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Water Temperature Dynamics in High Arctic River Basins

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Abstract

Despite the high sensitivity of polar regions to climate change, and the strong influence of temperature upon ecosystem processes, contemporary understanding of water temperature dynamics in Arctic river systems is limited. This research gap was addressed by exploring high-resolution water column thermal regimes for glacier-fed and non-glacial rivers at eight sites across Svalbard during the 2010 melt season. Mean water column temperatures in glacier-fed rivers (0.3 – 3.2 ºC) were lowest and least variable near the glacier terminus, but increased downstream (0.7 – 2.3 ºC km^{-1}). Non-glacial rivers, where discharge was sourced primarily from snowmelt runoff, were warmer (mean 2.9 – 5.7 ºC) and more variable, indicating increased water residence times in shallow alluvial zones and increased potential for atmospheric influence. Mean summer water temperature and the magnitude of daily thermal variation were similar to those of some Alaskan Arctic rivers but low at all sites when compared to alpine glacierized environments at lower latitudes. Thermal regimes were correlated strongly ($p<0.01$) with incoming shortwave radiation, air temperature, and river discharge. Principal drivers of thermal variability were inferred to be: (1) water source (i.e. glacier melt, snowmelt, groundwater); (2) exposure time to the atmosphere; (3) prevailing meteorological conditions; (4) river discharge; (5) runoff interaction with permafrost and buried ice and (6) basin-specific geomorphological features (e.g. channel morphology). These results provide insight into the potential changes in high-latitude river systems in the context of projected warming in polar regions. We hypothesise warmer and more variable temperature regimes may prevail in future as the proportion of bulk discharge sourced from glacial meltwater declines and rivers undergo a progressive shift towards snow- and groundwater sources. Importantly, such changes could have implications for aquatic species diversity and abundance and influence rates of ecosystem functioning in high-latitude river systems.

Introduction

Water temperature is a principal variable influencing the physical, chemical and biological properties of aquatic environments (Caissie, 2006; Webb *et al.*, 2008). Thermal regimes affect ecosystem structure and functioning directly by influencing metabolic rates, physiology and species life-history traits (Poole and Berman, 2001; Füreder, 2007; Friberg *et al.*, 2009). Water temperature also acts indirectly to mediate species interactions (Rahel and Olden, 2008), influence dissolved oxygen levels and the bioavailability of heavy metals (Isaak and Hubert, 2001; Fritioff *et al.*, 2005), and vary transmission rates of parasites and infectious disease (Marcogliese, 2008). River thermal regimes are highly dynamic over multiple spatiotemporal scales (Arscott *et al.*, 2001) and are controlled by numerous factors including atmospheric conditions, topography, discharge and hyporheic exchange (Caissie, 2006; Hannah *et al.*, 2008, 2009).

The role of water temperature as a driver of ecosystem processes is particularly significant in glacierized headwater river basins (Milner *et al.*, 2001; Brown *et al.*, 2005; Cadbury *et al.*, 2008; Roy *et al.*, 2011) due to strong coupling and high sensitivity between atmospheric and in-stream processes (Hannah *et al.*, 2007). Water source is hypothesised to play an important role in determining river temperature in glacierized catchments. For example, Brown *et al.* (2005, 2006) and Brown and Hannah (2008) recorded consistently low water temperature (-0.3 – 2.3 ºC) at a Pyrenean glacier snout and increased temperature (max. 15.4 ºC) at downstream sites, but noted that discontinuities in the longitudinal temperature gradient were introduced by cool thermally-stable groundwater tributary inputs to the river main stem. Similar findings have also been reported by Milner *et al.* (2001) and Cadbury *et al.* (2008) for other sites in alpine Europe and the Southern Alps of New Zealand, respectively. Additionally, while heat budgets of rivers are often dominated by net radiation inputs (Webb and Zhang, 1997; Evans *et al.*, 1998; Hannah *et al.*, 2004; 2008) especially in mountainous environments above the tree-line where little riparian shading occurs, sustained input of warm precipitation and associated runoff to glacial channels can decouple radiation-water temperature relationships, particularly under overcast skies when short-wave radiation inputs are reduced (Brown & Hannah, 2007; Chikita *et al.*, 2010).

While in-depth examinations of seasonal thermal regimes exist for several high-altitude headwater alpine catchments (Uehlinger *et al.*, 2003; Brown *et al.*, 2005, 2006; Cadbury *et al.*, 2008; Dickson *et al.*, 2010), river thermal dynamics remain relatively understudied in Arctic environments (for exceptions see Irons and Oswood, 1992; Chikita *et al.*, 2010). In contrast to alpine environments, high-latitude environments are characterised by stronger seasonality, lower incoming solar radiation, persistently colder air temperatures, and permafrost that underlies the majority of land masses >66 ºN (Power and Power, 1995). Permafrost lenses in the soil prevent deeper groundwater-surface water interactions (Judd and Kling, 2002), thus potentially limiting the capacity of thermally-stable groundwater inputs to buffer variability in temperature regimes (Brown *et al.*, 2005). It follows that differences in the magnitude and timing of incoming solar radiation received at high-latitudes may cause less diurnal variability but greater annual river temperature dynamics compared to those seen in alpine systems.

There is a general consensus that the Arctic will warm more rapidly than low-latitude regions due to the strong synergistic feedbacks that exist between atmospheric, cryospheric and hydrological systems at high latitudes (Holland and Bitz, 2003; Anisimov *et al.*, 2007; Serreze *et al.*, 2009). Long term trends indicate an increase in the rate of warming and precipitation in the Arctic during the latter half of the 20th Century (Serreze *et al.*, 2000; McBean *et al.*, 2005; Hinzman *et al.*, 2005), coupled with decreases in snow cover, reductions in glacier mass-balance, and melt-out of permafrost (Dyugerov and Meier, 2000; White *et al.*, 2007; Foster *et al.*, 2008). These changes are expected to influence strongly thermal regimes in Arctic rivers in the foreseeable future which, in turn, will alter physico-chemical habitat conditions for freshwater biota (Prowse *et al.*, 2006; Hannah *et al.*, 2007; Milner *et al.*, 2009).

This study addressed these research gaps by undertaking a high-resolution characterisation of spatiotemporal patterns in thermal dynamics across multiple river basins located on the High Arctic archipelago of Svalbard. We tested the following hypotheses:

(i) river temperature is determined principally by water source and prevailing hydroclimatological conditions,

(ii) groundwater inputs lead to relatively warmer and more variable thermal regimes than rivers sourced primarily from glacial runoff, and

(iii) water temperature in Svalbard is cooler and more stable compared to alpine rivers at lower latitudes as a consequence of the colder climate and reduced incoming solar radiation in the High Arctic.

The implications of this study are considered in the context of future environmental change and contextualised using current knowledge of water temperature dynamics in Arctic and alpine systems.

Methodology

Study area

The study was undertaken near the Ny Ålesund research station on the Brøgger peninsula (79º N, 12º E) in north-west Spitsbergen, the largest island of the Svalbard archipelago. The mean annual air temperature in Ny Ålesund is -6.3 ºC with the warmest mean temperature occurring in July (4.9 ºC; Norwegian Meteorological Institute, 2010). Precipitation is approximately 400 mm yr^{-1} and falls mainly as snow that covers the ground for at least 230 days yr^{-1} (Cannone *et al.*, 2004). Vegetation is sparse; trees are absent throughout the entire archipelago while slow-growing Mountain Avens (*Dryas octopetala*), Purple Saxifrage (*Saxifraga oppositifolia*) and mosses are found in low-altitude regions (Nakatsubo *et al.*, 2008). Sampling sites were located in two primary study areas: the Bayelva basin and the Stuphallet cliffs (Figure 1).

Bayelva basin

The 33.5 km² Bayelva basin contains two glaciers, Austre Brøggerbreen and Vestre Brøggerbreen, which cover 54% of the basin area and are surrounded by steep mountain ridges up to 700 m elevation (Hagen and Lefauconnier, 1995; ASTER GDEM, 2010). Austre Brøggerbreen is predominantly cold-based while Vestre Brøggerbreen is also believed to be dominated by a non-temperate thermal structure (Hodgkins, 1997; Hodson *et al.*, 2002). Both glaciers have retreated significantly in recent years and the mass-balance of Austre Brøggerbreen has been negative almost consistently since monitoring began in 1967 (Haeberli *et al.*, 2007; Barrand *et al.*, 2010). Seasonally-active braided streams flow across moraine deposits in the upper basin before joining in the lower reaches to form the Bayelva river which exits into Kongsfjorden after approximately 3 km. The basin is underlain by Tertiary, Triassic, Permian and Carboniferous sedimentary rocks which include sandstones, limestones and shale (Hjelle, 1993). Despite Svalbard being situated within a zone of continuous permafrost up to 500 m deep (Hagen and Lefauconnier, 1995), a shallow groundwater system develops in the Bayelva basin each summer with active soil layers >1 m in depth (Roth and Boike, 2001).

Stuphallet cliffs

The Stuphallet cliffs are situated approximately 8 km to the west of Ny Ålesund (Figure 1). Several small first-order rivers sourced from snowmelt and groundwater originate below the cliffs and flow across an area of poorly drained soils for 1-2 km before reaching Kongsfjorden. The cliffs are utilised by seabirds for nesting and breeding during summer months. Abundant vegetation growth occurs on poorly drained soils below the cliffs. Moss layers can reach 10 cm in thickness and species include Marsh Bryum (*Bryum pseudotriquetum*), Ribbed Bog Moss (*Aulacomnium palustre*) and Tomentypnum Moss (*Tomentypnum nitens*) (Cooper, 1996; Høj *et al.*, 2006).

