Alpine Stream Temperature Response to Storm Events

LEE E. BROWN
School of Geography, University of Leeds, Leeds, United Kingdom

DAVID M. HANNAH
School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, United Kingdom

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ABSTRACT

Despite continued interest in meteorological influences on the thermal variability of river systems, there are few detailed studies of stream temperature dynamics during storm events. This paper reports high-resolution (15 min) water column and streamed temperature data for storm events of contrasting magnitude, duration, and intensity for three streams (draining glacier, snow, and groundwater sources) across an alpine river system during summers 2002 and 2003. The results demonstrate clear spatial and temporal differences in water column and streamed thermal responses to precipitation events and streamflow peaks. Analysis of all storms across the three sites showed a decrease in water column temperature for 75% of events, with significant negative relationships between stream temperature and precipitation magnitude, precipitation intensity, and stream discharge peaks. Temperature decreases of 10.4°C were recorded, but temperature increases were less marked at up to 2.3°C. Temperature response to precipitation was dampened with increasing depth into the streamed at all sites. Spatial and temporal differences in thermal response to storm events were controlled by precipitation and stream discharge peak characteristics (above) plus antecedent basin conditions, which together determine the nature and rapidity of hydrological response. In this steep alpine basin, stream temperature variability appears to be enhanced by quick routing of precipitation to the river channel (i.e., direct precipitation/channel interception, rapid surface flow over impermeable bedrock/thin alpine soils, and subsurface flow through highly weathered scree slopes). This research highlights the need for integrated hydrometeorological research of precipitation event–hydrological response–stream temperature interactions to advance understanding of runoff generation processes driving event-scale thermal dynamics in alpine and other river systems.

1. Introduction

An understanding of the processes driving river temperature dynamics is fundamental for assessment and prediction of thermal response to climatic variability and change (Caissie 2006). The influence of meteorological conditions on stream temperature continues to be a research focus, particularly quantifying energy budgets (e.g., Hannah et al. 2004) and air–water temperature relationships (e.g., Webb et al. 2003). Other researchers have focused upon river thermal response to incoming shortwave radiation (Johnson 2004) and longer-term climate variability (e.g., Langan et al. 2001). Despite this interest in atmospheric forcing, detailed high temporal resolution data describing storm event (i.e., precipitation and induced river flow peak) effects on stream temperature are lacking.

The few studies of stream temperature response to storm events have produced contradictory results, probably due to study basin differences and time of year but maybe also because thermal responses were recorded incidentally (as part of related studies) and, thus, monitored in insufficient detail. River temperature decreases have been reported for isolated rainstorms in northern England (Smith and Lavis 1975) and heavy snowfall in headwater streams of north Virginia (Pluhowski 1972). Chutter (1970) observed more marked stream temperature decreases (up to 7.5°C) in the Vaal Dam basin, South Africa, during summer hailstorms. In contrast, water temperature increases of up to 1°C have been reported in the Georgia Piedmont (Shanley and Peters 1988) and up to 3°C in snow-
covered basins on Hokkaido Island, Japan (Kobayashi et al. 1999). Despite this evidence, recent temperate river energy budget studies have assumed heat advection by precipitation is negligible (e.g., Evans et al. 1998), and there remains incomplete understanding of factors determining precipitation and resultant flow event effects on stream temperature.

The streambed has been identified as a potentially important heat source/sink affecting overlying channel water (e.g., Evans et al. 1998; Hannah et al. 2004), with riverbed temperature suggested to reflect the nature and extent of groundwater–surface water interactions (Malcolm et al. 2004; Brown et al. 2005). A number of studies conducted with alpine basins have analyzed water column and riverbed temperature time series to identify gaining and losing river reaches and to quantify bed seepage (Silliman and Booth 1993; Alexander and Caissie 2003). However, very few studies have specifically investigated the effect of storm events on streambed temperature. Irons et al. (1989) showed streambed temperature decreases of ~1°C at 0.10-m depth for an Alaskan river following precipitation, which was explained by enhanced groundwater upwelling. Hannah et al. (2004) also noted depressed streambed temperature to 0.40-m depth associated with winter storm flow for a Scottish Cairngorm mountain stream but attributed this to the advection of colder channel water into the streambed (displacing warmer hyporheic/groundwater).

