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DOI:
10.1002/rra.3537

Received: 9 April 2019 | Revised: 9 August 2019 | Accepted: 11 August 2019
DOI: 10.1002/rra.3537

SPECIAL ISSUE PAPER

WILEY

Arctic river temperature dynamics in a changing climate

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Funding information
European Union Seventh Framework Programme, Grant/Award Number: 262693; Natural Environment Research Council (NERC), Grant/Award Number: NE/L501712/1

Abstract

Climate change in the Arctic is expected to have a major impact on stream ecosystems, affecting hydrological and thermal regimes. Although temperature is important to a range of in-stream processes, previous Arctic stream temperature research is limited—focused on glacierised headwaters in summer—with limited attention to snowmelt streams and winter. This is the first high-resolution study on stream temperature in north-east Greenland (Zackenberg). Data were collected from five streams from September 2013 to September 2015 (24 months). During the winter, streams were largely frozen solid and water temperature variability low. Spring ice-off date occurred simultaneously across all streams, but 11 days earlier in 2014 compared with 2015 due to thicker snow insulation. During summer, water temperature was highly variable and exhibited a strong relationship with meteorological variables, particularly incoming shortwave radiation and air temperature. Mean summer water temperature in these snowmelt streams was high compared with streams studied previously in Svalbard, yet was lower in Swedish Lapland, as was expected given latitude. With global warning, Arctic stream thermal variability may be less in summer and increased during the winter due to higher summer air temperature and elevated winter precipitation, and the spring and autumn ice-on and ice-off dates may extend the flowing water season—in turn affecting stream productivity and diversity.

KEYWORDS

Arctic, Greenland, hydrology, meltwater, river temperature, stream, thermal dynamics

1 | INTRODUCTION

In the last 100 years, the rise in air temperature in the Arctic has been substantially more pronounced than the global average (2.9°C compared with 0.8°C; Comiso & Hall, 2014; Overland et al., 2015). This trend of increased air temperature in the Arctic will continue alongside changes in precipitation and permafrost extent (Dyurgerov & Meier, 2000; Foster, Robinson, Hall, & Estilow, 2008; White et al., 2007), affecting both hydrology and thermal regimes (van Vliet et al., 2013) and potentially having large consequences for freshwater ecosystems.

Water temperature influences chemical, physical, and biological processes in all stream ecosystems (Caissie, 2006; Cory, Crump, Dobkowski, & Kling, 2013; McNamara, Kane, Hobbie, & Kling, 2008; Rawlins et al., 2010; Webb, Hannah, Moore, Brown, & Nobilis, 2008). In terms of biochemical and physical processes, higher water temperatures are known to increase weathering (Anderson, 2005) and nutrient uptake rates (Blaen, Milner, Hannah, Brittain, & Brown,

2014). In terms of biological processes, warmer water temperature causes higher metabolic demands of both individuals and ecosystems as a whole (Brown, Gillooly, Allen, Savage, & West, 2004). In Arctic and alpine regions, water temperature is the variable found to best explain macroinvertebrate community composition (Friberg, Bergfur, Rasmussen, & Sandin, 2013) and taxa richness (Castella et al., 2001; Friberg, Milner, Svendsen, Lindegaard, & Larsen, 2001), and increased water temperature can lead to a decrease in beta diversity (Finn, Khamis, & Milner, 2013).

Atmospheric conditions have been identified as having the largest control on water temperature dynamics in streams, particularly solar radiation due to the heat flux at the air–water surface boundary (Caissie, 2006; Evans, McGregor, & Petts, 1998; Khamis, Hannah, Brown, & Milner, 2015) with air temperature being the strongest explanatory variable. Nevertheless, there is evidence that snow depth and local geomorphology influence the relationship between air and water temperature in Arctic regions (Lisi, Schindler, Cline, Scheuerell, & Walsh, 2015). The predicted Arctic-wide increase in air temperature and precipitation and decrease in sea-ice extent by the end of the century (Anisimov et al., 2007; Vaughan et al., 2013) is likely to lead to large changes both in stream temperature dynamics and in the relationship between water temperature and atmospheric conditions. In the Zackenberg area of north-east Greenland, at approximately 60 km from the Greenland ice sheet, studies predict a 60% increase in precipitation (Hinkler, Hansen, Tamstorf, Sigsgaard, & Petersen, 2008; Rinke & Dethloff, 2008; Stendel, Christiansen, & Petersen, 2008) with the proportion falling as rain predicted to increase, affecting the relationship between air temperature and water temperature. Alongside this, air temperatures will likely increase, particularly in winter (Stendel et al., 2008), and there is predicted to be an 8- to 12-cm increase in active layer thickness (Hollesen, Elberling, & Jansson, 2011; Westermann et al., 2015). The increased nivation processes and permafrost degradation associated with these changes will lead to a rise in sediment entering streams and a decrease in channel stability, affecting water retention time and stream albedo (Blaen, Hannah, Brown, & Milner, 2013; Han, 1997; Richards & Moore, 2011), whereas increased snowmelt inputs could act as a buffer on water temperature. The large increase in Arctic air temperature expected during the winter months due to the decrease in sea ice extent (Chapman & Walsh, 2007; Walsh, Overland, Groisman, & Rudolf, 2011) is expected to have consequences on summer stream flow dynamics (Dahlke, Stedinger, Rosquist, & Jansson, 2012), influencing water temperature during peak productivity. This will be through decreases in river ice cover (Vaughan et al., 2013; although this is more relevant to lower arctic regions), changes to snowpack conditions, and increased rain-on-snow events during the winter. Furthermore, an increase in autumn and spring water temperatures will affect stream ice-on and ice-off timing, extending the length of summer stream flow period and highlighting the importance of full year studies on water temperature.

Water temperature dynamics and their importance at high latitudes and in alpine environments have been examined in past literature (Adams, Crump, & Kling, 2010; Blaen et al., 2013; Brown, Hannah, & Milner, 2005; Cadbury, Hannah, Milner, Pearson, & Brown, 2008; Comola, Schaefli, Rinaldo, & Lehning, 2015; Constantz, 1998; Khamis et al., 2015; King, Neilson, Overbeck, & Kane, 2016; Lisi et al., 2015; MacDonald, Boons, Byrne, & Silins, 2014; Madsen et al., 2015; Mellor, Dugdale, Garner, Milner, & Hannah, 2016; Vincent & Howard Williams, 1989). However, previous studies have often focused on areas with a large glacial influence, and there has been no high-resolution research focused on Greenlandic stream temperature dynamics. Furthermore, most existing data from the Arctic focus on the melt season, and Arctic winter stream water temperature dynamics therefore remain largely unknown.

This paper details Greenlandic stream temperature dynamics for the first time and builds on past stream water temperature studies conducted in other Arctic areas. It addresses the paucity of information on temperature dynamics in snowmelt streams, particularly during the winter period. To address this research gap, we compiled a high-resolution water temperature data series over 24 months from streams in north-east Greenland. Through this, we aimed to (a) characterize thermal variability in space and time, (b) infer key controls and processes on stream temperature, and (c) consider the implications of the findings in the context of hydroclimatic change in the Arctic.

2 | METHODS

2.1 | Study area

Field data were collected from around the Zackenberg research station (74°28′N, 20°34′W), within the Northeast Greenland National Park in the high Arctic climatic zone (Figure 1). The region is not connected to the ice sheet, which is located approximately 60 km away. Altitude within the study site varies between sea level and 1,450 m a.s.l. with a glacial plateau occurring above 1,000 m a.s.l. and wide horizontal valleys caused by glacial erosion below (Mernild, Liston, & Hasholt, 2007). The valley is in a zone of continuous permafrost and active layer thickness varies between 0.4 and 0.8 m (Hollesen et al., 2011; Westermann et al., 2015).