Sampling framework

Water column temperature was measured continuously from 6 July to 31 August 2010 (calendar days 187 to 242) at eight sites (Figure 1; Table 1). Sites in the Bayelva basin were selected to characterise water column temperatures near the glacier snouts (V1 and A1), along the river mainstem (V2 and A2), and at the Bayelva river mouth (BR). "V" denotes sites draining Vestre Brøggerbreen while "A" denotes Austre Brøggerbreen. Non-glacial sites in the Stuphallet cliffs area (S1, S2, S3) were considered to be representative of snowmelt and groundwater dominated river systems found in this region of Svalbard. Water temperature was measured using a combination of Tinytag Underwater dataloggers (Gemini Data Loggers (UK) Ltd.) and Campbell Scientific 107 thermistors and CS547A electrical conductivity probes connected to CR10X dataloggers. Instrumental accuracy was ±0.5 ºC. All internal datalogger clocks were synchronised and checked weekly. Tinytag dataloggers recorded water temperature every 15 minutes. Campbell Scientific instruments scanned every 10 s and 15 min averages were logged. All temperature sensors were cross-calibrated before and after the monitoring period across a temperature range greater than that experienced during fieldwork. Correction factors for individual sensors were computed based on mean values of all sensors during calibration (Hannah *et al.*, 2009). Instrumental drift over the monitoring period was negligible (<0.01 ºC) for all sensors and an order of magnitude less than instrument accuracy.

Meteorological data (short-, long- and all-wave incoming radiation (SW↓, LW↓ and AW↓, respectively); air temperature; relative humidity) were employed to characterise atmospheric influences on water temperature. Data were measured in Ny Ålesund (approximately 1 km and 8 km east of the Bayelva and Stuphallet cliffs, respectively) at 15 min resolution. SW↓ and LW ↓were measured using a Kipp & Zonen CMP11 pyranometer and an EPLAB precision infrared radiometer, respectively. Air temperature was measured using a Thies Clima PT100 resistance thermometer. Relative humidity was measured with a Vaisala HMP230 humidity sensor. For radiation, instantaneous values are given in W m^{-2} and daily flux total in MJ m^{-2} d^{-1}. Daily precipitation totals were available for Ny Ålesund. Additionally, Tinytag dataloggers housed in radiation shields were deployed at sites V1 and S2 to measure local air temperature at 15 min resolution. River stage at sites

V1 and V2 was monitored every 10 s using Druck PDCR 1840 pressure transducers and 15 min averages stored to Campbell Scientific CR10X dataloggers. River stage at site S3 was monitored every 15 min using Level TROLL 100 (In-Situ Inc.) loggers, although logistical constraints prevented installation until Day 195. Stage data were converted to discharge (Q) using rating curves derived from salt dilution gauging (Hudson and Fraser, 2005). Errors in discharge were 10–23% and similar to those reported in other studies of High Arctic hydrology (Hodgkins, 2001; Hodson *et al.*, 2002). Discharge at site BR was measured hourly by a compound crump weir and interpolated linearly to 15 min resolution.

Data analysis

Temperature-duration curves were constructed to compare overall variation in water column temperature at each sampling site (Brown *et al.*, 2005; 2006; Hannah *et al.*, 2009). Temperature-duration curves indicate the fraction of time that a temperature was equalled or exceeded at each site during the monitoring period. Average values for each 15 min time-step were computed across the entire melt season and selected 5-day periods to generate composites of temperature variation over the diurnal cycle (Uehlinger *et al.*, 2003). One-way ANOVA was used to evaluate seasonal differences in water temperature variables (mean, max., min., range, std. dev.) between glacial and non-glacial rivers. The degree of association between water-column temperature and hydroclimatological variables (Q, air temperature, short-wave, long-wave and all-wave incoming radiation, relative humidity) was assessed using Pearson's product moment correlation coefficients (*r*). Air-water column temperature relationships were calculated using air temperature measured at Ny Ålesund, V1 and S2. Five 5-day sub-periods were selected from the full time-series to characterise diurnal-scale variability in the dataset. These periods were selected to represent the range of hydroclimatological conditions experienced during the summer monitoring period (*cf.* Cadbury *et al.*, 2008) and were set by strong contrasts in air temperature, discharge and precipitation (Hodson *et al.*, 1998). Pearson's product moment correlation coefficients between water temperature and hydroclimatological variables were calculated for each period, and diurnal water temperature composites were derived to yield visual patterns in water temperature for each period. Seasonal hysteresis patterns between discharge and water temperature were explored using values for each 15 min timestep averaged over the summer monitoring period.

Results

The results are presented at nested temporal scales. Water temperature patterns were investigated over the 55-day monitoring period; these stream temperature analyses are set in a hydroclimatological context to infer key drivers and processes, using climatological and river discharge data. To examine diurnal patterns in stream temperature in greater detail, five periods of 5 days each were selected that spanned the range of hydroclimatological conditions experienced across the field seasons.

Seasonal hydroclimatological context

The 2010 melt season was characterised mainly by cool, dry hydroclimatological conditions with the warmest air temperatures recorded in early July coinciding with higher AW↓ (Figure 2). Cooler air temperature later in the season was associated with decreases in incoming SW↓ under heavily overcast conditions. Air temperature was highest invariably at V1 and lowest in Ny Ålesund (seasonal means 5.4 ºC and 4.9 ºC, respectively), although all air temperature time-series were strongly inter-correlated (r>0.96, p<0.001). Precipitation events were short and episodic (Figure 2) and total precipitation inputs during the 55 day monitoring period were very low (17.4 mm). The greatest prolonged period of precipitation (days 224 – 227) coincided with a cold period (days 225 – 229) during which air temperature at all sites exhibited a marked decline (Figure 4). A second cold period (days 238 – 242) occurred at the end of the monitoring period. With the exception of these two periods, air temperature at all sites displayed no clear seasonal trends but varied on a sub-daily basis in conjunction with incoming radiation inputs.

Longitudinal increases in the magnitude of river discharge were observed in the Bayelva basin, although patterns of discharge were similar at all sites (Figure 3; Figure 4). Discharge was associated strongly with air temperature but not evidently affected by precipitation events. Mean discharge over the monitoring period in the Bayelva basin was 0.89 $m^3 s^{-1}$, 1.41 $m^3 s^{-1}$ and 2.69 $m^3 s^{-1}$ at V1, V2, and BR, respectively. Following peak flow at all sites on days 220 and 221, discharge decreased markedly and remained low for the remainder of the melt season. Mean discharge at S3 below the Stuphallet cliffs (0.04 $m^3 s^{-1}$) was markedly lower than recorded in the Bayelva basin, draining a much smaller basin area of 0.6 km^2 *cf.* 33.5 km^2 (Table 2). Diurnal peaks associated with high air temperature and SW↓ were superimposed on a gradual decline in discharge over the duration of the monitoring period, although the magnitude of variation (range and std. dev.) was 1-2 orders of magnitude lower for Stuphallet cliffs rivers than at sites in the Bayelva basin.

Seasonal water column temperature dynamics

One-way ANOVA showed water temperature for the Stuphallet cliffs rivers was significantly warmer (mean F=6.09; p<0.05) and more variable (std. dev. F=6.47; p<0.05) than in the glacierized Bayelva basin (Table 3; Table 4; Figure 4; Figure 5). The coldest mean temperature was recorded at A1 and the warmest at S2 (Table 3). Diurnal cycles were evident at all sites but varied in magnitude with water temperature at glacial snouts (sites V1 and A1) exhibiting less variation than those downstream and in non-glacial systems. Meltwater sourced from Austre Brøggerbreen was colder and thermally less variable than from Vestre Brøggerbreen. The longitudinal temperature gradient observed from V1 to V2 (average rise 2.3 ºC) was punctuated by the confluence with the colder Austre Brøggerbreen river, with cooler water temperature recorded downstream at site BR (Table 3). Comparatively flat temperature-duration curves constructed for the entire monitoring period were indicative of thermally-constant conditions at A2, A1 and V1 while steeper curves signified greater thermal variability at other sites (Figure 6). These patterns were also apparent in time-series plots (Figure 7); water column temperatures recorded at sites in close proximity to glaciers exhibited less diurnal variability than those further downstream or in non-glacierized basins.

Local air-water column temperature correlations were consistently stronger than those based on air temperature for Ny Ålesund (Table 5). Correlations were weaker near glacial snouts, particularly at A1, but increased systematically downstream. The comparatively strong air-water relationships for non-glacial fed sites (S2 and S3) did not hold for S1, thus air-water column temperature correlations for the Stuphallet cliffs sites were not always higher than those in the Bayelva basin. Typically, AW↓ and SW↓ were better correlated with water column temperature than air temperature at all sites, while correlations of water column temperature with relative humidity were consistently negative ($-0.06 > r > -0.36$, $p<0.01$) (Table 5). Positive water column temperature-discharge correlations were observed at V1, V2 and BR in the Bayelva basin. The strongest relationship occurred at the glacial snout with a progressive decline in correlation strength downstream. A weak, albeit significant, temperature-discharge relationship was also recorded at S3. Water temperature and discharge plots indicated positive hysteresis at V1, V2 and BR where lower water temperature was associated with the falling limb of the hydrograph (Figure 8). No evidence of water temperature-discharge hysteresis was observed at S3.

Sub-seasonal context

Period 1 – Early melt season with high discharge and warm air temperature (days 190-194)

High mean daily AW↓ (41.7 MJ m^{-2} d^{-1}) and SW↓ (13.9 MJ m^{-2} d^{-1}) was observed in this period close to the summer solstice. Mean air temperature was high during this period (7.4 ºC in Ny Ålesund) with air temperature at site V1 reaching a seasonal maximum of 11.2 ºC on day 190. Precipitation inputs were very low (1.8 mm). Mean discharge was 1.33, 2.73 and 5.54 m^3 s^{-1} at V1, V2 and BR, respectively.

The widest range of instantaneous water column temperature between sites was found during this period, from a maximum of 12.3 ºC at S2 to a minimum of 0.1 ºC at A1. For the majority of sites, mean temperature correlated strongly with SW↓ with air-water column temperature correlations weaker (Table 5). Distinct differences existed between water column temperature at non-glacier fed sites below the Stuphallet cliffs: high mean and maximum temperature at S2 contrasted with lower and less variable temperature at S1 (Figure 9a). Water column temperature at all monitored sites exhibited moderate positive correlations ($0.15 > r > 0.26$, $p<0.01$) with river discharge (Table 5).