For alpine streams, distinct annual, seasonal, and diurnal fluctuations in water column temperature have been explained by changing water source contributions and fluctuations in solar radiation receipt and air temperature (Brown et al. 2005, 2006a). Alpine basins are characterized by water source contributions (glaciers, snow, and groundwater) that vary markedly in space and time (Brown et al. 2003, 2006c). This hydrological dynamism is hypothesized to underpin high thermal heterogeneity within alpine proglacial floodplains (e.g., Malarad et al. 2001; Brown et al. 2005). However, there is currently no research on alpine water column and streambed temperature response to storm events.

This paper addresses the above research gaps by reporting on detailed, high-resolution (15 min) monitoring of water column and streambed temperatures for storm events of different magnitude, duration, and intensity. Field data (collected in summers 2002 and 2003) are presented for three alpine streams in the French Pyrénées sourced by snowmelt, glacier melt, and groundwater. The research aims were 1) to examine water column and streambed thermal response to storm events of different magnitude, duration, and intensity; 2) to compare temperature responses to storm events for streams draining alpine subbasins with different primary water sources; and (3) to improve understanding of the key drivers of spatial and temporal water column and streambed temperature dynamics during storm events.

2. Methodology

a. Study area

Field observations were made in the Taillon–Gabiétoüs basin, Cirque de Gavarnie, French Pyrénées, (43°6′N, 0°10′W; Fig. 1) between 1 July (day 181) and 2 September (day 244) 2002 and 2003. Hereafter, dates are referred to using the calendar day and year, and time is quoted in coordinated universal time (UTC). Briefly, the basin covers 7.7 km², spans an altitudinal range of 3144 to 1900 m at the most downstream sampling site, and is characterized by steep valley slopes (30°–70°). Two headwater cirques contain the Taillon and Gabiétoüs Glaciers, and permanent snow and ice compose ~5% of the basin area. The upper basin drains Marbore sandstone interspersed with limestone. The Vallée des Pouey Asp (lower basin) is a wide, gentle gradient valley underlain mainly by sandy limestone (Santonien and Conacien series). North-facing slopes are predominantly bedrock mantled with glacial moraine fills and scree, but south-facing slopes have shallow soils with vegetation cover (grasses and alpine herbs). The study area is located in alpine meadow above the tree line, so stream channels are openly exposed to the atmosphere. Hannah et al. (2006) provide a full basin description.

The basin contains four distinct and highly dynamic hydrological stores: 1) the Taillon and Gabiétoüs Glaciers, 2) seasonal snowpacks below 2700 m, 3) a karst groundwater system, and 4) hillslope aquifers. These water sources contribute different proportions of flow to streams within the Vallée des Pouey Asp, with inputs varying at diurnal to seasonal time scales (Brown et al. 2006c). Hannah et al. (2000) have demonstrated significant precipitation influences upon the melt season river flow regime of this glacierized basin.

b. Data collection

To characterize meteorological conditions, an automatic weather station (AWS) was located near the confluence of the Taillon and Crampettes streams (Fig. 1). Air temperature (T_{air}) was monitored at ~1.25 m above the ground using a Campbell Scientific HMP35AC temperature–humidity probe. Incoming shortwave radiation was measured directly using a Skye Instruments 1110 pyranometer. Rainfall was recorded at ground
level using a Campbell Scientific ARG100 tipping-bucket (0.2-mm resolution) gauge. Water column and streambed temperatures were monitored at two sites on the snowmelt and glacier-fed Taillon stream located upstream (A) and downstream (C) of the groundwater-fed (hillslope/spring) Tourettes tributary upon which a third site (B) was situated (Fig. 1).

