channels. Similar to that observed in the main Kårsa River, a two-sample t-test applied to the regression slopes did not reveal any significant difference in air temperature sensitivity between 2008 and 2009 (p>0.05), indicating that the sensitivity of the braids to changes in air temperature is stable inter-annually.

3.4 Temporal variability and response to hydrometeorology

Cluster analysis applied to the air temperature and precipitation data identified four distinct groups of meteorological conditions (Table 3). Observations of river temperature corresponding to each of these groups show that temperature dynamics (ie. magnitude of inter-site differences, diurnal range) vary substantially in relation to prevailing hydrometeorology. *Group 1 (12 days)* was characterised by low air temperature (3.9±1.8 °C) and high precipitation (10.1±8.2 mm d^{-1}). Water temperatures were low and diurnal range minimal (Figure 7) at all sites. In the main Kårsa River, the longitudinal temperature gradient (difference between K1 and K6) was weakest of all four groups. In terms of lateral temperature variability, water temperatures at B3 and B4 (groundwater-fed channels) were warmer than at B5 and B6 (snowmelt-fed), while temperatures at B6 (draining the northerly slope) were similar to those at B1 and B2 (glacier-fed). *Group 2 (35 days)* comprised moderately low air temperature and low precipitation (5.5±1.0 °C, 1.2±1.3 mm d^{-1}). Water temperature was again low, with similar diurnal range to group 1 in the main Kårsa River but increased range in the braids. The longitudinal temperature gradient was increased with respect to group 1. Lateral variability was different to group 1, with temperatures at B6 observed to be higher than B1 and B2, while B5 (draining the southerly slope) was similar to B3 and B4. *Group 3 (42 days)* was marked by moderate air temperature and precipitation (8.1±1.0 °C, 2.4±1.3 mm d^{-1}). Water temperature at all sites was higher than groups 1 and 2; diurnal range was similar to group 2 except at B5 and B6 which were notably higher. The longitudinal temperature gradient of the main Kårsa River was consistently higher than groups 1 and 2, while in the braids, temperature at B6 was higher than B1 and B2 but lower than B3, B4 and B5. *Group 4 (35 days)* was dominated by high air temperature (11.8±1.4 °C) and low precipitation (1.3±2.3 mm d^{-1}). Water temperature at all sites was highest of the four groups, as was diurnal range within the main Kårsa River and at sites B5 and B6 within the braids. The Kårsa River's longitudinal temperature gradient was strongest of all groups, while in terms of lateral variability (in the braids), temperatures were highest at B5; B6 was again warmer than B1 and B2 but cooler than B3/B4.

In terms of air temperature sensitivity, results of the ARIMA models applied to each group indicate that sensitivity of both the Kårsa River and the braids to air temperature was weakest within Group 2 and strongest within Group 1 (Table 3). Interestingly, the groups comprising medium (Group 3) and high (Group 4) air and water temperature metrics only yielded moderate levels of air temperature sensitivity. Furthermore, model *p*-values indicate that the air temperature covariate is not statistically significant at several group/site combinations. Table 3 demonstrates that under moderately low temperature/low precipitation conditions (Group 2), no sites except B1 yield significant air temperature sensitivity. Similarly, for Groups 1 and 3 the upstream-most sites in the Kårsa River (K1 and K1-K3 respectively) do not reveal significant correlations. Within the braids, the groundwater driven sites (B4 and B3-B4 respectively) are not significantly sensitive to air temperature under moderate or high temperature conditions (Groups 3 and 4), while the northerly snowmelt channel (K6) is not sensitive to air temperature under high temperature conditions (Group 4). In terms of inter-site variability, air temperature sensitivity within the main Kårsa River shows similar trends to that reported in section 3.2, with non-monotonic downstream increases in sensitivity (K1 – K6) exhibited by all groups. While among the braids site B5 is consistently the most sensitive to air temperature and sites B1/B2 least sensitive across all groups, sites B3, B4 and B6 display moderate levels of sensitivity that vary in terms of relative magnitude as a function of differing hydrometeorological conditions.