Period 2 – Mid-season warm period with increasing discharge, (days 203-207)

Breaks in cloud cover allowed for brief peaks of high SW↓ (max 717 W m^{-2}), although average daily totals s (10.7 MJ m^{-2} d^{-1}) were below the seasonal mean. Air temperature at all sites exceeded the seasonal average by approximately 0.7 ºC. A trace amount of precipitation (0.8 mm) occurred solely on day 207 at the end of the period. Discharge was relatively high, particularly at V1, and diurnal discharge ranges were the greatest of any selected period.

With the exception of BR and S2, mean water column temperature was higher than Period 1 despite lower incoming short-wave radiation and air temperature during this period (Table 2; Table 3). Radiation-water column correlations were lower than Period 1, although air-water column correlations increased (Table 5). A reduction in temperature at S2 and an increase at S1 reduced variability between non-glacier fed rivers compared to Period 1 (Figure 9b). Relatively high minimum water temperature moderated the sub-daily temperature range and contributed to less sub-daily variability at all sites (Table 3; Figure 9b).

Period 3 – Precipitation-influenced cold period with low discharge (days 224-228)

Low mean daily SW↓ (8.5 MJ m^{-2} d^{-1}) caused a significant reduction in mean AW↓ (33.4 MJ m^{-2} d^{-1}) during this period. Although precipitation over the period (5 mm) was relatively high for this arid region, a substantial fraction fell as snow in the early morning of day 224 and on the evening of day 226. Snowfall and reduced radiative inputs were associated with suppressed air temperature and reduced glacial meltwater discharge at all sites in the Bayelva basin. Declines in discharge were less marked at the non-glacier-fed S3.

The coldest water column temperatures occurred during this period (Table 2; Table 3). Daily maximum water column temperature was suppressed, thus temperature ranges were small at most sites with less inter-site variation in comparison to other periods (Table 3; Figure 9c). Despite weak or insignificant relationships between water column temperature and incoming short-wave radiation (Table 5), correlations with local air temperature were significant at all sites and stronger than at any other period($0.69 > r > 0.91$, $p<0.01$). Discharge was strongly correlated with water column temperature at sites in the Bayelva basin, particularly at V1 (r=0.82, p<0.01; Table 5).

Period 4 – Late season warm period with high flows (days 231-235)

Clear skies gave rise to the highest mean daily SW↓ (14.0 MJ m^{-2} d^{-1}) of any period and produced very pronounced sub-daily cycles in SW↓. Air temperature at all sites exhibited a large sub-daily range (0.4 – 11.2 ºC) and reached a seasonal maximum on day 232 (5.9 – 6.7 ºC). Compared with the previous period, discharge increased at sites in the Bayelva basin but not in the Stuphallet cliffs area.

Mean water column temperature was high during this period (Table 3) and large diurnal ranges occurred at most sites (Figure 9d). SW↓-water and air-water column temperature correlations were strong during this period ($=0.3 > r > 0.76$, $p<0.01$). The water column temperature-discharge relationship at site S3 was the strongest of any sub-period (r=0.21, p<0.01; Table 5), although relatively weak when compared to those observed at glacier-fed sites ($0.21 > r > 0.69$, $p<0.01$).

Period 5 – Late season cold period with flow recession (days 238-242)

Mean daily SW↓ (5.6 MJ m^{-2} d^{-1}) during this period was the lowest of the season. Mean air temperature was low at all sites (1.7 – 2.1 ºC) with a relatively low diurnal range (< 4.3 ºC) in comparison with other periods. Discharge was the lowest of any sub-period at all sites and showed limited sub-daily variation. Two precipitation events (days 240 and 242) resulted in a total of 2.8 mm of rainfall during the period (Table 2).

Mean water temperature was among the coldest recorded during the monitoring period (Table 3). Temperature variability (range and std. dev.) was low at most sites, although diurnal cycles remained visible but less pronounced than during Periods 1 and 4 (Table 3; Figure 9e). SW↓-water and air-water column temperature correlations were generally strong (r>0.50, p<0.01 for most sites) with the exception of V1 where water column temperature, in contrast to earlier periods, appeared to be decoupled from meteorological variables. Water column temperature-discharge relationships were positively correlated at V1 and S3 (r=0.15 and 0.65, respectively, p<0.01) but insignificant at V2 and BR (Table 5).

Discussion

The high-resolution data generated by this study have provided new insight into spatiotemporal water temperature patterns within Arctic river basins, and demonstrated the strong influence of hydroclimatological conditions and water source on river temperature regimes. Clear differences in river thermal dynamics are evident across this region of Svalbard: significantly warmer and more variable water temperature regimes occured in non-glacierized basins where flow was maintained principally by meltwater derived from seasonal snowpacks and shallow groundwater, while mean water temperature at glacier-fed sites was lower and more thermally-stable, particularly near the glacier terminus.

Controls on seasonal water temperature dynamics

Mean water temperature, and the relative magnitude of daily thermal variation, were broadly similar to Arctic systems at lower latitudes, although the maximum summer temperature was approximately 9 ºC lower in Svalbard (79°N) than in Alaskan rivers located between 66 - 69 ºN (Irons and Oswood, 1992; Chikita *et al.*, 2010). Water temperature was lower in all of the study rivers when compared with those recorded in alpine environments (Uehlinger *et al.*, 2003; Brown *et al.*, 2005; Cadbury *et al.*, 2008). This finding reflects the reduced magnitude of atmospheric energy inputs (characterised herein by AW↓, SW↓ and air temperature) and strong seasonality experienced in high-latitude regions. Changes in SW↓ accounted for much of the variability in AW↓ and appeared to be the primary driver of water temperature at all sites (*cf.* Joly and Brossard, 2007), and also of glacier meltwater generation in the Bayelva basin as inferred from discharge associations (*cf.* Hodgkins, 2001). The role of SW↓ as a major river heat source is well-documented (Hannah *et al.*, 2008). This is also consistent with the predominantly negative LW↓- and relative humidity-water temperature relationships, because both variables can be viewed a surrogates for cloud cover and SW↓ typically decreases under overcast conditions (Oke, 1987).

In general, water temperature increased longitudinally downstream of the glacier terminus with a 0.7 ºC km^{-1} and 2.3 ºC km^{-1} temperature increase from Austre Brøggerbreen and Vestre Brøggerbreen, respectively. Such longitudinal rises in water temperature are typical of glacial river systems; previously documented increases have ranged from 0.4 – 0.6 ºC km^{-1} (Uehlinger *et al.*, 2003; Cadbury *et al.*, 2008), although on rare occasions have been recorded as high as 7 ºC km^{-1} (Brown *et al.*, 2005; Brown and Hannah; 2008). Buried ice in the proglacial area (Engeset and Weydahl, 1998) could suppress rises in water temperature by modifying riverbed thermal gradient and associated heat exchange (Hannah *et al.*, 2008). High suspended sediment loads in these glacier-fed rivers (Hodson *et al*., 1998) may also affect water column temperature by modifying albedo and increasing short-wave absorption (Han, 1997; Richards and Moore, 2011). Additionally, differences in the rate of temperature increase between the two Svalbard glacier-fed rivers can be explained in part by basin-specific features. Firstly, river discharge between A1 and A2 was confined to a narrow, incised channel that limited exposure to atmospheric influences. In contrast, meltwater from Vestre Brøggerbreen spread laterally across the floodplain between V1 and V2, hence width:depth ratios were high and potential for warming increased (Webb and Nobilis, 1994; Brown and Hannah, 2008). Furthermore, discharge at V1 comprised only a portion of bulk meltwater originating from Vestre Brøggerbreen. Additional lateral drainage channels converge in a shallow lake below the glacial snout before forming a confluence with waters from V1, resulting in increased discharge at V2. Pro-glacial lakes have been identified previously as modifiers of longitudinal temperature profiles in glacial rivers (Burgherr and Ward, 2001; Milner *et al.*, 2001; Moore *et al.*, 2009) with outflow temperatures typically greater than those found in river systems without lakes (Hieber *et al.*, 2002).

Mean water temperature at site BR (2.7 ºC) was 0.5 ºC cooler than at V2, despite being situated 1500 m further downstream. Tributary inputs can interrupt temperature gradients in river systems (Milner *et al.*, 2001; Knispel and Castella, 2003; Brown and Hannah, 2008). In the Bayelva basin, a reduction in mean water temperature between V2 and BR was likely to be attributable to the confluence of the colder discharge from Austre Brøggerbreen with warmer waters from Vestre Brøggerbreen below V2. Additional inputs of extra-glacial waters to the Bayelva river, and their capacity to modify thermal regimes, were considered to be negligible following peak snowmelt in early July given the shallow groundwater system (Roth and Boike, 2001), low basin storage and minimal precipitation that occurred during the monitoring period.

Positive relationships between water column temperature and river discharge were strong with clear diurnal cycles observed in both variables for a greater part of the monitoring period. The temperature-discharge relationship was particularly strong near the snout of Vestre Brøggerbreen where a small and narrow hysteresis loop reflected relatively low variability in both variables. This is a characteristic feature of glacier-fed rivers (Uehlinger *et al.*, 2003) because discharge and water temperature dynamics in these systems are influenced strongly by radiation receipt and air temperature (Hock, 2005; Hannah *et al.*, 2007; Chikita *et al.*, 2010), thus potential diurnal increases in water temperature can be offset by corresponding rises in discharge. The larger, more vertically elongated hysteresis loop at V2 reflected higher variability in water temperature over a relatively low discharge range, and *vice versa* at BR. Stronger temperature-flow hysteresis effects such as these have not been documented previously for glacier-fed rivers, although similar air-water temperature hysteresis relationships are known to occur in larger temperate rivers influenced by inputs from snowmelt which can lead to reduced water temperature despite high air temperature (Webb and Nobilis, 1994; van Vliet *et al.*, 2011). Diurnal differences in timing between peak water temperature (early afternoon) and discharge (early evening) suggest that water temperature responded rapidly to variation in atmospheric controls. However, discharge lagged temperature due to delayed drainage from the Vestre Brøggerbreen glacier (Hodson *et al.*, 1998). Weaker water column temperature-discharge relationships further downstream in the Bayelva basin indicate a lack of additional meltwater inputs downstream of glacial snouts, and a progressive differentiation of discharge and water column temperature dynamics in response to sustained atmospheric exposure.