Temperatures were measured in the water column \( (T_w) \) and streambed at 0.05- \( (T_{b0.05}) \), 0.20- \( (T_{b0.20}) \), and 0.40-m \( (T_{b0.40}) \) depth, using Campbell Scientific 107T thermistors. Streambed thermistors were inserted into a thin, backfilled pilot hole, which allowed sensors to be installed without damage while ensuring contact with substrate. In 2002, the thermistor at 0.05-m depth at site A suffered a recurrent fault so data are not presented. Thermistors were cross calibrated across and beyond the field temperature range before and after deployment to obtain correction factors. River stage was measured using Druck PDCR-830 pressure transducers at sites B and C and 25 m upstream of site A. Stream discharge \( (Q) \) was calculated across the range of observed flows using the velocity area method. Stage–discharge rating curves were constructed to provide continuous estimates of river flow. Instrumentation was removed after the 2002 field season and reinstalled in 2003 to avoid damage during harsh winter weather conditions.
ditions and extremely high river flows during spring melt. While every effort was made to microsite equipment in the same location in both years, interannual changes in the environment (especially following spring melt) are unavoidable in dynamic alpine river system.

All sensors were scanned every 10 s and 15-min averages (totals for precipitation) were stored on Campbell Scientific dataloggers. All datalogger time stamps were synchronized prior to installation, and internal clocks were physically checked every day throughout both monitoring periods. Upper streamed sediments were characterized by measuring b-axis lengths of 100 randomly selected clasts. As previously reported (Brown et al. 2005), sediments were coarsest at site A (D50 = 89 mm) with site C being similar but more fine skewed (D50 = 85 mm). Site B was characterized by finer sediments (D50 = 58 mm).

c. Data analysis

Several methods exist to characterize precipitation events (reviewed by Jones 2000). The 95th percentile (upper 5%) typically identifies “extreme” events, but in this study a wider range of precipitation episodes was of interest. Therefore, storm events were identified by falling within the upper quartile (≥75th percentile = 7.9 mm day⁻¹) of ranked daily precipitation totals across both melt seasons. Data analysis was structured to investigate stream thermal response 1) across all storm events at the three sites (i.e., pooled dataset) and 2) for a subsample of events. Water column temperature was considered in both analyses, whereas investigation of streamed temperature was reserved for the subsample of storms to allow closer inspection of event dynamics. Five “periods” of 4 days were chosen for detailed consideration. The selected periods spanned the range of observed event types and also prestorm, concurrent, and poststorm event conditions. Periods of the same length were selected for comparison but some contain multiple precipitation events; these events are considered individually throughout.

For all ≥75th percentile storm events, the difference in water column temperature from the onset to cessation of precipitation was calculated to quantify “temperature change” over the event. In addition, the difference in water column temperature immediately before and after the main event peak (i.e., at the maximum precipitation intensity) was calculated. Storm events were characterized using the following precipitation metrics: total (magnitude), duration, mean intensity, maximum (peak) intensity, and start time of precipitation. Start time was examined to assess stream thermal response to storm events as a function of the diurnal temperature cycle.

As a measure of antecedent moisture conditions, the median (50th percentile; 2.8 mm day⁻¹) and lower quartiles (≤25th percentile; 0.8 mm day⁻¹) of daily precipitation totals were calculated to enable the number of days since precipitation inputs of different magnitude to be determined. In addition, peak stream discharge and standardized peak discharge (peak discharge divided by preevent discharge) were used as measures of increased thermal capacity and comparable (between sites and storms) maximum storm flow change, respectively. Pearson’s correlation coefficients were calculated to examine relationships between precipitation and flow event characteristics and stream temperature response. Correlations were deemed significant where P < 0.05.