4. DISCUSSION

4.1 Longitudinal temperature variability and influence of lakes

Spatio-temporal variability of river temperature is initially determined by differences in water source and subsequently modified by prevailing meteorological conditions (Hannah and Garner 2015). In the main Kårsa River, water temperature dynamics and sensitivity to air temperature generally increased downstream with distance from the glacier terminus, in line with previous studies of glacier-fed river systems (e.g. Uehlinger et al. 2003, Brown et al. 2005, Brown and Hannah 2008, Cadbury et al. 2008, Blaen et al. 2013). The increase in water temperature occurs due to accumulation of heat within the water column as it moves downstream (Garner et al. 2014b), producing a longitudinal temperature trend as the river warms from its cold glacial source towards dynamic equilibrium with the atmosphere (Edinger et al. 1968). Water temperature closer to atmospheric equilibrium is coupled more strongly to climate and meteorological conditions and thus is more sensitive to climatological and meteorological variability (Garner et al. 2014a, 2015). This explains the increased standard deviation and higher mean temperatures found in the downstream reaches (K5 and K6).

Despite the increased temperature standard deviation noted in the downstream reaches, results of the modified Tukey-Kramer multiple comparison tests present a slightly contradictory picture of thermal processes within the Kårsa River. No significant inter-site variability was noted between the downstream-most loggers (K5 and K6) in 2008, indicating that there was little temperature change between K5 and K6, and that longitudinal warming was concentrated in the upstream reaches (sites K1-K4). However, in 2009, K5 and K6 were found to be statistically dissimilar, indicating that there were significant temperature differences in the downstream reaches. This change in longitudinal (inter-site) variability between 2008 and 2009 likely reflects the fact that mean air temperature was 1.1 °C lower in 2008, meaning that atmospheric equilibrium was reached sooner (further upstream). Conversely, in 2009, warmer air temperatures and increased precipitation leading to higher discharge meant that atmospheric equilibrium was not reached until further downstream, explaining why site K6 was significantly warmer than K5. Furthermore the higher air temperatures in 2009 presumably contributed to increased meltwater input into the Kårsa River (eg. Cadbury et al., 2008), again delaying atmospheric equilibrium until further downstream and contributing to the increase in inter-site variability.

The interruption to the downstream trend of increasing air temperature sensitivity as a function of distance from the glacier at K4 is likely due to the presence of a large ribbon lake (Bajimus Gorsajavri) between 3.8 and 7.5 km downstream of the glacier snout. Previous studies in glaciated basins have documented water temperature increases and reductions in diurnal variability (or standard deviation) associated with the presence of small (predominantly proglacial) lakes (e.g. Hieber et al. 2002, Uehlinger et al. 2003, Richards et al. 2007, Robinson and Matthaei, 2007). Accordingly, water emerging from the lake at site K4 was less variable (in terms of standard deviation) and less responsive to climate and meteorological variability than locations upstream. However, the mean rate of thermal accumulation within the lake (0.8 °C km^{-1}) was substantially lower than that recorded in similar studies (eg. 2.1 °C km^{-1} in Val Roseg, Switzerland; Uehlinger et al., 2003). A number of causes may be hypothesised for this disparity. First, atmospheric heat energy inputs are reduced in the Arctic in comparison to lower latitude environments (Blaen et al. 2013). Given this and the relatively large volume of water in Bajimus Gorsajavri (i.e. 0.018 km^3), rates of thermal accumulation may have been decreased in comparison to studies conducted at lower latitudes or in smaller (lower volume) lakes (eg. 0.0015 km^3; Uehlinger et al. 2003) due to a reduction in energy inputs per unit volume (eg. Poole and Berman 2001). Second, in comparison to water in proglacial lakes (e.g. Hieber et al. 2002, Uehlinger et al. 2003, Richards et al. 2007, Robinson and Matthaei 2007) that are fed directly from cold glacial meltwater (which can warm substantially within the lake prior to reaching dynamic equilibrium), Bajimus Gorsajavri was fed by water that had already warmed while travelling downstream and was thus closer to dynamic equilibrium with the atmosphere (eg. Edinger et al. 1968); this may have prevented large increases in water temperature within the lake. Third, long term air temperature warming has actually been associated with cooling trends in some glacial lakes (eg. Zhang *et al.*, 2014) due to increased meltwater inputs, and the decreased thermal accumulation Bajimus Gorsajavri in relation to other lakes may reflect the fact that warm air temperatures increase advective cooling of the lake at a rate in excess of radiative warming. Finally, the reduced thermal accumulation observed in Bajimus Gorsajavri and resulting minimal increase in downstream water temperature (in comparison to studies involving smaller lakes) likely also reflects the lake's long residence time (130 days). While smaller lakes are more responsive to air temperature, the longer residence time of Bajimus Gorsajavri means that temperatures at its outlet will in part reflect hydrometeorological influences on water entering the lake much earlier in the season, meaning that water temperatures downstream of the lake may lag hydrometeorological conditions during the study period. Together, these findings suggest that the impact of lakes on longitudinal temperature patterns in proglacial streams varies strongly as a function of a) latitude, b) lake volume and c) lake residence time, meaning that care must be taken when applying concepts from non-arctic alpine environments to more northerly regions where the ice-free season is much shorter.