The geology is divided by the Zackenberg river and comprises Caledonian gneiss and granite in the west and cretaceous and tertiary sandstones and basalts in the east at higher altitudes of Palnatoke and Aucella mountains. Loose and sometimes well-developed soils (Hasholt & Hagedorn, 2000; Mernild et al., 2007) occupy the valley and lower slopes. Vegetation distribution is largely divided by the area's geology (Elberling et al., 2008). In the west, bog bilberry (*Vaccinium uliginosum*) heath is more abundant, among areas with scattered boulders and fens with high species diversity. To the east, lowland vegetation comprises Arctic white heather (*Cassiope tetragona*) heaths, Arctic willow (*Salix arctica*) snow beds, grasslands, and fens. At higher altitudes, between 150 and 300 m, mountain avens (*Dryas* sp.) heath dominates (Bay, 1998).

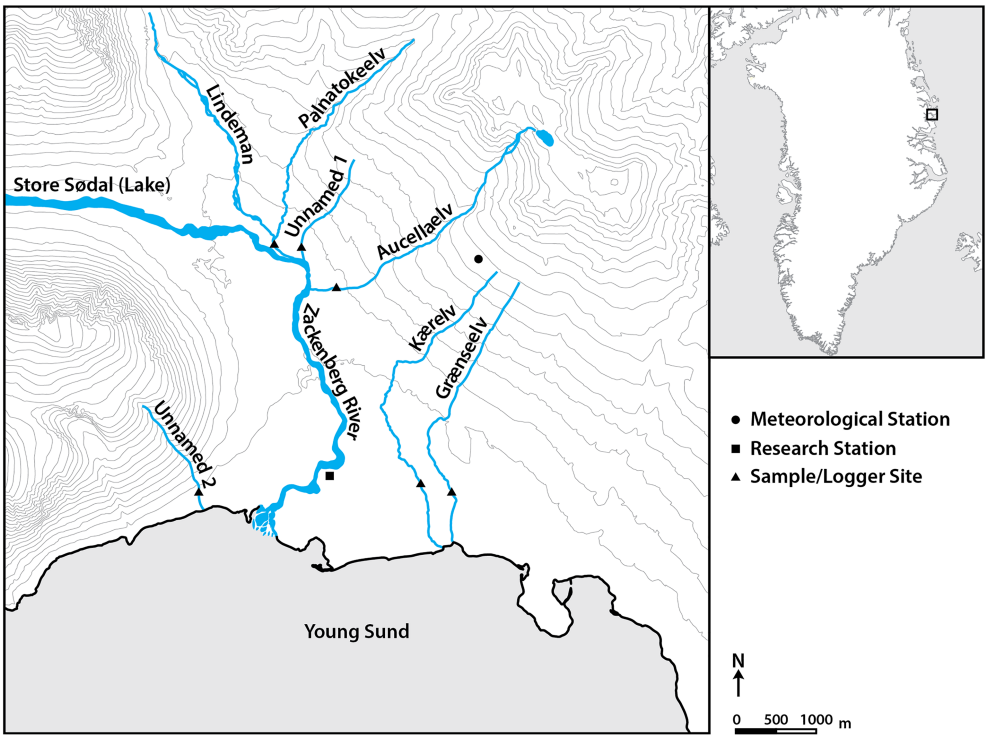

FIGURE 1 Site map and study streams, with contour interval of 20 m [Colour figure can be viewed at wileyonlinelibrary.com]

The mean annual air temperature is −9.1°C. The warmest month is July with a mean air temperature of 5.8°C and the coldest month is February with a mean air temperature of −22.4°C. Annual precipitation is 261 mm and falls mainly as snow (Hansen et al., 2008).

To date, hydrological research in this region has focused on sediment and solute transport of Zackenberg river and the regions streams (Hasholt et al., 2008; Hasholt & Hagedorn, 2000; Ladegaard-Pedersen et al., 2016; Rasch, Elberling, Jakobsen, & Hasholt, 2000), while stream thermal dynamics are unknown.

2.2 | Field sites and stream sampling framework

Six streams were included in the study, of which three (Lindeman, Unnamed1, and Aucellaelv) are located within the Zackenberg valley and are tributaries of the larger Zackenberg river (drainage basin: 512 km^2, 20% glacier cover [Mernild, Hasholt, & Liston, 2008]) that discharges into the Young Sund (Figure 1). The other three (Unnamed2, Kærelv, and Grænseelv) are found alongside the fjord coast and discharge directly into Young Sund. Site selection was restricted by the high mobility and high erosion levels of some streams and the borders of locally protected areas. Nonetheless, sites were chosen to represent the valley floor and low altitude areas.

Water temperature was measured at four sites between September 2013 and July 2014 (Kærelv, Grænseelv, Aucellaelv, and Unnamed2), and four sites between July 2014 and July 2015 (Kærelv, Grænseelv, Aucellaelv, and Unnamed1), although equipment failure at Kærelv caused a gap in the data for this stream between October 2014 and July 2015. A high flow event also caused a loss of data at Grænseelv, Aucellaelv, and Unnamed1, with observations consequently only available for Kærelv during summer 2015. We used Gemini TinyTag Aquatic 2 loggers (stated accuracy of ±0.5°C) covered with radiation shields, which recorded water temperature continuously during the study period (cf. Garner, Malcolm, Sadler, & Hannah, 2014). The loggers recorded temperature every 30 min and were replaced at the start of each field season to ensure long recording. Stream bed temperature

TABLE 1 Site characteristics measured during 2014 field campaign

Site	Approximate distance from source (km)	Altitude (m a.s.l.)	Channel width (m)	Discharge (L/s)	Mean EC (μS cm^{-1})*	Aspect (facing)	Sediment D_{50} (mm)
Kærelv	4.00	47	3.54	151 (n = 1)	36	S	51
Grænseelv	2.57	19	2.96	189 (n = 1)	32	S	33
Unnamed1	3.30	113	9.10	335 (n = 3, σ: 202.7)	42	SW	90
Aucellaelv	4.30	68	6.10	484 (n = 2, σ: 96)	88	SW	95
Unnamed2	2.50	52	1.50	NA	31	S	35
Lindeman	NA	50	10.00	NA	52	S	NA

was measured at three sites (Kærelv, Grænseelv, and Lindeman) using Campbell Scientific 107 temperature probes inserted at depths of 0.05, 0.25, and 0.40 m. The probes were attached to a CR1000 data logger which scanned every 10 s and recorded a mean of these values every 15 min. All sensors were cross calibrated before deployment and internal clocks were synchronized.

In terms of hydromorphic conditions, Kærelv and Grænseelv were composed of stable channels, whereas the other streams were observed to be more dynamic. Aucellaelv was characteristed by its braided, highly mobile stream bed and high suspended sediment load. Site characteristics are presented in Table 1. Stream discharge (measured during the summer field campaigns using the velocity–area method) varied between sites, with the lowest values recorded in Kærelv and Grænseelv during the field campaign in 2014 (151 and 189 L/s, respectively). Unnamed1 showed high variability with the lowest measurement of 181 L/s and the highest of 622 L/s during the field campaign in 2014 (Table 1). Discharge was higher at all sites during the field campaign in 2015 compared with 2014. Streambed sediment size (D50, obtained from measuring the b-axis of 100 clasts) ranged from 33 mm in Grænseelv to 95 mm in Aucellaelv (Table 1).