Non-glacier fed rivers below the Stuphallet cliffs were warmer and exhibited greater thermal variation (diurnal and seasonal) than those in the Bayelva basin. Similar positive associations between mean water temperature and the daily temperature range have also been recorded for Arctic Alaskan rivers (Irons and Oswood, 1992). High mean water temperature and strong diurnal thermal cycles in non-glacier fed rivers are indicative of water derived from shallow hillslope groundwater systems (Kobayashi *et al.*, 1999; Brown *et al.*, 2005). Unlike some rivers in Alaska where flow is often maintained on a perennial basis by spring discharge (Parker and Huryn, 2011), sub-permafrost aquifer discharge on the Brøgger peninsula is thought to be restricted by permafrost aquitards and limited largely to the temperate parts of glacier base areas (Haldorsen *et al.*, 2002) and the exit of a now abandoned coal mine near Ny Ålesund (Haldorsen *et al.*, 2010). Therefore, deeper groundwater-surface water interactions are likely to be limited in the Stuphallet cliffs area, resulting in saturated areas of supra-permafrost standing water where flow velocities are retarded further by abundant vegetation growth. These waters have strong potential for greater atmospheric equilibration. The majority of river discharge in this area is sourced from snowpack meltwater that reaches rivers by near-surface pathways in the shallow alluvial zone rather than as overland flow (supported by field observations). The seasonal decline in discharge at S3 supports this premise as it indicates a decline in source water after snowpack depletion (Malard *et al.*, 1999; Brown *et al.*, 2006). Additionally, relatively high mean electrical conductivity values recorded at S2 are indicative of solute enrichment acquired during flow through shallow alluvial groundwater systems (Malard *et al.*, 1999; Hodson *et al.*, 2002). Greater residence time in the alluvial zone accounts for the weak water column temperature-discharge relationship observed at S3, and also for the higher water column temperature at S2 and S3 due to the prolonged exposure of soil water to atmospheric influence. Cooler mean water temperature at S1 than at other non-glacial sites may be explained by differences in residence times: minimal soil development at Kvadehuksletta towards the western end of the Brøgger peninsula (Hallet and Prestrud, 1986) facilitates rapid runoff of meltwater from cold snowpacks, resulting in a thermal regime bearing closer resemblance to the glacier-fed Bayelva sites compared with areas where organic 'soil' layers are deeper and atmospheric exposure time is greater.

Controls on sub-seasonal water temperature dynamics

Sub-seasonal patterns in river thermal dynamics appeared to be related largely to changes in hydroclimatological variables and relative water source contributions to bulk flow. The weaker relationship of water temperature with both air temperature and river discharge early in the melt season was likely related to the input of cold meltwater from valley snowpacks (Webb and Nobilis, 1994; Brown *et al.*, 2006). River temperature regimes became more responsive to climatological forcing (particularly SW↓) following the loss of river network snowpack cover by the end of July (Malard *et al.*, 1999). Cooler water temperature at all sites in late August coincided with pronounced decreases in SW↓ following the first sunset of summer and the end of the polar day.

Discharge patterns at BR from mid-July to late-August tracked those at V1 and V2 to a greater extent than earlier in the melt season, suggesting a relative (but not absolute) increase in the contribution of glacial meltwater to flow in the lower Bayelva river in late summer. While precipitation inputs were minimal throughout the monitoring season, sub-periods with higher precipitation coincided with lower water and air temperatures. Discharge trends were not affected by precipitation events as documented previously in other glacial basins and elsewhere (Brown *et al.*, 2005; Brown & Hannah, 2007; Chikita *et al.*, 2010), most likely because the volume of precipitation during each rainfall event in Svalbard was much lower than typically experienced in alpine regions (Brown and Hannah, 2007). Such low precipitation inputs are unlikely to have directly induced cooler river temperature by heat advection as noted by Brown and Hannah (2007). However, the presence of cloud cover associated with precipitation events reduces atmospheric energy receipt, thus influencing river thermal regimes (Mohseni and Stefan, 1999).

Conclusion and implications

This study investigated water temperature dynamics, and explored links to controlling hydroclimatological factors, in High Arctic river basins located in north-west Svalbard. High spatiotemporal heterogeneity of water column temperatures were related to river water source and prevailing meteorological conditions (Hypothesis i), and also basin-specific features (specifically channel geomorphology and the presence of lakes), river discharge, and (in the case of glacier-fed rivers) distance from source. A conceptual model summarising the relative influence of these factors on river temperature over a longitudinal gradient is presented in Figure 10a. Non-glacier fed rivers were more hydrologically stable and generally exhibited warmer temperature and higher thermal variability than those fed by glacial meltwater (supporting Hypothesis ii). Mean water temperature and the relative magnitude of daily thermal variation in all rivers exhibited similar patterns to those in Alaska (Chikita *et al.*, 2010; Irons and Oswood, 1992), but were markedly lower than those recorded in alpine environments (e.g. Brown *et al.*, 2005; Cadbury *et al.*, 2008) due to inferred runoff interaction with permafrost and the relatively low magnitude of incoming solar radiation and cooler air temperatures associated with the high-latitude geography of Svalbard (Hypothesis iii). The key differences between Arctic and alpine river thermal regimes at seasonal and sub-daily temporal scales are outlined in Figure 10b.

Projected warming in the Arctic during the 21st Century (Holland and Bitz, 2003; Anisimov *et al.*, 2007; Serreze *et al.*, 2009) is expected to produce an initial increase in glacial meltwater generation in large systems (Fleming and Clarke, 2003; Milner *et al.*, 2009), followed by a long-term decline in discharge as glaciers waste and recede (Barnett *et al.*, 2005). Furthermore, model projections suggest a future reduction in seasonal snow cover and greater number of snow-free days each year (Anisimov *et al.*, 2007), and increased groundwater discharge associated with an increase in the depth of seasonal permafrost thawing (Walvoord and Striegl, 2007). Ultimately, such changes will reduce the absolute and relative contributions of ice and snow meltwaters to total river flow. The results of this study suggest that the coldest and most thermally-stable conditions are found in close proximity to glacial snouts. Thus, future changes in Arctic river temperature regimes are expected to comprise of increased mean water temperature and greater thermal heterogeneity as the proportion of river discharge sourced from meltwater declines (Hannah *et al.*, 2007; Brown *et al.*, 2009; Milner *et al.*, 2009). The greatest increases are likely in late summer and early autumn following melting of seasonal snowpacks (Webb and Nobilis, 1994).

River thermal shifts could affect species diversity and abundance in benthic communities (Milner *et al.*, 2001, Brown *et al.*, 2007; Jacobson *et al.*, 2012) and have implications for rates of ecosystem functioning (e.g. nutrient uptake, leaf litter decomposition) in high-latitude aquatic ecosystems (Friberg *et al.*, 2009). Further inter-disciplinary studies (*cf.* Hannah *et al.*, 2007; Parker and Huryn, 2011) are needed to characterise and explain ecological patterns in relation to physicochemical habitat conditions in high-latitude rivers over multiple spatiotemporal scales. Such research could enable the development of predictive models and facilitate a greater understanding of the response of Arctic river ecosystems to climate change.