4.2 Lateral temperature variability and influence of water source

Findings from the braids show that lateral water temperature variability is potentially greater than longitudinal variability in these upstream reaches of the Kårsa River. Temperature standard deviation at site B5 was actually greater than that exhibited by any site within the main Kårsa River. This, coupled with the high inter-site variability highlighted by the Tukey-Kramer multiple comparison tests, demonstrates that lateral temperature variability within the braids creates considerable heterogeneity of thermal habitats. Such findings have important implications for hydroecology studies in proglacial environments, and emphasise the importance of considering both longitudinal and lateral temperature gradients when studying such systems. The high levels of lateral (inter-site) temperature variability are driven largely by differences in water source between the individual braids. Water sourced from glacial melt was generally coldest and least variable while water sourced from groundwater was warmer and more variable, similar to observations reported by Uehlinger et al. (2003) and Blaen et al. (2013). Both the glacier- and snowmelt-fed channels were similarly insensitive to air temperature, presumably because the relatively thermal stability of these channels (as evidenced by their relatively low temperature standard deviation in comparison to the snowmelt-fed sites) means that they are comparatively 'further' from achieving atmospheric equilibrium. Water temperature dynamics in the snowmelt-fed channels were much more sensitive to air temperature, especially at B5 (southerly slope) which, in contrast to B6 (northerly slope), was exposed to highly variable solar radiation conditions (eg. Beylich et al. 2004, Boyer et al. 2000, Hannah et al. 2006, 2007). At low air temperature, water drained from the southerly slope was of a similar temperature to that of the groundwater fed streams while water temperature in B6 was similar to that of the glacier-fed channels, presumably due to differences in solar heating between the north and south slopes (eg. Malard et al. 1999, Blaen et al. 2013). As air temperature (and thus solar heating) increased, the temperature of water drained from both the northerly and southerly slopes increased, but B5 achieved notably higher maximum temperatures due to increased exposure of B5 to solar radiation in comparison to B6.

In contrast to the main Kårsa River, where inter-site variability increased between 2008 and 2009, modified Tukey-Kramer multiple comparison tests indicate that temperature differences between the braided channel sites actually decreased in 2009. However, these apparently contradictory results likely arise from the same processes. In the main stem, increased glacial meltwater release resulting from higher air temperatures in 2009 likely increased inter-site variability by slowing the rate at which atmospheric equilibrium was reached, essentially increasing the length of the longitudinal warming gradient. In the braids, the large influx of cool meltwater driven by the higher temperatures instead acted to reduce temperature differences between sites B3, B4 and B5, rendering them statistically similar in terms of temperature in 2009. These findings demonstrate the importance of both water source and prevailing hydrometeorological conditions in creating lateral temperature heterogeneity in proglacial streams.