2.3 | Meteorological observations

Meteorological variables were used to assess atmospheric influences on water temperature. Air temperature and precipitation were obtained from the main climate station located near the research station on the valley floor, close to all streams, other data were obtained from a weather station (hereafter referred to as M3) that is located on the south-west facing slope of Aucella mountain at 420 m a.s.l. and represents atmospheric conditions close to the stream sources (Figure 1). Both weather stations were maintained by the Greenland Ecosystem Monitoring Programme. Data included in this study were air temperature (°C), relative humidity (%), snow depth (cm), incoming shortwave radiation (SWR; W m^{-2}) and incoming longwave radiation (LWR; W m^{-2}), and precipitation (mm). Data were recorded to a CR1000 Campbell Scientific data logger every half-hour; precipitation data were recorded hourly. Table S1 provides details of instrumentation and their specifications.

2.4 | Data analysis

Due to the large quantity of data, the data were analysed at nested temporal scales from longer to shorter durations. Data are presented from the two winter periods although emphasis is placed on summer 2014 because stream temperatures during this period are the most variable and responsive to climatological variables, and also because this data series was the most complete. From the summer 2014 series, five 6-day periods were chosen to describe diurnal variation and to represent the full range of summer climatological conditions the area experiences. Periods were chosen to highlight low and high air temperature and precipitation events throughout the short summer season. These six-day

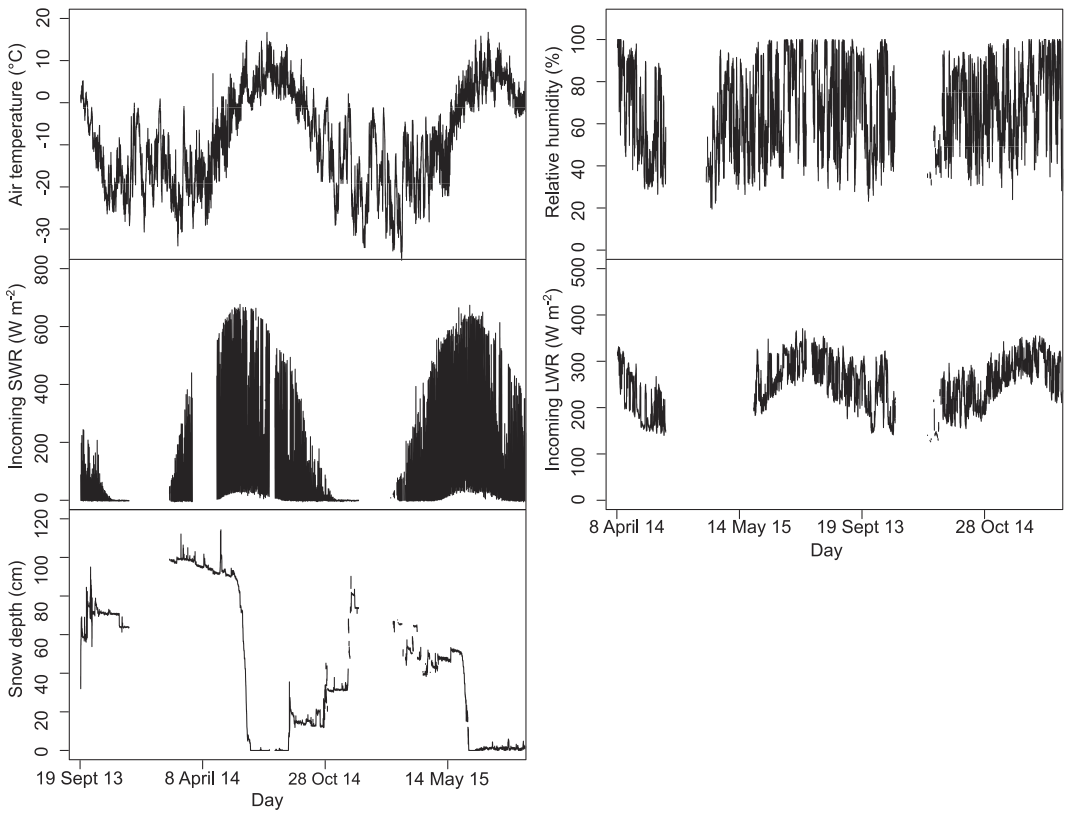

FIGURE 2 Time series of air temperature, relative humidity, incoming shortwave radiation (SWR) and longwave radiation (LWR) and snow depth between September 2013 and September 2015

periods were decided to be a time frame large enough to highlight conditions before and after climatic events. Descriptive statistics were calculated on these six-day periods and used to characterize water temperature and meteorological conditions. One-way analyses of variance (ANOVAs) were undertaken to analyse differences in water temperatures between streams.

Descriptive statistics were also calculated for water temperature and meteorological variables during all time periods to characterize environmental conditions. Temperature duration curves were established for three time periods (September 2013 to July 2014, July 2014 to July 2015, and July 11 to September 15, 2014) to represent the two years' data and to allow for comparison of water temperature variability between streams (e.g., Blaen et al., 2013; Khamis et al., 2015).

For the summer data, autoregressive integrated moving average (ARIMA) models were fitted to assess the relationship between climatological variables and water temperature and to account for serial autocorrelation within the data. Models were fitted in the "Forecast" package (Hyndman, 2016) for *R* between daily-averaged water temperature for each stream and meteorological data. Nagelkerke pseudo-R^2 values were calculated to assess model strength; *p* values are provided to indicate significance of models rather than the covariates themselves. One-way ANOVAs were used to determine differences in water temperature between streams.

TABLE 2 Descriptive statistics for air temperature, relative humidity, snow depth, soil moisture at 10 cm depth, incoming shortwave, and longwave radiation and precipitation during the summer periods

Descriptive statistics	Air temperature	Relative humidity	Snow depth	Soil moisture (10 cm)	Incoming shortwave radiation	Incoming longwave radiation	Precipitation
	°C	%	cm	%	MJ m^{-2} day^{-1}	MJ m^{-2} day^{-1}	mm
Season July 11 to September 15							
Mean	3.7	69.4	6.2	45.6	11.69	25.17	0.0
σ	4.6	18.3	8.0	3.5	6.51	2.73	0.2
Max	15.2	100.0	35.5	47.1	28.03	29.90	1.9
Min	−5.3	29.3	0.0	34.9	2.30	19.08	0.0
July 13–18							
Mean	3.5	91.5	0.0	46.9	6.48	28.21	0.2
σ	1.2	10.2	0.0	0.1	1.36	1.63	0.4
Max	6.4	100.0	0.0	47.1	8.41	29.31	1.9
Min	1.1	55.1	0.0	46.6	5.50	24.62	0.0
July 19–24							
Mean	11.0	55.8	0.0	46.9	22.49	25.72	0.0
σ	2.0	9.9	0.1	0.1	5.57	2.22	0.0
Max	15.2	90.3	0.4	47.1	26.70	29.90	0.0
Min	5.2	35.5	0.0	46.7	12.92	23.28	0.0
August 9–14							
Mean	4.3	67.7	0.1	46.9	14.62	24.99	0.0
σ	3.3	19.1	0.2	0.1	3.33	1.73	0.0
Max	9.3	100.0	1.1	47.0	19.39	27.32	0.0
Min	−2.2	32.9	0.0	46.7	9.91	22.91	0.0
August 22–27							
Mean	2.5	82.5	8.0	47.0	6.23	27.12	0.2
σ	3.6	14.3	9.3	0.1	3.49	1.22	0.3
Max	11.0	100.0	35.5	47.1	13.16	28.10	1.7
Min	−0.7	56.0	0.0	46.7	3.75	24.61	0.0
September 10–15							
Mean	−1.7	62.5	14.5	35.7	7.31	22.65	0.0
σ	2.4	19.5	0.3	0.7	3.12	2.96	0.2
Max	6.6	99.7	15.5	37.8	10.19	27.11	1.3
Min	−4.5	32.4	13.2	34.9	2.30	19.22	0.0

Note. Air temperature and precipitation recorded at Zackenberg Research Station, all other data recorded at meteorological station ME3.