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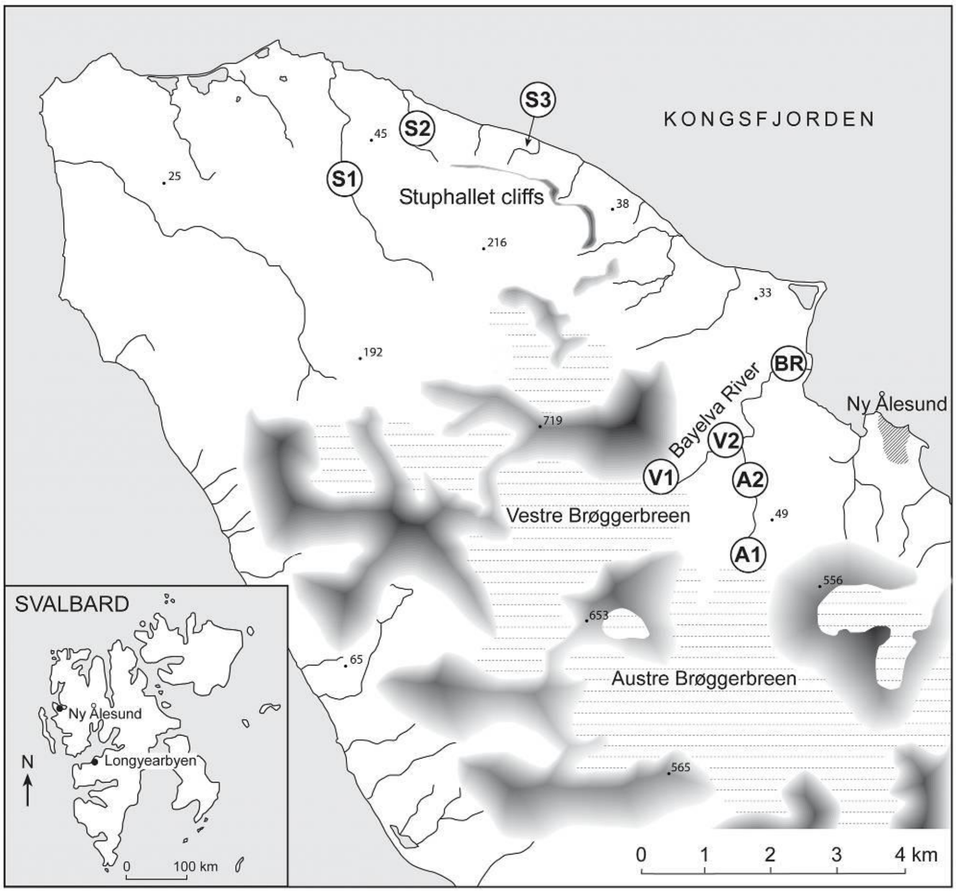
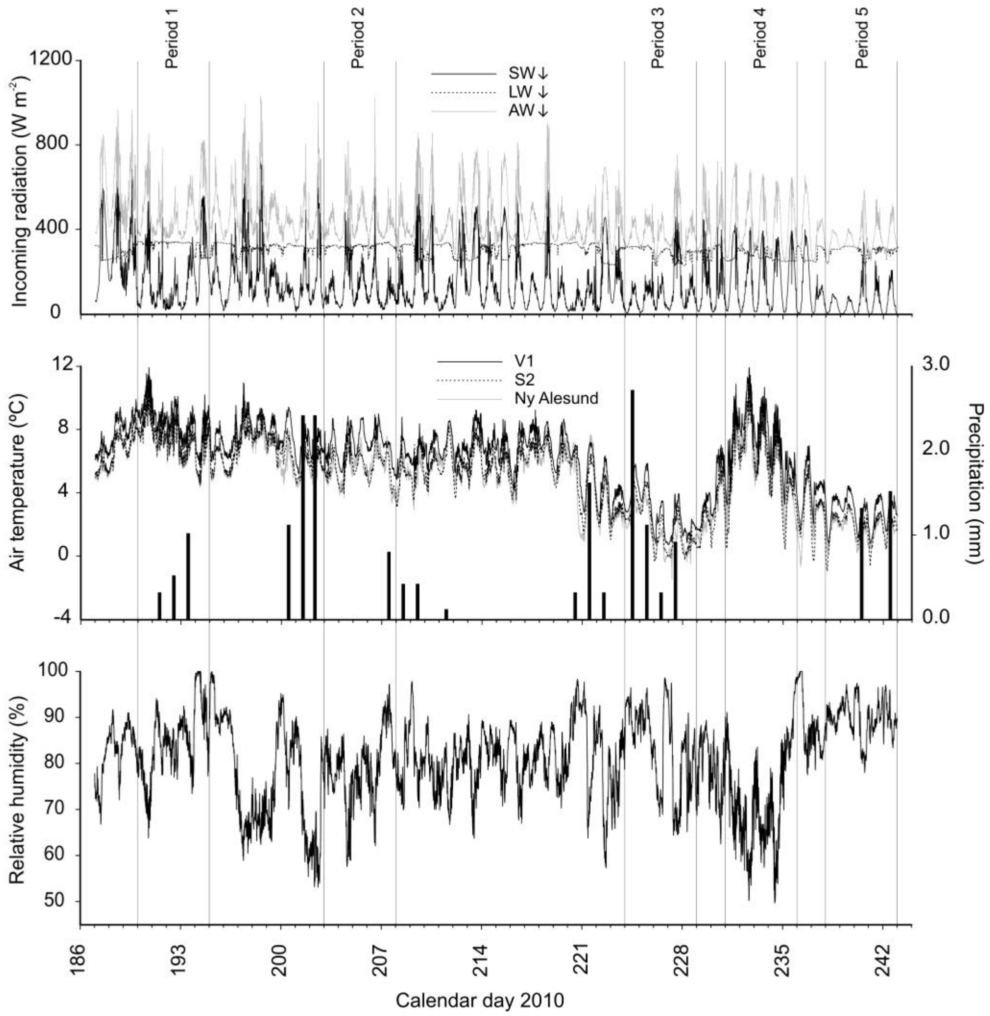
Figures

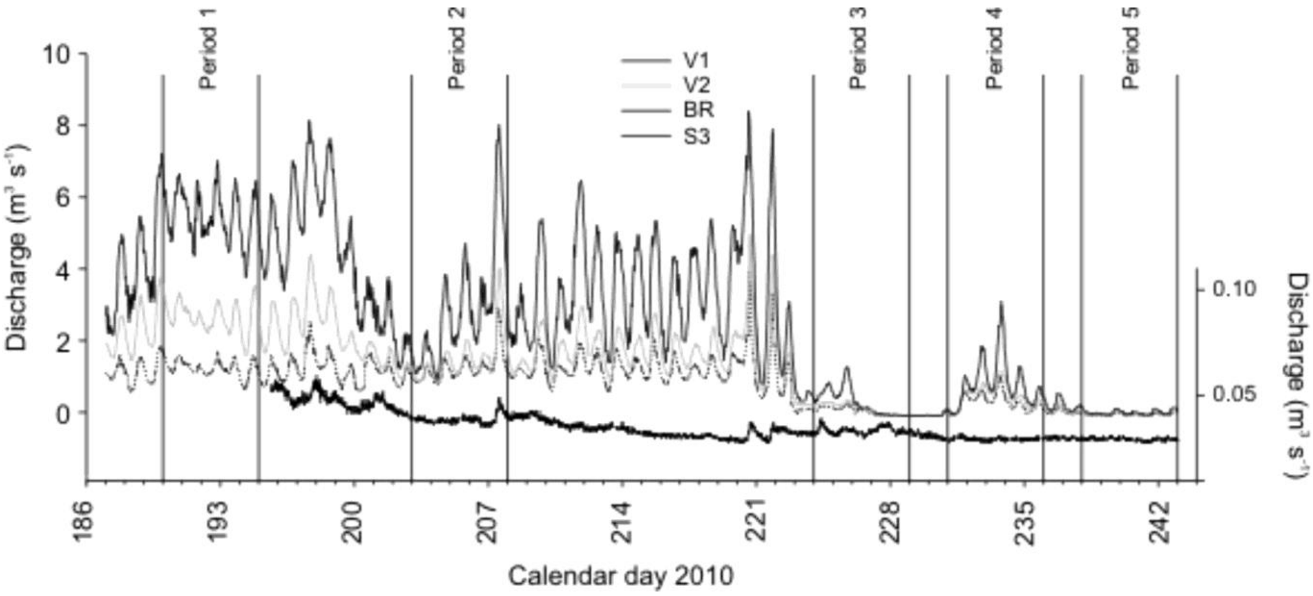
1 – Map of study area showing sampling sites, approximate river courses, relief (shaded), spot height measurements in m, and glacier cover (dashed areas).



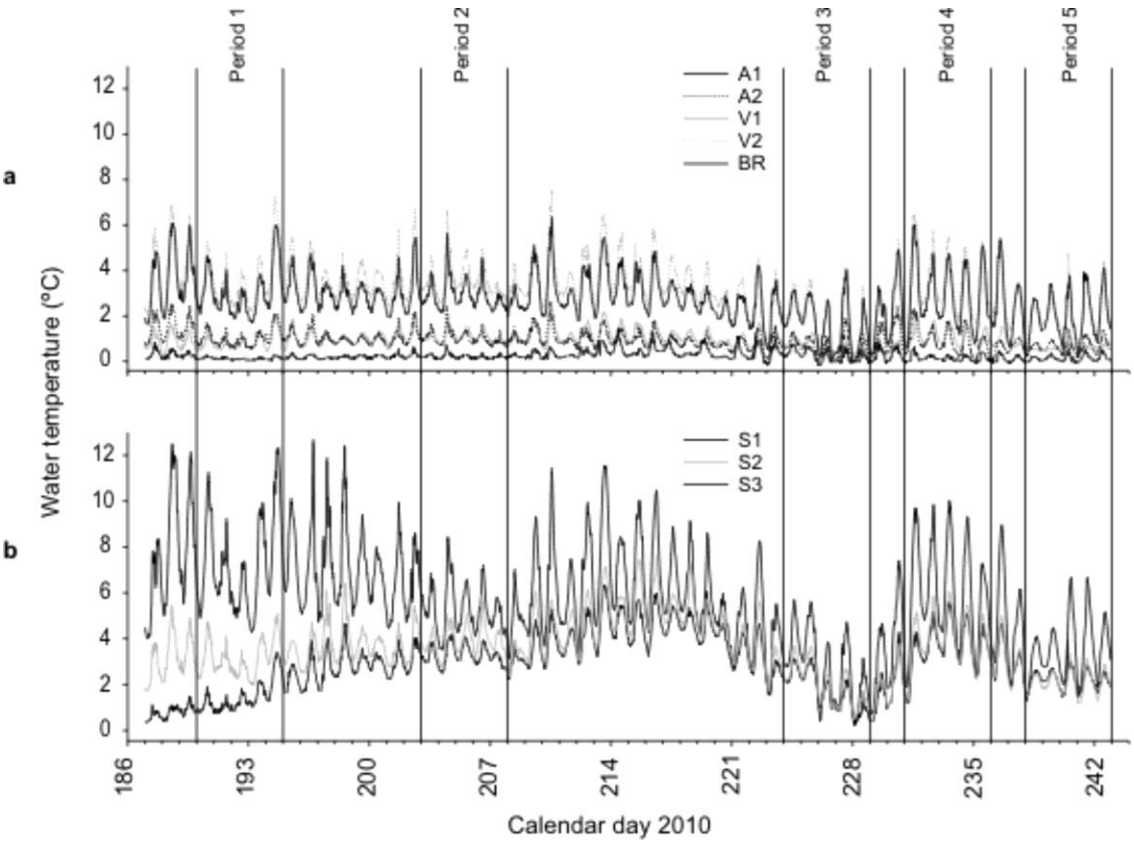
2 –a) Short-, long- and all-wave radiation inputs, b) Air temperature and precipitation inputs, and c) Relative humidity for the 2010 melt season