4.3 Temporal variability and response to air temperature and precipitation

Results of the cluster analysis applied to mean temperature and precipitation metrics show that in both the main Kårsa River and within the braids, coolest water temperatures generally occurred during low air temperature, high precipitation days (group 1) and warmest water temperatures during high air temperatures and low precipitation (group 4). However, results of the ARIMA models indicate that the picture linking air-water temperature sensitivity to different hydrometeorological conditions is considerably more complex than these findings would suggest. While sensitivity of water temperature to air temperature is weaker (and indeed, generally non-significant) at moderately low temperatures (group 2; see table 3), the relationship is *not* strongest when air temperatures are warmest (group 4). Instead, sites within the main stem and the braids are most sensitive to air temperature during times of low air temperature and high precipitation (Group 1). This result is likely due to two interacting processes. First, the air-water temperature relationship is maximised during relatively cool atmospheric conditions because during higher temperatures, the increased influx of cool meltwater from temperature-driven glacier melt moderates the air-water temperature relationship (eg. Cadbury et al., 2008). Second, Group 1 was characterised by high precipitation, and it is possible that warm precipitation during this period acted to increase water temperature, bringing it closer to atmospheric equilibrium and thus more sensitive to air temperature. This hypothesis is supported by observations from the braids, which showed that some precipitation events increased maximum temperature and accentuated the diurnal temperature range in the snowmelt channels. Similar temperature increases in response to precipitation events were observed by Cadbury et al. (2008) in a glaciated river basin in New Zealand, where warming was attributed to channel interception of warm precipitation and rapid routing of precipitation over/through warm hill slopes. The wide braidplain and shallow soils/permeable screes in the braided section likely contributed to similar hydromorphic processes in the braids. However, in the main Kårsa River, high precipitation events reduced water temperature and diurnal range in agreement with previous studies (eg. Brown et al. 2005, Brown and Hannah 2007, Blaen et al. 2007), presumably due to meltwater inputs from precipitation-driven glacier ablation (eg. Smart et al. 2000, Cadbury et al. 2008). This suggests that while the strength of the air-water temperature relationship in the braids is driven by both air temperature and precipitation, the relationship in the Kårsa River is predominantly controlled by air temperature. These conflicting results show that the picture governing hydrometeorological controls on the spatio-temporal variability of water temperatures in in the Kårsa River basin is highly complex, and care should therefore be taken to account for these processes when applying statistical models to simulate water temperature in arctic rivers as a function of air temperature or related covariates.

5. CONCLUSION

The results of this study shed new light on patterns and processes of river temperature variability in arctic environments and their links to hydrometeorological conditions. In terms of longitudinal river temperature patterns, this study shows that the downstream warming gradient is influenced both by interannual differences in air temperature and by the presence of ribbon lakes within along the river channel. However, unlike other studies which show that proglacial lakes in lower-latitude environments can engender substantial increases in river temperature, here, the presence of a lake did not produce nearly as large a temperature increase. This interesting result is potentially unique to high latitude environments such as the Kårsa Valley and has implications for the modelling of river temperatures in such environments with regards to ensuring accurate predictions of the effects of climate change on arctic river systems. This study also highlights the importance of considering lateral temperature variability when documenting river temperature patterns. Temperatures recorded in the upper braided section of the Kårsa River were more variable than along the entire length of the main channel, emphasising the very high levels of thermal habitat heterogeneity that can exist in braided arctic river systems. This result has significant implications for the distribution of biotic communities in such regions. Furthermore, the temperature of individual braided channels was found to be highly dependent on their source, with snowmelt channels (particularly on southern facing hillslopes) highly sensitive to air temperature. This means that the effect of climate change on river temperature could vary substantially across a relatively a relatively small lateral and longitudinal gradients, and its impact on biota within such environments could therefore be highly localised and difficult to predict. It is therefore important that research into process-based understanding of the climatological and hydrological drivers of river temperature within glaciated basins continues with a view to more accurately understanding the impacts of climate change on these sensitive environments.