3. Results

a. Melt season hydrometeorology

Melt season hydrometeorological patterns are detailed by Brown et al. (2005, 2006a). Although this paper focuses on the event scale, a brief melt season context is provided herein. The 2002 field season was wetter than 2003 (297.4 cf. 252.6 mm). In 2003, precipitation events were generally separated by longer drier periods (days 190–195, 197–204, and 209–217), but individual storms were more intense than in 2002 (Figs. 2a and 3a). Of the days on which precipitation was recorded, 55 days had total rainfall above the 25th percentile, 38 above the median, and 18 above the 75th percentile. In total, 21 individual events >75th percentile were recorded (i.e., some days had multiple events). Mean air temperature was lower in 2003 than 2002 (cf. 15.1°C and 11.7°C; Figs. 2a and 3a). Averaged over the two field seasons, discharge at site A was slightly greater in 2003 (0.09 cf. 0.06 m³ s⁻¹). Site B discharge was marginally higher in 2002 (0.07 cf. 0.06 m³ s⁻¹), while site C showed the same average discharge in both years (0.20 m³ s⁻¹). Although mean discharge was not markedly different between years at each site, peak flows were much higher in 2003 (approximately double those in 2002; Fig. 3b). The difference between the discharge sum for site A plus B compared with site C was due to a karstic tributary downstream of site A and a glacial/snowmelt-fed tributary below site B (Fig. 1).

b. Melt season water column and streamed temperatures

Seasonal patterns in water column and streamed temperatures are discussed at length by Brown et al. (2005, 2006a). In short, average water column temperatures at all sites were warmer in 2003 than 2002 (A:
In both 2002 and 2003, temperature range and standard deviation decreased, and minimum (maximum) temperatures were warmer (cooler), with increasing depth into the streambed at all sites (Figs. 2 and 3). At site A, seasonally averaged bed temperature during 2002 (2003) increased by just 0.2°C (0.4°C) from the water column to the streambed at 0.40-m depth (Figs. 2c–e and 3c–e). At site B, mean seasonal temperature was similar (within 0.2°C sensor accuracy) for the water column and streambed at all depths within years (2002: between 9.4° and 9.7°C; 2003: between 11.0° and 11.1°C). At site C, mean streambed temperature was cooler with depth in 2002 ($T_w = 8.8°C$ cf. $T_{b0.4} = 8.1°C$)
but was similar from the water column to 0.40-m depth in 2003 ($T_w = 10.3^\circ C$ cf. $T_{s0.4} = 10.5^\circ C$).

c. Storm event characteristics and water column temperature response

The majority of storms resulted in a decrease in water column temperature (15, 17, and 15 of the total of 21 storms at sites A, B, and C, respectively). Temperature change of between 0$^\circ$ and $-1^\circ$C was the most frequent response to storm events (Fig. 4). A statistically significant inverse relationship was found between total precipitation and temperature change using the pooled dataset, indicating greater temperature depression for higher magnitude storms (Fig. 5a). No significant rela-

Fig. 3. (a) Air temperature and precipitation, (b) stream discharge at sites A–C, and water column and streambed temperatures at sites (c) A, (d) B, and (e) C during the 2003 melt season.
relationship between temperature change and precipitation duration, mean intensity, maximum intensity, or start time was evident (Figs. 5b–f), although a broadly negative association between precipitation duration and temperature change was evident (Fig. 5b). Peak precipitation intensity showed a statistically significant inverse relationship with temperature change (Fig. 5d); thus, higher peak precipitation intensities were related to greater temperature reductions. The association between instantaneous temperature change (i.e., at time of maximum precipitation intensity) and maximum intensity illustrated a threshold-like response with limited temperature change at intensities below 10 mm 0.25 h$^{-1}$ but marked declines in water column temperature (up to 10.4°C) at higher intensities (Fig. 5e). The relationship between precipitation start time and temperature change is biased by the fact that most precipitation events occurred during the afternoon and early evening (Fig. 5f). Nevertheless, available data indicated greatest temperature changes during the afternoon. No consistent relationships were found between temperature change and time since precipitation events of differing magnitude (i.e., exceeding median, upper, and lower quartiles); therefore, plots are not presented herein. Peak stream discharge yielded a statistically significant inverse relationship with temperature change (Fig. 6a). Similarly, standardized peak discharge exhibited a statistically significant negative association with temperature change, indicating higher relative peak storm flow produced greater temperature reduction (Fig. 6b).