3 | RESULTS

3.1 | Interannual and seasonal meteorological context

The winter of 2013–2014 was cooler (mean of −13.4°C) than winter 2014–2015 (mean of −11.6°C) and received greater snowfall (85 cm vs. 43 cm). In both years, June is the month of peak snow melt and is the first month of the year where mean air temperatures rise above 0°C (June 2014: 3.4°C, June 2015: 4.1°C). In both years, July was the warmest month (mean temperature 2014: 5.6°C, 2015: 7.4°C), with lowest temperatures recorded during February 2015 (−29.7°C; Figure 2). Cooler air temperatures towards the end of the summer period were associated with decreased shortwave and longwave radiation and an increase in snow depth. (Figure 2; Table 2).

There was no observed seasonality in relative humidity throughout the 24-month monitoring period (Figure 2). Precipitation data were not available for January–May 2014; however, for the months when data were available, January 2015 was wettest (112-mm total precipitation) and June 2014 was driest (4-mm total precipitation). Precipitation during the summer monitoring months consisted of short episodic events. A total of 64 mm was measured between July 11 and September 15, 2014, primarily caused by three storm events on July 14–16 (31 mm), August 23–26 (28 mm), and September 15 (4 mm). The precipitation event coincided with a period of low air temperatures (see Period 1; Figure 3; Table 2).

3.2 | Interannual and seasonal stream temperature variability

3.2.1 | Summer period

Streams were found to be highly variable both temporally and between sites in terms of temperature dynamics. During the summer, the warmest mean temperature was recorded in Unnamed1 (5.6°C) and the coldest in Aucellaelv (3.3°C; Table 3). Stream temperature variability (defined as the temperature standard deviation) is similar among all streams apart from Unnamed2, which exhibited higher variability (σ = 5.0). Temperature duration curves showed similarity between streams in thermal regimes while also highlighting some clear differences (Figure 4). For example, the low temperatures experienced by Unnamed2 showed a contrasted thermal regime to other streams in the area. Other streams that displayed atypical trends include Unnamed1, which was found to remain warmer for longer compared with other streams during the same time period, and Aucellaelv, which recorded lower water temperatures than other streams during summer 2014 (Figure 4). Diurnal temperature oscillations were evident for all sites during the summer months (Figure 5). During this period, water temperatures were frequently found to be higher than air temperature in all four streams.

ARIMA models showed stream water temperature to be significantly correlated with air temperature, relative humidity, incoming shortwave radiation and precipitation for all streams, and incoming longwave radiation in Kærelv and Grænseelv (Table 4). For the summer period, all streams were significantly different from one another in relation to water temperature except for Kærelv and Unnamed1 (Table 5). A strong correlation was observed between water temperature and stream bed temperature at 0.05 m for all three streams monitored (r = between .977 and .999), which remained significant with increasing depth though with reduced correlation strength. At 0.40 m, Aucellaelv showed the highest correlation (r = .709), Kærelv showed a correlation of .596, whereas Lindeman had the lowest (r = .393) with bed temperatures of 0.0°C at the start of the monitoring period but that increased to 3°C by the end (Figure 6).

3.2.2 | Winter period

Winter data were available between September 2013 to May 2014 and September 2014 to May 2015 (Table S2). The winter season in

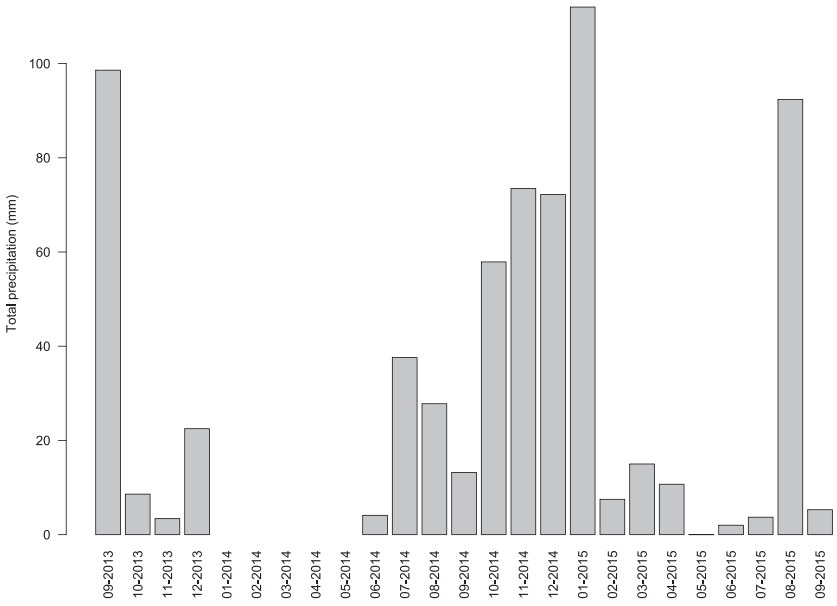

FIGURE 3 Monthly precipitation during the study period recorded at the Zackenberg Research Station meteorological station

TABLE 3 Descriptive statistics for water column temperature from four streams during the summer periods, 2014 (°C)

Descriptive statistics	Kærelv	Grænseelv	Aucellaelv	Unnamed1
Season July 11 to September 15				
Mean	5.4	4.8	3.3	5.6
σ	3.6	3.1	2.5	3.6
Max	14.0	12.8	10.1	14.9
Min	−0.1	0.0	−1.0	−1.9
Period 1: July 13–18				
Mean	5.1	4.0	2.7	5.2
σ	1.6	1.6	1.8	1.9
Max	10.0	8.3	9.0	11.0
Min	2.8	2.2	0.6	2.9
Period 2: July 19–24				
Mean	8.9	7.3	4.8	9.8
σ	2.9	2.6	1.6	3.0
Max	13.7	11.6	7.7	14.9
Min	2.9	2.1	1.5	3.0
Period 3: August 9–14				
Mean	7.4	6.9	4.7	7.1
σ	2.5	2.5	2.3	0.9
Max	12.5	12.1	9.6	9.7
Min	3.6	3.2	1.8	5.8
Period 4: August 22–27				
Mean	4.7	4.5	3.0	4.7
σ	2.5	2.3	2.2	2.8
Max	12.4	12.0	10.1	12.4
Min	2.0	1.9	0.5	0.8
Period 5: September 10–15				
Mean	0.2	0.2	0.3	0.3
σ	0.2	0.2	0.9	2.0
Max	1.1	1.2	4.4	10.0
Min	−0.1	0.0	−0.5	−1.9

2014 began with a large decrease in water temperature around September 27 before subsequently increasing and then stabilizing over winter due to the frozen water being less susceptible to diurnal fluctuations and due to the insulating effect of snow. At the end of the winter season, the time of spring flow resumption was 11 days later in 2015 (June 8) compared with 2014 (May 28) but occurred at a similar time in all streams and was represented by a sudden increase in water temperature.