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TABLES

Table 1. Descriptive statistics of hydrometeorological variables during summers of 2008 and 2009. Air temperature and precipitation taken from AWS located at K1, discharge calculated from pressure transducer located at K2. Air temperature and discharge metrics computed from 15-minute time series; precipitation metrics computed from daily totals.

	Air temperature (°C)		Precipitation (mm)		Discharge (m^3s^{-1})	
	2008	2009	2008	2009	2008	2009
Mean (air temperature, discharge) / Total (precipitation)	7.45	8.59	103.2	192.6	1.92	2.75
Maximum	18.78	18.8	26.4	20.2	6.06	4.89
Minimum	0.31	0.30	0	0	0.26	0.47
Standard deviation	3.15	3.84	3.9	4.7	0.88	0.91

Table 2. Descriptive statistics of water temperature dynamics and ARIMA models fitted between air and water temperature along the main glacier-fed channel (Ki) and within the braids (Bi) during summers of 2008 and 2009. Air temperature was a significant predictor of water temperature for all ARIMA models (p<0.01). Note that the R^2_E values refer to the entire ARIMA model (air temperature covariate and autocorrelation structure) and should not be used to assess the relative predictive strength of the air temperature covariate alone.

	Mean		Max.		Min.		SD		ARIMA Slope		ARIMA R^2_E	
	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
K1	1.8	1.9	4.4	4.0	0.4	0.3	0.7	0.8	0.089	0.085	0.87	0.95
K2	4.5	4.7	9.8	9.0	1.5	1.5	1.4	1.4	0.221	0.205	0.83	0.82
K3	5.0	5.2	10.6	10.0	1.6	1.7	1.6	1.6	0.241	0.218	0.81	0.79
K4	9.3	9.7	13.8	15.5	4.9	6.2	1.3	1.7	0.143	0.135	0.76	0.92
K5	11.0	11.6	17.0	17.9	6.0	7.4	1.7	2.0	0.236	0.189	0.86	0.94
K6	10.9	12.0	17.1	18.0	3.4	7.3	2.0	2.0	0.261	0.230	0.88	0.93
B1	2.7	3.1	6.4	5.7	1.1	0.7	0.9	0.8	0.162	0.141	0.91	0.91
B2	3.5	3.4	7.1	6.2	1.7	0.8	0.9	0.9	0.185	0.155	0.87	0.90
B3	8.5	8.6	12.5	11.7	5.1	5.0	1.2	1.1	0.219	0.163	0.76	0.92
B4		8.9		12.8		5.4		1.4		0.141		0.76
B5	7.7	8.7	14.7	15.4	3.9	2.5	1.8	2.5	0.425	0.446	0.91	0.93
B6	4.4	5.0	9.8	9.3	1.3	0.5	1.5	1.6	0.391	0.285	0.82	0.86

Table 3. Descriptive statistics of water temperature dynamics and ARIMA models fitted between air and water temperature along the main glacier-fed channel (K_i) and in the braids (B_i) classified by cluster (Groups 1 – 4). Grey shaded text indicates non-significant *p*-value for ARIMA air temperature covariate.