d. Event hydrometeorology and stream temperature response for selected storms

1) Period 1: Prolonged duration, low-intensity precipitation event (days 195–198; 14–17 July 2002)

This cold period (mean $T_{air} = 7.6°C$) with persistent valley and ridge-top cloud (hence low incoming short-wave radiation, most notably on day 196) experienced prolonged, low-intensity precipitation that began at 1300 UTC on day 196 (Table 1; Fig. 7a). However, there was little precipitation in the preceding 4–5 days (Table 1). The lowest discharges of the 2002 field season were recorded during this period, with mean discharge at site A less than at site B (0.04 cf. 0.06 m$^3$ s$^{-1}$) due to reduced snow- and ice melt contributions to streamflow. The lowest diurnal discharge ranges of the 2002 melt season were recorded on day 195 at site A (0.01 m$^3$ s$^{-1}$), but discharge increased markedly on day 196 with onset of the extended precipitation episode.

At the beginning of period 1, meltwater-driven discharge cycles and clear diurnal water column and streambed temperature fluctuations were absent (Fig. 7). Average streambed temperatures were similar to the water column at sites A and B but cooler at site C, and temperature range decreased from the water column to 0.40-m depth (Fig. 7). Water column and streambed temperatures became similar during a lagged discharge rise (i.e., not concurrent with rainfall) at site A (day 197 at 0600 UTC; Fig. 7b), but no change in thermal profiles occurred at sites B and C. Temperature gradients at all sites steepened after 1200 UTC on day 197 as cloud cover broke, with larger diurnal fluctuations and vertical differences on day 198 due to stronger atmospheric heating (i.e., clear sky evident from shortwave radiation and increased air temperature; Fig. 7a).

2) Period 2: Short duration, moderate-intensity precipitation event (days 217–220; 5–8 August 2002)

Clear diurnal air temperature and incoming shortwave radiation fluctuations characterized this period, although mean air temperature was relatively low (10.1°C; Fig. 8a). A short precipitation event on the afternoon of day 217 reached a maximum intensity of 4.6 mm 0.25 h$^{-1}$ (Table 1). Notably, precipitation fell around dusk and after nightfall, as evidenced by shortwave radiation receipt. Previously, 15 days passed since the last >75th percentile event. Stream discharges were low compared with seasonal averages (Fig. 2), but, during the storm event, they increased concurrently to approximately double pre- and postevent levels at all sites (Figs. 8b–d).

Patterns of heating and cooling were associated with changing atmospheric conditions, particularly cloud cover (Fig. 8a), with diurnal stream temperature fluctuations evident throughout (Figs. 8b–d). Mean streambed temperatures were similar at all depths at sites A and B (7.8°C–7.9°C and 9.9°C–10.0°C, respectively) but
were cooler with depth at site C (9.2°–8.6°C). During the storm event, water column and streambed temperature responses were negligible at all sites (Fig. 8). Only minor decreases were observed at sites A and B, while no temperature change occurred at site C.

3) Period 3: Short Duration, High-Intensity Precipitation Events (Days 228–231; 16–19 August 2002)

The heaviest rainstorms of the 2002 melt season occurred on day 228 (peak intensity = 11.6 mm 0.25 h⁻¹) and days 230–231 (second peak intensity = 11.4 mm 0.25 h⁻¹). Before this period, 10 days passed since the last >75th percentile precipitation event (Table 1). Mean air temperature was 14.9°C but ranged widely (Fig. 9a). Diurnal patterns of incoming shortwave radiation showed relatively clear skies in the morning and building cloud cover in the afternoon (to a lesser extent on day 228), with radiation receipt declining ahead of the onset of rainfall. At sites A and C, the second precipitation peak on days 230–231 resulted in the highest discharges over this 4-day period (0.34
and 0.83 m$^3$ s$^{-1}$, respectively), whereas at site B, all storm flows were of similar magnitude (~0.50 m$^3$ s$^{-1}$; Figs. 7b–d). At site A, discharge peaks lagged precipitation inputs and were less flashy compared with the other two sites.