All streams were frozen to the bed during winter, although Unnamed2 may have flowed intermittently during milder episodes (Figure 5). Therefore, all data presented are ice temperatures, not flowing water. Compared with the summer period, this meant that stream temperature during winter showed minimal diurnal variability and did not respond to fluctuations in meteorological variables in Grænseelv, Aucellaelv, Unnamed1, and, to a lesser extent, Kærelv (Figure 7). However, water temperature did indeed display some variability in Kærelv between October 30 and December 27, 2013. Water temperature in Unnamed2 fluctuated throughout the whole of winter 2013–2014, where it was significantly more variable than other streams (max: $F(1,2) = 46.02$, $p = .021$; min: $F(1,2) = 23.93$, $p = .039$; σ: $F(1,2) = 46.998$, $p = .020$), recording both higher maximum and lower minimum temperatures. Data are available for two winter periods for Grænseelv and Aucellaelv. Whereas Grænseelv displayed no significant differences between the 2 years, water temperature at Aucellaelv was significantly cooler during winter 2013–2014 compared with winter 2014–2015 ($F(1,14) = 5.484$, $p = .035$).

3.3 | Subseasonal stream temperature variability

Due to the large data set, five time periods of 6 days were selected to highlight climatological events experienced across the summer season in order to examine diurnal patterns of water temperature. These represent a combination of warm and dry, cold and wet, and cold and dry climatological conditions representative of the early, mid, and late summer season (Figure 8).

3.3.1 | Period 1: Early season low air temperatures with high precipitation (Days 194–199, July 13–18, 2014)

Relatively low mean incoming SWR (130 W m^{-2}) and the highest mean incoming LWR (326 W m^{-2}) define this snow-free period along with the highest precipitation inputs (total 32 mm) and the highest mean relative humidity (91%) of all periods. Mean air temperature was low (3.5°C). The mean water column temperature was below the summer average in all streams, with Aucellaelv exhibiting a particularly low temperature (2.7°C) in relation to the other streams (between 4.0°C and 5.2°C). The one-way ANOVA results revealed Aucellaelv to have a significantly different thermal regime to all other streams (Table 5).

3.3.2 | Period 2: Early season warm and dry period (Days 200–205, July 19–24, 2014)

The highest mean incoming SWR (255 W m^{-2}) was observed during this period due to clear skies along with high mean incoming LWR (301 W m^{-2}). There was no recorded precipitation and low mean relative humidity (56%) persisted. This period had a mean air temperature of 11.0°C and recorded the highest temperature during summer (15.2°C).

Mean water temperatures were observed to be above the summer average. Indeed, Unnamed1 recorded the highest summer water temperature during this period (14.9°C). Kærelv and Grænseelv also recorded high temperatures (max: 13.7°C and 11.6°C, respectively). Mean water temperature was lower in Aucellaelv (4.8°C) compared with other streams (between 7.4°C and 9.8°C) as was variability (σ: 1.6 compared with between 2.6 and 3.0). Water temperature was significantly different between all streams (Table 5).

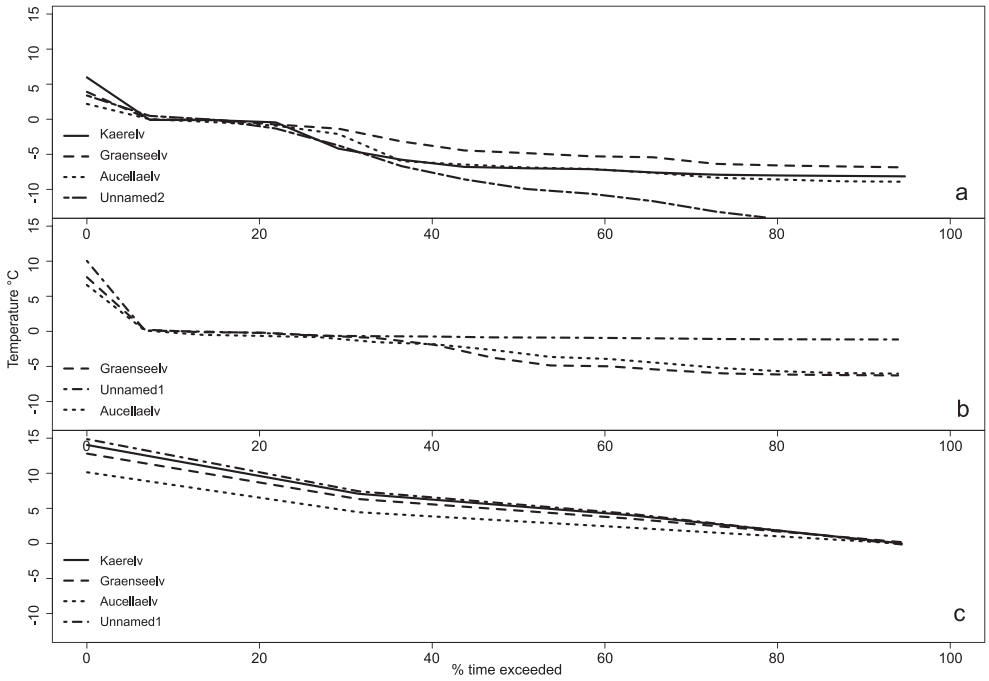

FIGURE 4 Temperature duration curves (a) Sept 2013 to July 2014, (b) July 2014 to July 2015, and (c) July 11 to September 15, 2014

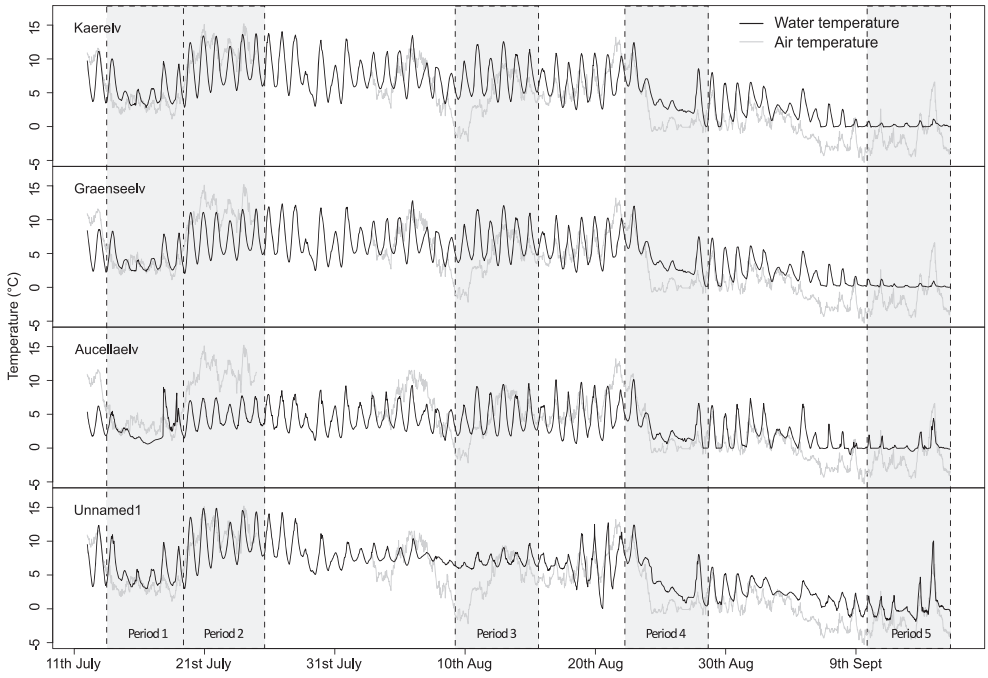

FIGURE 5 Time series for the study summer season July 11 to September 15, 2014, with six-day periods highlighted. Periods are ordered to place similar conditions together as opposed to chronologically

3.3.3 | Period 3: Midseason mild and dry period (Days 200–205, August 9–14, 2014)