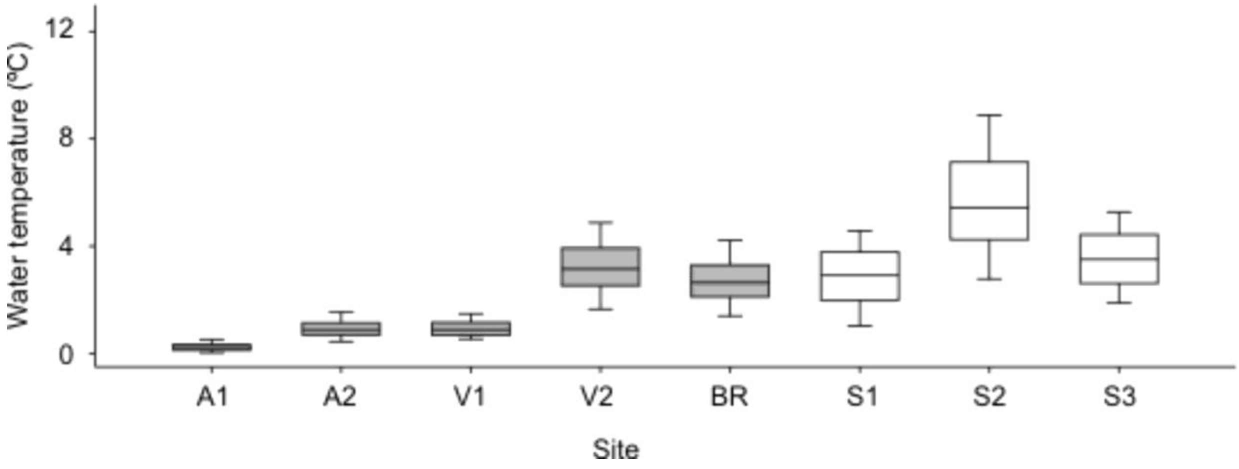
3 –River discharge at sites V1 (Vestre Brøggerbreen snout), V2 (Bayelva river mainstem), BR (Bayelva river mouth) and S3 (Stuphallet cliffs) for the 2010 melt season



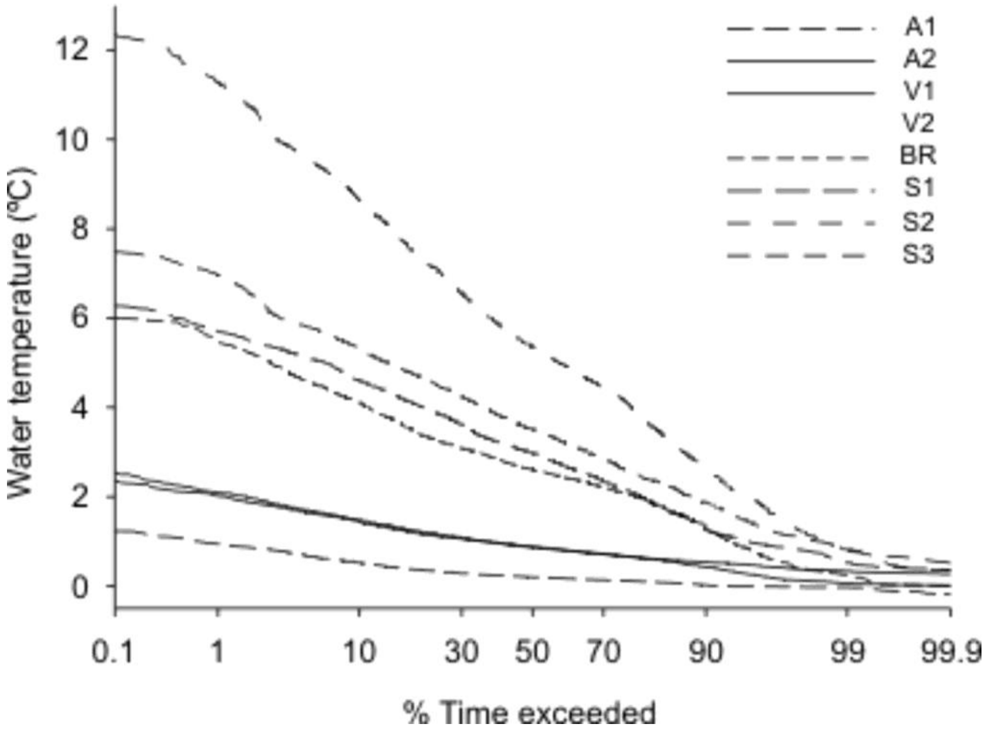
4 – Water column temperature at a) glacier-, and b) non-glacier-fed sites for the 2010 melt season



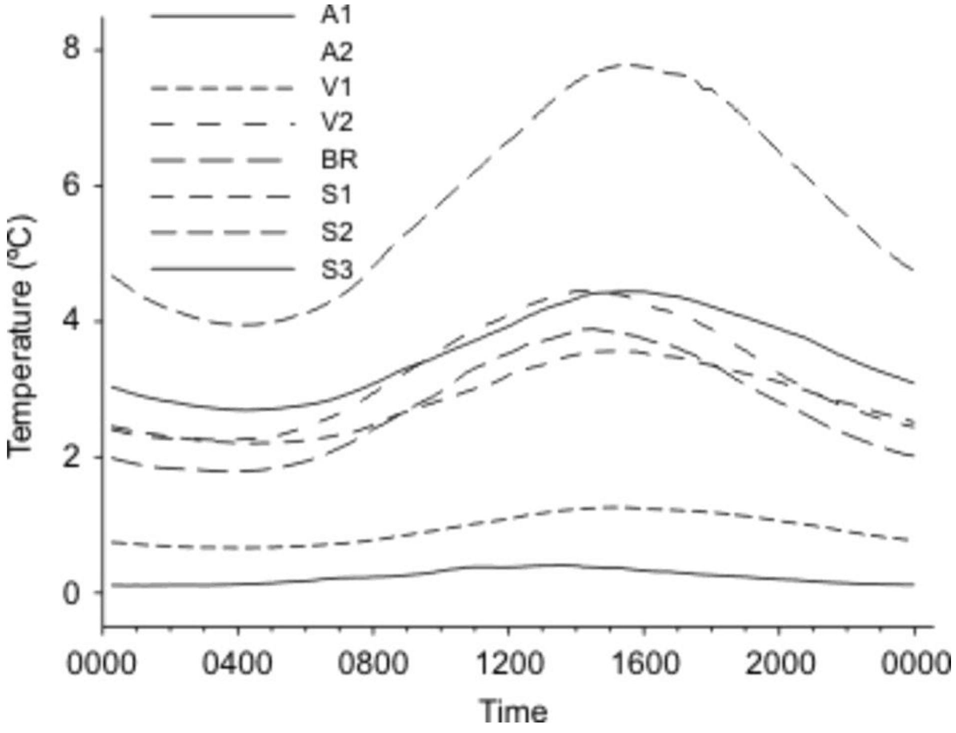
5 – Water column temperature boxplots for glacier-fed (shaded) and non-glacier-fed (unshaded) sites for the 2010 melt season



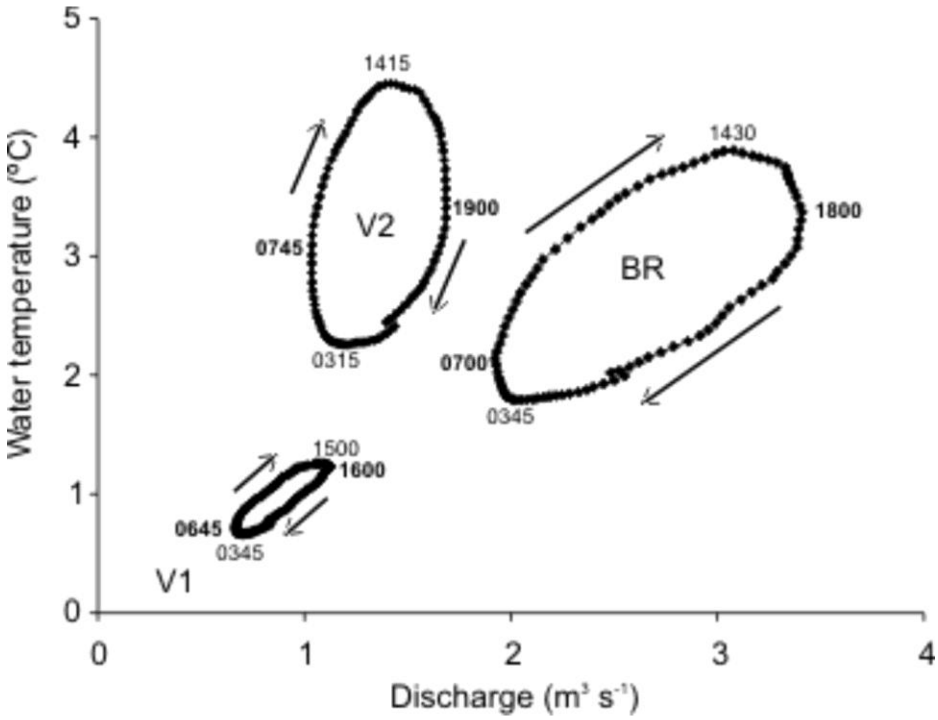
6 – Water column temperature-duration curves for the 2010 melt season