	Mean	Max.	Min.	SD	ARIMA slope	ARIMA R^2_E	Mean	Max.	Min.	SD	ARIMA slope	ARIMA R^2_E	Mean	Max.	Min.	SD	ARIMA slope	ARIMA R^2_E	Mean	Max.	Min.	SD	ARIMA slope	ARIMA R^2_E
	Group 1						Group 2						Group 3						Group 4					
K1	1.4	2.1	0.9	0.4	0.058	0.74	1.7	2.3	0.7	0.5	0.035	0.56	1.9	2.6	0.7	0.5	0.091	0.69	2.2	3.0	1.1	0.6	0.123	0.90
K2	3.8	4.6	2.9	0.5	0.241	0.89	4.2	5.4	2.9	0.5	0.120	0.39	4.6	5.8	2.8	0.6	0.241	0.13	5.4	6.5	4.1	0.7	0.234	0.67
K3	4.1	5.0	3.3	0.6	0.260	0.81	4.6	6.0	3.2	0.5	0.123	0.36	5.1	6.4	3.1	0.6	0.256	0.12	5.8	7.1	4.4	0.8	0.248	0.64
K4	9.2	11.7	7.6	1.2	0.488	0.43	9.1	11.6	6.9	1.2	0.085	0.51	9.4	12.5	6.4	1.2	0.482	0.43	10.2	14.3	8.4	1.6	0.320	0.67
K5	10.5	13.1	7.9	1.5	0.663	0.66	10.6	13.0	8.7	1.1	0.191	0.49	11.2	14.5	8.8	1.1	0.532	0.49	12.4	15.6	10.3	1.5	0.369	0.65
K6	10.4	13.2	6.7	1.8	0.753	0.70	10.5	12.9	8.0	1.2	0.263	0.45	11.3	14.7	9.0	1.2	0.627	0.52	12.9	16.0	10.7	1.4	0.320	0.68
B1	2.4	3.0	1.9	0.4	0.175	0.77	2.5	3.1	2.2	0.2	0.108	0.40	2.9	3.6	2.3	0.3	0.191	0.61	3.5	4.2	2.8	0.4	0.114	0.72
B2	2.6	3.3	2.0	0.5	0.209	0.68	3.2	3.9	2.4	0.4	0.104	0.56	3.5	4.0	2.8	0.4	0.149	0.58	3.9	4.7	3.0	0.4	0.114	0.74
B3	7.9	9.3	6.3	0.9	0.466	0.71	8.1	9.2	6.9	0.6	0.152	0.17	8.5	10.8	7.3	0.8	0.528	0.42	9.4	11.3	8.0	0.9	0.279	0.61
B4	8.2	10.0	6.3	1.2	0.587	0.84	7.9	8.7	6.3	0.8	-0.003	0.15	8.7	10.6	7.1	1.3	0.374	0.60	9.6	11.0	7.5	1.0	0.093	0.30
B5	6.2	8.7	4.1	1.6	0.640	0.60	7.2	8.6	5.2	0.9	0.131	0.20	8.1	11.1	6.1	1.2	0.631	0.58	10.2	13.0	7.6	1.6	0.395	0.80
B6	3.3	4.6	2.1	0.9	0.355	0.70	3.9	4.5	2.9	0.4	0.204	0.18	4.7	6.3	3.8	0.6	0.369	0.47	6.0	7.2	4.5	0.8	0.150	0.67

FIGURE CAPTIONS

Figure 1. (a) Location of the Kårsa valley in relation to Scandinavia (b) Kårsa River basin showing location of glacier and ribbon lakes and temperature logger sites K1-K6 (c) Upper braided section of Kårsa River showing temperature logger sites (B1-B6). 'ANS' marks location of Abisko Scientific Research Station

Figure 2. Air temperature, precipitation and discharge during (a) 2008 and (b) 2009 field seasons. Air temperature and precipitation recorded by AWS installed at K1. Discharge recorded by stage loggers located at K1, K2 and K6

Figure 3. River temperature along the main glacial channel during the (a) 2008 and (b) 2009 field seasons. Coloured lines denote temperature logger sites K1-K6.

Figure 4. Daily mean air vs. water temperature observations at loggers K1-K6 (a-f respectively) within the main glacial channel. Slopes from derived from ARIMA model (air temperature covariate). Note that the x- and y-axis scales are the same for all plots allowing for comparison.

Figure 5. River temperature within the braids during the (a) 2008 and (b) 2009 field seasons. Coloured lines denote temperature logger sites B1-B6.

Figure 6. Daily mean air vs. water temperature observations at loggers B1-B6 (a-f respectively) within the braids. Slopes from derived from ARIMA model (air temperature covariate). Note that the x- and y-axis scales are the same for all plots allowing for comparison.

Figure 7. Water temperature composites showing variability in diurnal signal under different meteorological conditions (cluster groups 1-4) at sites K1-K6 (a-f respectively) within the main glacial channel

Figure 8. Water temperature composites showing variability in diurnal signal under different meteorological conditions (cluster groups 1-4) at sites B1-B6 (a-f respectively) within the braids