A mean incoming SWR of (196 W m^{-2}) and a low incoming LWR (289 W m^{-2}) define this period. There were no precipitation inputs during these 6 days and mean relative humidity was 67%. Mean air temperature for this period (4.3°C) was higher than the summer mean (3.7°C). Mean water temperature was also above the summer average during this period. Strong significant differences in temperature between Kærelv and Aucellaelv, Grænseelv and

TABLE 4 ARIMA models fitted between daily averages of stream water temperature recorded in four streams during the summer period and meteorological variables

Stream		Air temperature	Relative humidity	Snow depth	Incoming shortwave radiation	Incoming longwave radiation	Precipitation
Kærelv	Slope	0.289	−0.023	0.029	0.008	−0.008	−4.867
	Nagelkerke pseudo-R^2	.343	.456	.353	.549	.399	.246
	p value	**<.001**	**.004**	.683	**<.001**	**.035**	**<.001**
Grænseelv	Slope	0.254	−0.019	0.006	0.006	−0.007	−4.142
	Nagelkerke pseudo-R^2	.329	.454	.341	.508	.382	.222
	p value	**<.001**	**.005**	.924	**<.001**	**.049**	**<.001**
Aucellaelv	Slope	0.232	−0.016	0.000	0.005	−0.004	−3.968
	Nagelkerke pseudo-R^2	.296	.342	.255	.370	.272	.233
	p value	**<.001**	**.026**	.996	**.002**	.263	**<.001**
Unnamed	Slope	0.311	−0.029	−0.001	0.006	−0.006	−5.846
	Nagelkerke pseudo-R^2	.344	.410	.266	.373	.290	.309
	p value	**<.001**	**.001**	.993	**.002**	.171	**<.001**

Note. Bold values = significant correlations.

Aucellaelv, and Unnamed1 and Aucellaelv were observed, with weaker (but still significant differences) recorded between Kærelv and Grænseelv (Table 5). Aucellaelv had a substantially lower mean water temperature compared with other streams that had similar water temperatures (4.7°C compared with between 6.9°C and 7.4°C).

3.3.4 | Period 4: Late season low air temperatures, high precipitation, and high snow cover (Days 234–239, August 22–27, 2014)

This period received the lowest mean incoming SWR of all the periods (81 W m^{-2}) due to cloud cover and being further from summer solstice, and the second highest incoming LWR (314 W m^{-2}). There were high precipitation inputs (28 mm), high relative humidity (82%), and a high maximum snow depth compared with other periods (36 cm), marking the end of the summer season. Air temperature during this period was cold, with a mean temperature of 2.5°C. Mean water temperatures were low during this period (between 3.0°C and 4.7°C) and below the summer average, with minimum temperatures between 0.5°C and 2.0°C. Aucellaelv and Unnamed1 had significantly lower minimum temperatures compared with Kærelv and Grænseelv (Table 5).

3.3.5 | Period 5: End of season cold period with low precipitation and declining soil moisture (Days 253–258, September 10–15, 2014)

The mean incoming SWR during this period was very low (85 W m^{-2}), and the mean incoming LWR was the lowest of all periods (262 W m^{-2}). Precipitation inputs totalled 4 mm and were combined with low relative humidity (62%) and a maximum snow depth of 16 cm. The coldest mean air temperature of all periods was recorded (−1.3°C). Water temperature was also coldest during this period, with minimum temperatures being close to freezing (between 0.0°C and −0.5°C). During this period, Kærelv and Grænseelv had significantly lower water temperatures. Compared with other periods, there is little difference in water temperature between streams, with the only significant differences being between Kærelv and Grænseelv, and Kærelv and Aucellaelv (Table 5).

4 | DISCUSSION

4.1 | Interannual and seasonal patterns and controls on water temperature variability

The streams at Zackenberg demonstrated high temperature variability both temporally and between streams. Water temperature in all streams at Zackenberg demonstrated a high degree of coupling with meteorological variables during the summer months, but not during the winter. However, winter meteorological conditions appeared to influence summer stream thermal habitat. During summer 2013, all streams experienced low flows with channels drying out at some sites after an unusually dry winter with minimal snowfall. This indicates the importance of snow as a water source for the region's streams and highlights the importance of winter snowfall on summer stream characteristics. High snow depth in spring 2014 led to increased insulation of streams. This, combined with 2 days of positive air temperatures and high incoming SWR, caused the earlier onset of spring ice-off compared with 2015, where shallower snow depth led to higher air–water temperature coupling, preventing ice-off until later in the season even though air temperature was above 0°C.

The presence of the 200- to 300-m deep permafrost layer (Christiansen, Sisgaard, Humlum, Rasch, & Hansen, 2008) prevents surface water interaction with deep groundwater, and during peak snowmelt (June–July), this leads to poor drainage and allows standing water to accumulate in fen areas and local depressions. These shallow, clear pools of standing water are heated through incoming solar radiation,

TABLE 5 One way analysis of variance results for water temperature differences between streams (DF(1, 6358) for all analyses)

	Kærelv		Grænseelv		Aucellaelv		Unnamed1	
Stream	***F***	***p***	***F***	***p***	***F***	***p***	***F***	***p***
Season July 11 to September 15								
Kærelv			**46.08**	**<.0001**	**743.844**	**<.0001**	2.31	.128
Grænseelv					**459.262**	**<.0001**	**70.57**	**<.0001**
Aucellaelv							**844.29**	**<.0001**
Unnamed1								
Period 1: July 13–18								
Kærelv			**53.44**	**<.0001**	**256.04**	**<.0001**	1.13	.287
Grænseelv					**91.41**	**<.0001**	**68.78**	**<.0001**
Aucellaelv							**281.98**	**<.0001**
Unnamed1								
Period 2: July 19–24								
Kærelv			**52.59**	**<.0001**	**437.37**	**<.0001**	**12.524**	**<.001**
Grænseelv					**437.37**	**<.0001**	**116.78**	**<.0001**
Aucellaelv							**599.57**	**<.0001**
Unnamed1								
Period 3: August 9–14								
Kærelv			**3.95**	**.0473**	**173.28**	**<.0001**	3.48	.0625
Grænseelv					**124.99**	**<.0001**	0.61	.436
Aucellaelv							**260.41**	**<.0001**
Unnamed1								
Period 4: August 22–27								
Kærelv			0.68	.411	**72.56**	**<.0001**	0.06	.806
Grænseelv					**63.52**	**<.0001**	1.04	.308
Aucellaelv							**66.80**	**<.0001**
Unnamed1								
Period 5: September 10–15								
Kærelv			**5.73**	**.0169**	**6.87**	**.008**	1.80	.181

(Continues)

TABLE 5 (Continued)

	Kærelv		Grænseelv		Aucellaelv		Unnamed1	
Stream	***F***	***p***	***F***	***p***	***F***	***p***	***F***	***p***
Grænseelv					2.99	.084	0.87	.350
Aucellaelv							0.02	.883
Unnamed1								

Note: Bold indicates statistically significant difference between streams.