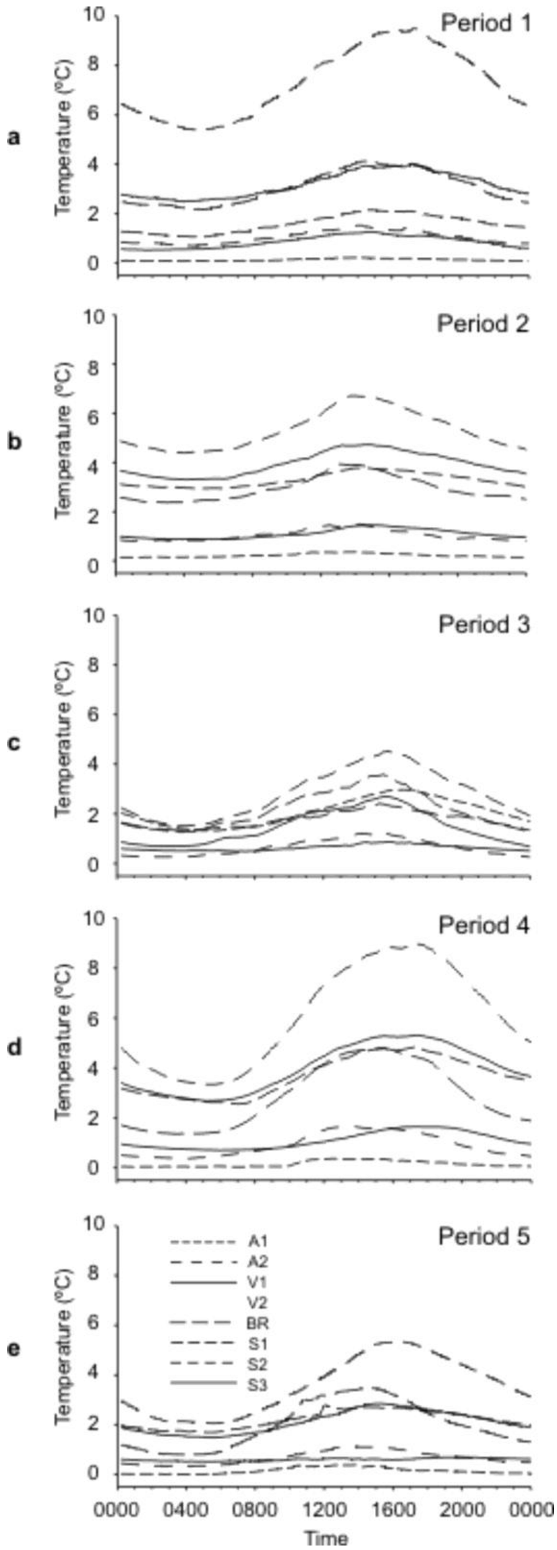
7 – Composite of daily water column temperature dynamics for the 2010 melt season



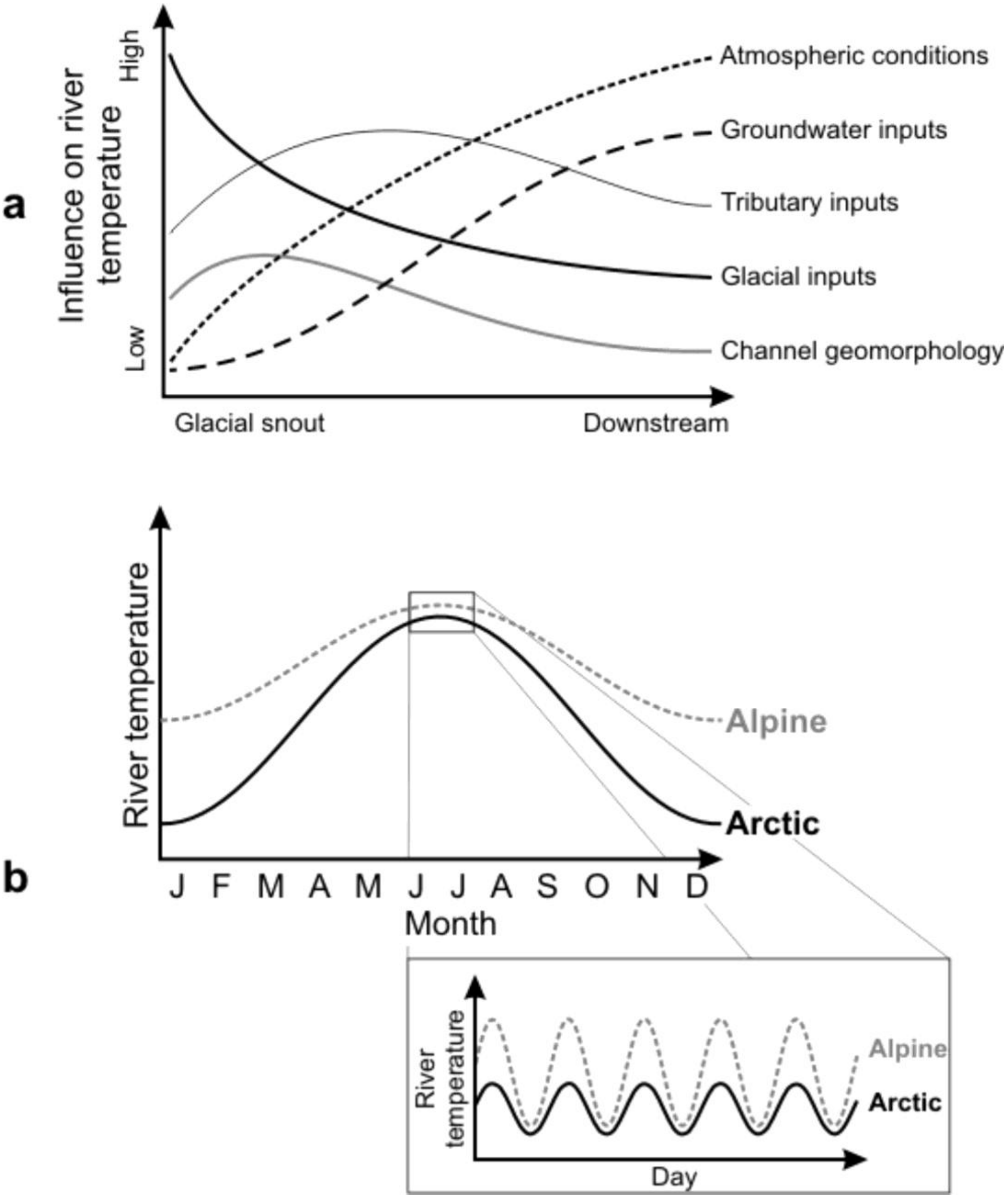
8 – Hysteresis patterns in discharge-water temperature relationships at sites V1 (Vestre Brøggerbreen snout), V2 (Bayelva river mainstem) and BR (Bayelva river mouth) for the 2010 melt season. Time values represent mean maxima and minima for discharge (bold) and water temperature



9 – Sub-seasonal composites of daily water column temperature dynamics for a) Period 1 (days 190-194), b) Period 2 (days 203-207), c) Period 3 (days 224-228), d) Period 4 (days 231-235), and e) Period 5 (days 238-242) for the 2010 melt season



10 – Conceptual models of a) the relative influence of drivers of water temperature over a longitudinal gradient in an Arctic river basin, and b) key differences between Arctic and alpine river thermal regimes at seasonal and sub-daily temporal scales



Tables

1 – Descriptions and major characteristics of monitoring sites

2 – Descriptive statistics for air temperatures (Ny Ålesund, site V1, site S2), incoming short-, long- and all-wave radiation, precipitation, relative humidity, and river discharge (sites V1, V2, BR and S3)

3 – Descriptive statistics for water column temperature at glacier-fed (sites V1, V2, A1, A2 and BR) and non-glacier-fed (sites S1, S2, S3) monitoring sites

4 – One-way ANOVA results of water temperature descriptive statistics between glacier-fed (n=5) and non-glacier-fed (n=3) sites for the 2010 melt season

5 – Correlation coefficients for water temperature relationships with incoming short-, long- and all-wave radiation, air temperature, relative humidity and river discharge

Table 1

Site	*Location*	*Primary source*	*Distance from glacier (m)*	*Catchment area (km^{-2})*	*Aspect (facing)*	*Mean EC ($\mu S\ cm^{-1}$)*
V1	Bayelva	Vestre Brøggerbreen glacier	100	2.1	E	43
V2	Bayelva	Vestre Brøggerbreen glacier	1000	10.2	E	56
A1	Bayelva	Austre Brøggerbreen glacier	100	9.4	N	-
A2	Bayelva	Austre Brøggerbreen glacier	1000	9.7	N	35
BR	Bayelva	Austre and Vestre Brøggerbreen glaciers	2500	33.5	NE	58
S1	Stuphallet	Snowmelt and groundwater	n/a	4.6	N	-
S2	Stuphallet	Snowmelt and groundwater	n/a	0.9	N	120
S3	Stuphallet	Snowmelt and groundwater	n/a	0.6	N	-