Mean temperatures increased from the water column to 0.40-m depth at site A (7.3°–7.6°C) but decreased into the streambed at sites B and C (10.3°–10.0°C and 9.5°–8.9°C, respectively). Short-term fluctuations in water column and streambed temperatures were evident on days 228 and 230–231 coinciding with rainfall (Figs. 9b–d). On day 228, temperatures decreased by 3.8°C in the water column and 1.8°–2.0°C at 0.20-m depth at sites A and B (Figs. 9b,c). At site C, water column temperature decreases were slightly higher (4.4°C) and 0.20-m depth decreases lower (1.0°C; Fig. 9c). During the first peak of the double-peaked precipitation event on days 230–231, water column and 0.20-m depth temperature decreases were lower than day 228 at site A (2.9° and 1.8°C, respectively), whereas, at sites B and C,
slight water column temperature increases (1.2° and 0.7°C, respectively) occurred but streambed temperatures remained unchanged. The second precipitation peak on days 230–231 resulted in decreased temperatures at all sites. At site A temperatures decreased by 1.8° C (water column) and 1.0°C (0.20-m depth). Water column temperatures decreased by 2.5°C and 1.5°C at sites B and C, respectively. Temperature decreases at 0.20-m depth were lower at site B (0.8°C) than site C (1.0°C).

4) PERIOD 4: VERY HIGH INTENSITY HAIL-/RAINSTORM FOLLOWED BY PROLONGED DURATION, LOW-INTENSITY RAINFALL (DAYS 203–206; 22–25 JULY 2003)

In midsummer 2003 (day 204), a very heavy (99th percentile) hail-rainstorm occurred during an otherwise warm period (mean $T_{air} = 14.2°C$) with marked diurnal incoming shortwave radiation cycles (Fig. 10a). Both shortwave radiation and air temperature began to
decline prior to the hail-/rainstorm. Maximum air temperature for the period was 21.5°C but during the storm decreased to 6.1°C. Maximum precipitation intensity was the highest of all events detailed herein (12.8 mm 0.25 h⁻¹). However, mean precipitation intensity was low because of light rainfall for 14 h after the peak on day 204 (Table 1). There were no precipitation events >75th percentile in the preceding 16 days. Discharge maxima were by far the highest of all events selected at sites B and C (0.69 and 1.46 m³ s⁻¹, respectively). For site A, peak discharge was also the highest but closer in magnitude to other periods (i.e., periods 3 and 5).

This period exhibited clear diurnal fluctuations in water column and streambed temperatures punctuated by a major temperature decrease coinciding with the hail-/rainstorm (Figs. 10b–d). Minimum water column temperatures were the lowest recorded for the 2003 melt season at all sites, but thermal response varied.
between sites. Rapid drops in water column and 0.05-m depth temperatures of 10.1°C at site A, 10.4°C at site B, and 9.7°C at site C were recorded. Large temperature decreases were also observed in the streambed. Temperatures decreased at 0.20-m (0.40 m) depth by 4.3°C (3.4°C) at site A and 7.4°C (5.0°C) at site C (Figs. 10b,d). At site B, temperature decreases were less at 0.20-m depth (2.3°C) with no discernable effect at 0.40-m depth (Fig. 10c).