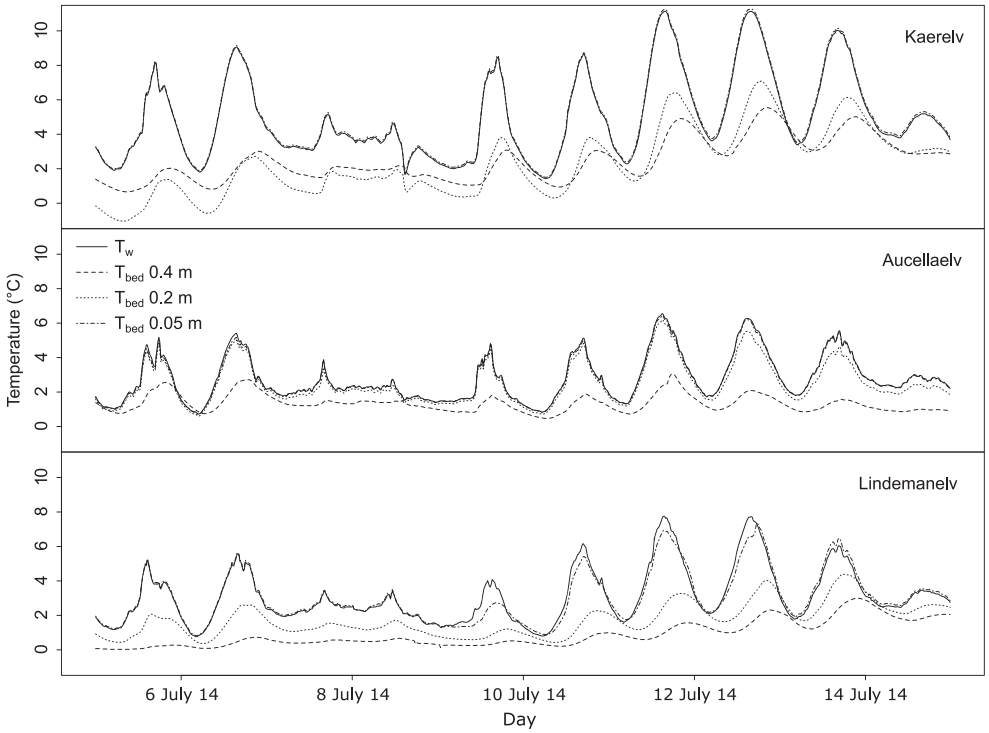

FIGURE 6 Time series of stream water column and bed temperature for Kærelv, Aucellaelv, and Lindeman between July 5 and 14, 2014

prior to flowing into streams, which acts to raise stream temperature above air temperature. This likely explains our unexpected finding that water temperatures recorded during the summer months were frequently warmer than air temperature. As water temperature was higher than air temperature in all four streams, it is extremely unlikely that this finding results from sensor error and, instead, represents the first documented observation of this unusual phenomenon.

The high variability and low temperatures exhibited by Unnamed2 could be due to two reasons. First, Unnamed2 lies on crystalline bedrock, whereas the other streams flow over sedimentary rock and soils. Crystalline rocks generally have a higher thermal conductivity than sedimentary rocks (Drury, 1987; Midttomme & Roaldset, 1999), which, given the thick permafrost layer, will lead to increased bed heat flux away from the stream and thus drive cooler water temperatures. Second, Unnamed2 had a steeper gradient than the other streams, which were located within wide valleys. This gradient resulted in increased shading and a shorter surface residence during the summer months which, in combination with Unnamed2's higher altitude source, maintained water temperatures low. Furthermore, the steeper gradient meant that snow was unable to develop deep cover during winter due to high wind exposure, preventing insulation by ice/snow cover and rendering Unnamed2 more sensitive to climatic forcing.

The colder water temperatures that characterized Aucellaelv compared with other streams may be due to either the comparatively large upstream snowpack driving increased meltwater inputs compared with other streams (resulting in lower thermal coupling between water and air temperature; Lisi et al., 2015) or to the poorly developed unconsolidated soil in the area, leading to shorter residence times and faster meltwater run-off (Blaen et al., 2013). The sensitivity of stream thermal dynamics to snow melt inputs is highly variable over seasonal and annual timescales, and alone, not a valuable indicator of future stream thermal dynamics (Arismendi, Safeeq, Dunham, & Johnson, 2014; Lisi et al., 2015).

4.2 | Subseasonal stream temperature variability

The subseasonal periods highlighted the impact of meteorological events on water temperature dynamics. Low air temperature and rainfall events resulted in reduced water temperature and diurnal variability, something that has been noted in other alpine and arctic studies (Blaen et al., 2013; Brown et al., 2005; Brown & Hannah, 2007; Mellor et al., 2016). Rainfall is thought to reduce water temperature in these systems by melting snow and, consequently, increasing meltwater inputs to streams (e.g., Cadbury et al., 2008; Smart, Owens, Lawson, & Morris, 2000). In these high latitude regions, this process likely impacts stream thermal dynamics to a greater extent than the influence of direct advective heat transfer from rain to streams.

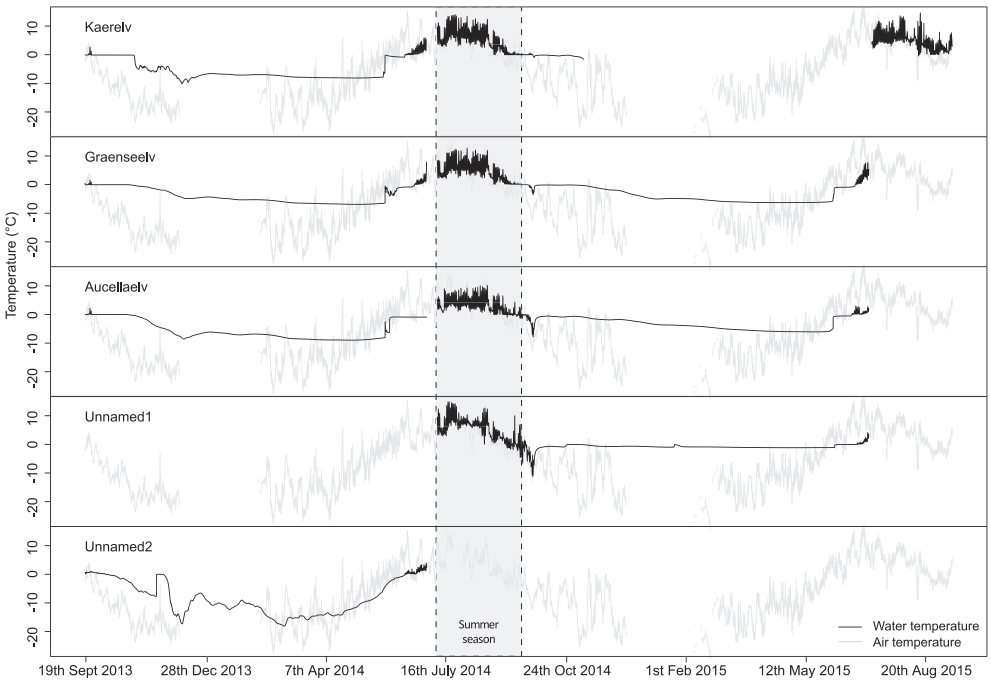

FIGURE 7 Time series of water temperature for all streams during 24-month study period. The study summer season is highlighted