Table 2

	Air temperature (NÅ)	Air temperature (V1)	Air temperature (S2)	SW↓	LW↓	AW↓	Precipitation	Rel. humidity	Q			
									V1	V2	BR	S3
	ºC	ºC	ºC	MJ m^{-2} day^{-1}	MJ m^{-2} day^{-1}	MJ m^{-2} day^{-1}	mm day^{-1}	%	m^3 s^{-1}			
*Season (days 187-242)**												
Mean (sum)	4.93	5.41	5.06	12.61	25.97	38.57	(17.00)	80.95	0.89	1.41	2.69	0.04
Max	10.90	11.17	10.80	28.38	29.21	51.79	2.70	100.00	3.94	4.99	8.44	0.06
Min	-1.50	-0.05	-0.95	2.65	22.14	28.99	0.00	49.70	0.00	0.01	0.01	0.03
Range	12.40	11.22	11.75	25.74	7.07	22.80	2.70	50.30	3.94	4.98	8.43	0.03
Std dev	2.32	2.30	2.29	6.07	1.97	5.44	0.61	9.39	0.64	1.07	2.19	0.00
Period 1 (days 190-194)												
Mean (sum)	7.36	7.77	7.40	13.86	27.88	41.74	(1.80)	84.79	1.33	2.73	5.54	-
Max	10.90	11.17	10.80	25.75	29.21	50.62	1.00	100.00	1.80	3.60	7.08	-
Min	4.30	4.83	4.47	6.57	24.87	35.78	0.00	63.80	0.73	1.66	3.83	-
Range	6.60	6.34	6.33	19.18	4.34	14.84	1.00	36.20	1.07	1.94	3.25	-
Std dev	1.18	1.14	1.14	7.60	1.78	5.94	0.42	7.38	0.22	0.41	0.67	-
Period 2 (days 203-207)												
Mean (sum)	5.62	6.32	5.67	10.66	27.51	38.17	(0.80)	79.10	1.33	1.61	3.02	0.04
Max	7.80	8.24	7.87	15.06	28.38	41.26	0.80	97.20	3.02	4.06	8.04	0.05
Min	3.30	4.26	3.88	7.51	26.21	35.54	0.00	57.60	0.85	0.95	1.00	0.03
Range	4.50	3.98	3.98	7.55	2.17	5.73	0.80	39.60	2.17	3.11	7.04	0.02
Std dev	0.98	0.95	0.92	3.05	0.81	2.42	0.36	7.31	0.40	0.65	1.60	0.00
Period 3 (days 224-228)												
Mean (sum)	1.55	2.02	1.88	8.47	24.96	33.43	(5.00)	83.46	0.21	0.29	0.51	0.03
Max	4.20	5.12	4.83	16.23	27.35	38.45	2.70	98.60	1.10	1.27	3.15	0.04
Min	-1.50	-0.05	-0.36	4.89	22.22	30.92	0.00	64.40	0.00	0.01	0.01	0.03
Range	5.70	5.17	5.19	11.34	5.13	7.53	2.70	34.20	1.10	1.26	3.14	0.01
Std dev	1.21	1.42	1.46	4.46	2.07	3.10	1.05	9.20	0.24	0.32	0.62	0.00
Period 4 (days 231-235)												
Mean (sum)	5.93	6.69	5.93	13.96	23.56	37.51	(0.00)	72.25	0.25	0.36	0.61	0.03
Max	10.90	11.17	10.80	15.62	25.26	39.09	0.00	98.70	1.10	1.27	3.15	0.03
Min	0.80	2.47	0.41	12.11	22.24	36.25	0.00	49.70	0.01	0.02	0.03	0.03
Range	10.10	8.70	10.38	3.51	3.02	2.84	0.00	49.00	1.09	1.25	3.12	0.00
Std dev	2.16	1.96	2.39	1.26	1.28	1.12	0.00	10.82	0.24	0.32	0.61	0.00
Period 5 (days 238-242)												
Mean (sum)	1.65	2.06	1.85	5.25	25.86	31.11	(2.80)	89.83	0.03	0.05	0.10	0.03
Max	3.10	3.68	3.32	7.91	27.50	32.25	1.50	97.40	0.08	0.13	0.24	0.03
Min	0.00	0.04	-0.95	2.65	24.26	28.99	0.00	78.00	0.01	0.02	0.03	0.01
Range	3.10	3.64	4.27	5.27	3.23	3.27	1.50	19.40	0.07	0.12	0.21	0.00
Std dev	0.68	0.91	0.87	2.13	1.18	1.47	0.77	3.92	0.02	0.03	0.06	0.00

** S3 discharge data from day 195 to 242*

Table 3

	Site							
	V1	*V2*	*A1*	*A2*	*BR*	*S1*	*S2*	*S3*
Season (days 187-242)								
Mean	0.94	3.21	0.25	0.94	2.72	2.87	5.67	3.55
Max	2.42	7.45	1.43	2.58	6.36	6.29	12.66	7.62
Min	0.23	-0.03	-0.21	0.00	-0.01	0.26	0.23	0.46
Range	2.19	7.48	1.63	2.58	6.37	6.04	12.42	7.16
Std dev	0.37	1.26	0.21	0.43	1.11	1.28	2.33	1.31
Period 1 (days 190-194)								
Mean	0.84	3.56	0.13	1.03	3.01	1.46	7.23	3.14
Max	2.02	7.25	0.29	2.11	6.01	3.39	12.28	5.08
Min	0.43	2.21	0.05	0.55	1.71	0.76	4.28	1.96
Range	1.59	5.04	0.24	1.56	4.30	2.64	8.00	3.12
Std dev	0.35	1.16	0.05	0.37	1.01	0.66	2.02	0.75
Period 2 (days 203-207)								
Mean	1.09	3.62	0.22	1.04	2.93	3.28	5.30	3.94
Max	2.09	6.67	0.74	2.39	5.63	4.17	8.40	5.91
Min	0.71	2.60	0.11	0.61	2.18	2.51	3.50	2.78
Range	1.37	4.07	0.63	1.78	3.46	1.67	4.90	3.12
Std dev	0.26	0.75	0.09	0.29	0.62	0.42	1.03	0.60
Period 3 (days 224-228)								
Mean	0.63	1.81	0.23	0.64	1.65	1.75	2.82	2.03
Max	1.27	4.08	0.77	1.88	4.01	3.15	5.66	3.69
Min	0.24	-0.03	-0.21	0.00	-0.01	0.26	0.23	0.46
Range	1.03	4.11	0.97	1.88	4.02	2.89	5.43	3.23
Std dev	0.25	1.10	0.24	0.43	1.03	0.80	1.46	0.87
Period 4 (days 231-235)								
Mean	1.09	3.49	0.15	0.91	2.86	3.67	6.03	3.97
Max	1.95	6.47	0.61	2.36	5.99	5.64	10.03	6.09
Min	0.57	0.81	-0.03	0.06	0.52	1.18	1.93	1.41
Range	1.38	5.66	0.65	2.30	5.47	4.46	8.10	4.67
Std dev	0.36	1.37	0.14	0.54	1.35	0.98	2.20	1.10
Period 5 (days 238-242)								
Mean	0.60	2.15	0.15	0.67	1.98	2.21	3.55	2.10
Max	0.84	4.71	0.59	1.46	4.10	3.90	6.67	3.33
Min	0.46	0.49	-0.04	0.15	0.23	1.43	1.29	1.17
Range	0.38	4.22	0.63	1.31	3.86	2.47	5.38	2.16
Std dev	0.09	0.93	0.14	0.29	0.98	0.40	1.27	0.48

Table 4

	F	*p*
Mean	6.09	0.05
Maximum	5.09	0.07
Minimum	8.96	0.02
Range	4.38	0.08
Std dev	6.47	0.04

Table 5

Site	*r* SW↓	LW↓	AW↓	Air temperature (Ny Ålesund)	Air temperature (Local)	Relative humidity	Discharge
Season (days 187-242)							
V1	0.50	-0.02 ^	0.54	0.54	0.56	-0.36	0.49
V2	0.67	0.04	0.73	0.67	0.70	-0.32	0.40
A1	0.23	0.02 ^	0.25	-0.03 *	-0.01 ^	-0.06	-
A2	0.69	-0.03 ^	0.73	0.50	0.53	-0.30	-
BR	0.70	-0.01 ^	0.74	0.60	0.63	-0.30	0.39
S1	0.19	0.02 ^	0.21	0.33	0.35	-0.28	-
S2	0.60	0.07	0.66	0.76	0.79	-0.30	-
S3	0.45	0.07	0.50	0.64	0.67	-0.33	0.09
Period 1 (days 190-194)							
V1	0.85	-0.62	0.83	0.12	0.14	0.01 ^	0.22
V2	0.88	-0.60	0.88	0.19	0.22	-0.02 ^	0.15
A1	0.79	-0.49	0.80	0.44	0.45	-0.26	-
A2	0.91	-0.64	0.90	0.23	0.28	-0.05 ^	-
BR	0.87	-0.64	0.85	0.30	0.31	-0.12 *	0.26
S1	0.77	-0.76	0.71	-0.06 ^	-0.07 ^	0.21	-
S2	0.81	-0.66	0.78	0.37	0.41	-0.19	-
S3	0.83	-0.65	0.81	0.31	0.33	-0.14	-
Period 2 (days 203-207)							
V1	0.59	-0.17	0.58	0.58	0.73	-0.63	0.11 *
V2	0.69	-0.16	0.70	0.57	0.68	-0.61	-0.19
A1	0.73	-0.19	0.73	0.25	0.38	-0.34	-
A2	0.74	-0.23	0.73	0.36	0.50	-0.51	-
BR	0.74	-0.17	0.74	0.50	0.63	-0.60	0.04 ^
S2	0.63	-0.16	0.63	0.63	0.82	-0.51	-
S1	0.51	-0.10 *	0.52	0.74	0.87	-0.49	-
S3	0.64	-0.06 ^	0.66	0.64	0.80	-0.38	0.07 ^
Period 3 (days 224-228)							
V1	0.10 *	0.47	0.28	0.67	0.71	0.27	0.82
V2	0.51	0.33	0.67	0.72	0.78	-0.12 *	0.45
A1	0.06 ^	0.56	0.27	0.75	0.76	0.25	-
A2	0.63	0.23	0.76	0.64	0.69	-0.26	-
BR	0.52	0.29	0.67	0.70	0.75	-0.16	0.44
S1	0.12 *	0.52	0.31	0.84	0.91	0.25	-
S2	0.35	0.42	0.53	0.80	0.91	0.05 ^	-
S3	0.20	0.49	0.39	0.83	0.91	0.19	0.17
Period 4 (days 231-235)							
V1	0.30	0.25	0.36	0.57	0.57	-0.38	0.69
V2	0.76	0.09 *	0.81	0.65	0.60	-0.47	0.21
A1	0.70	0.06 ^	0.75	0.48	0.43	-0.31	-
A2	0.74	0.10 *	0.80	0.65	0.60	-0.50	-
BR	0.76	0.06 ^	0.81	0.59	0.53	-0.40	0.23
S1	0.41	0.18	0.46	0.63	0.69	-0.51	-
S2	0.53	0.21	0.60	0.71	0.76	-0.53	-
S3	0.45	0.23	0.52	0.70	0.76	-0.54	0.21
Period 5 (days 238-242)							
V1	0.22	-0.19	0.17	0.10 *	0.26	-0.33	0.65
V2	0.69	-0.01 ^	0.74	0.59	0.69	-0.32	0.09 ^
A1	0.76	-0.03 ^	0.82	0.44	0.53	-0.26	-
A2	0.69	-0.01 ^	0.73	0.39	0.44	-0.32	-
BR	0.70	0.04 ^	0.77	0.64	0.74	-0.28	0.03 ^
S1	0.51	-0.07 ^	0.53	0.68	0.66	-0.44	-
S2	0.51	-0.12	0.51	0.55	0.59	-0.43	-
S3	0.52	-0.09 *	0.53	0.65	0.62	-0.41	0.15

*$p<0.01$ except for * $p<0.05$ and ^ non-significant* *- denotes not measured*

Season: n=5377 for all variables except discharge at S3 where n=4549

Subseason: n=480 for all sites