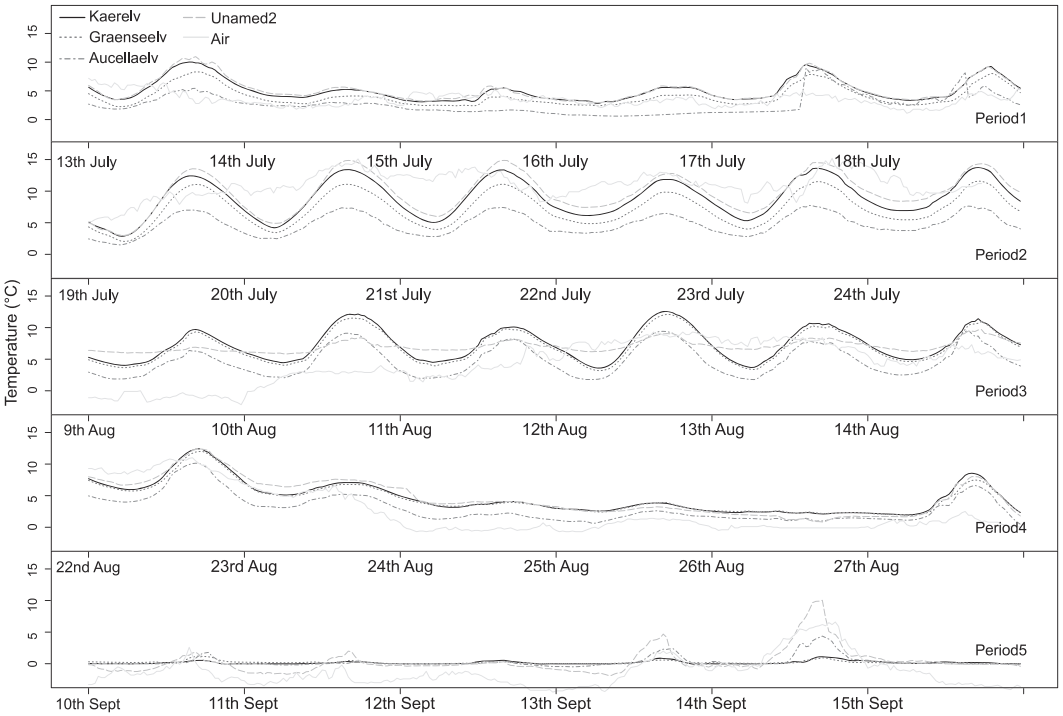

FIGURE 8 Time series of stream temperature during subseasonal periods in 2014

Early in the summer season, water temperatures were predominantly controlled by the large snow melt inputs (Brown, Hannah, & Milner, 2006; Blaen et al., 2013) where the advective fluxes from these cold water inputs exceed surface energy exchanges (Leach & Moore, 2014; Lisi et al., 2015). Coupling of water and air temperatures is known to increase towards the end of summer with the decrease in meltwater inputs (Blaen et al., 2013; Malard, Tockner, & Ward, 1999).

The largest difference in thermal regimes between streams was during peak summer months, with streams became increasingly thermally-similar towards autumn and into winter (excluding Unnamed2) as found in other studies (Caissie, Satish, & El-Jabi, 2005). The air–water temperature coupling is known to break down when air temperatures drop below 0°C, (Mohseni & Stefan, 1999). August 28 marked the start of a steady decrease in water temperatures, corresponding to reduced incoming SWR. During late summer, the streambed could play an important role in stream temperature dynamics whereby the residual ground heat accumulated over summer results in a thermal gradient that heats the water column (Alexander, MacQuarrie, Cassie, & Butler, 2003) and due also to the increased importance of groundwater inputs caused by the active layer being at its deepest (Rasch et al., 2000).

4.3 | Global context and implications of a changing climate

The results from this study in Greenland fit into the growing body of literature on high resolution stream temperature dynamics throughout Arctic and Alpine regions. Zackenberg streams showed high temporal variability in water temperature compared with sites in Svalbard (Blaen et al., 2013), Swedish Lapland (Mellor et al., 2016), the New Zealand Alps (Cadbury et al., 2008), and the European Pyrenees (Brown et al., 2005). They also showed higher mean water temperatures compared with groundwater and snowmelt streams studied at a similar latitude (79°N) in Svalbard (Blaen et al., 2013).

The lower latitude of Zackenberg compared with Svalbard means that streams receive higher SWR inputs. However, Zackenberg receives lower SWR inputs when compared with alpine areas. The higher variability in stream temperature at Zackenberg compared with other areas could therefore be due to the reduced importance of groundwater inputs, as seen by the low stream bed temperatures indicating the very shallow active layer in some parts of the valley. Groundwater inputs normally act to stabilize water temperature (Constantz, 1998), and their absence or reduced importance could therefore explain the variable stream temperatures observed in this study.

Zackenberg streams are predicted to receive increased snowmelt run-off and groundwater inputs by the end of the century due to increased snow depth and active layer thickness. This could potentially engender a weaker coupling between water temperature and climatic forcing. Streambed heat flux could become an increasingly important factor influencing stream thermal dynamics due to warmer bed temperatures and increased soil water influxes to stream environments. This, combined with a shift towards lower channel stability, could lead to reduced summer water temperature variability, causing thermal dynamics in Zackenberg streams to be increasingly similar to those in other Arctic and Alpine regions where groundwater inputs moderate temperature dynamics. Conversely, the predicted increase in summer rainfall events could lead to more frequent short-term cool spells. During the winter, an increase in air temperature and the number of thaw days could see increased water temperature variability.

Changes in water temperature regimes could have ecosystem-wide implications. Previous studies have found water temperature changes to impact in-stream processes such as nutrient uptake (Blaen et al., 2014) as well as causing changes to biological community structure, abundance, and diversity (Adams et al., 2010; Brown, Hannah, & Milner, 2007; Jacobsen, Milner, Brown, & Dangles, 2012; Madsen et al., 2015; Milner, Brittain, Castella, & Petts, 2001; Vincent & Howard Williams, 1989). Given this, research on Arctic water temperature dynamics and drivers is vital in order to better understand changes to wider ecosystem processes under a changing climate.

Future studies on water temperature in the Zackenberg region would benefit from more frequent discharge measurements, which are lacking in the present study. These data would allow better comparison between streams and of seasonal variability, taking stream size into account when comparing water temperature dynamics.

5 | CONCLUSION

This paper contributes to the growing body of literature on Arctic stream thermal dynamics by providing insights into Greenlandic streams, particularly snowmelt-dominated systems that are currently underrepresented in the literature and by providing a detailed description of thermal dynamics during the winter months for the first time. Spatial and temporal variation in stream thermal dynamics is largely related to a combination of climatological conditions, geology, and local geomorphology. With the projected change in climate, Zackenberg streams will be subjected to increased snowmelt run-off and groundwater inputs due to increased snow depth and active layer thickness, possibly leading to a weaker coupling between water temperature and climatic forcing. Changes in water temperature regimes could impact in-stream processes such as nutrient uptake as well as causing changes to biological community structure, abundance, and diversity. Although stream temperature was highly coupled with meteorological variables during the summer months, during the winter, streams were mainly frozen to the stream bed or did not flow. Further research into the relationship between snow depth and water temperature in Arctic streams as well as on the meteorological drivers of spring flow resumption and autumn freeze-up in streams is necessary to fully understand the impact of a changing climate on these sensitive systems.

Data availability statement

Data that support the findings of this study are available from the corresponding author upon reasonable request.

ACKNOWLEDGEMENTS

Catherine Docherty was funded by a Natural Environment Research Council (NERC) studentship (NE/L501712/1). Fieldwork to Zackenberg was funded through the European Union Seventh Framework Programme (FP7/2007–2013) under grant 262693 (INTERACT). Climate data from the Greenland Ecosystem Monitoring Programme were provided by Asiaq - Greenland Survey and the Department of Bioscience, Aarhus University, Denmark in collaboration with Department of Geosciences and Natural Resource Management, Copenhagen University, Denmark. The authors thank Biobasis, Geobasis and Zackenberg logistics for all of their field assistance. We thank Chantal Jackson for Figure 1. We appreciated the considered and constructive comments of the two anonymous reviewers. Professor Geoff Petts provided huge inspiration as exceptional academic, mentor, and friend, and he kindled some of the authors' interest in river water temperature and cold region hydroecology.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Docherty CL, Dugdale SJ, Milner AM, Abermann J, Lund M, Hannah DM. Arctic river temperature dynamics in a changing climate. *River Res Applic*. 2019. https://doi.org/10.1002/rra.3537