5) Period 5: Short duration, high-intensity precipitation event (days 232–235; 20–23 August 2003)

During this late summer period, mean air temperature remained fairly warm (14.5°C) with daily incoming shortwave radiation cycles of reduced amplitude compared with periods 2–4 (Fig. 11a). Total precipitation was low but fell mostly during an event on day 234. Averaged over the 4-day period streamflows were relatively low, although it was just 5 days since the last >75th percentile precipitation event. The rainfall event on day 234 corresponded with four-, nine-, and seven-fold discharge increases from preevent levels at sites A, B, and C, respectively (Figs. 11b–d). Notably, unlike the other selected periods, this precipitation event yielded a concurrent decline in both incoming shortwave radiation and air temperature, perhaps suggesting a more localized storm.

Water column and streambed temperature responses to the short, intense precipitation event on day 234 were markedly different between sites (Figs. 11b–d). Mean stream temperature during the period increased into the streambed at site A (9.1°C–9.6°C), but temperatures were similar at all depths at the other two sites (B: 11.2°C–11.4°C; C: 10.4°C–10.6°C). At sites A and C, peak precipitation and discharge coincided with slight temperature decreases (0.6°C and 1°C, respectively) in both the water column and at 0.05-m depth. Immediately following the precipitation and discharge peaks, temperatures quickly recovered (i.e., increased by 0.6°C at site A and 1.1°C at site C). In contrast for site B, the storm yielded a warming effect of 2.3°C in the water column and at 0.05-m depth and 0.3°C at 0.20-m depth (Fig. 11c).

4. Discussion

To our knowledge, this research is the first high temporal resolution hydrometeorological assessment of water column and streambed thermal variability associated with storm events of different magnitude, duration, and intensity, not just within an alpine basin but for any river system. High-resolution (15 min) data collection revealed clear spatial and temporal differences in water column and streambed temperature responses to storm precipitation and resultant discharge peaks. Most storms (75% of pooled events) yielded a decline in water column temperature, which was similar to some previous studies (Chutter 1970; Pluhowski 1972; Smith and Lavis 1975). However, the precipitation event and flow characteristics responsible for previ-
ously documented stream temperature changes during storms were unknown.

This study provides new information on the key event characteristics influencing water column temperature during storms. Statistically significant, inverse relationships between temperature change and magnitude (total) and peak intensity of precipitation were found. Although precipitation duration showed a generally negative association with temperature change, this relationship was not statistically significant due to the longest duration storm being low mean intensity. Examinations of precipitation start time and temperature change showed most storms took place in midafternoon and early evening, typically following building of ridge-top cloud during late morning and around midday. The greatest decreases in water column temperature were observed during the afternoon, which can be explained by the likelihood of warmer prestorm water column temperatures in the middle of the day (as a result of diurnal heating; Caissie 2006), hence, greater thermal contrast between channel water and apparently cooler storm water inputs. However, this interpretation requires some caution due to the bias in timing of observed storms and the limited occurrence of water column temperature increases during afternoon storms. Thus, although time of day may be an important consideration in understanding the magnitude of storm-driven temperature changes, the extent of stream temperature response to storms cannot be explained simply as a function of the diurnal heating cycle. Water column temperature change at the time of maximum precipitation intensity showed a nonlinear response to peak intensity, with limited thermal alteration below 10 mm 0.25 h \(^{-1}\) then major temperature declines above this apparent threshold. These results suggest that at lower peak intensities, precipitation inputs may be equilibrated (in terms of heat exchange), insufficient in relative contribution to induce a thermal response, or attenuated hydrologically (i.e., stored or buffered) prior to entering the stream.

Peak and standardized peak discharge showed a statistically significant inverse relationship with temperature change, suggesting that with greater storm flow volume and thermal capacity the water column was unable to equilibrate quickly with its surroundings. Antecedent moisture conditions (as indexed by days since precipitation events of varying magnitude) did not demonstrate a consistent relationship with temperature change for the pooled dataset; however, detailed analysis for the subsample of storms points toward the potential influence of this factor (below). It is possible that during some events, storm characteristics may have overridden the effect of basin priming in this alpine environment, because steep slopes, scree, exposed bedrock, and poorly developed/thin soils permit relatively rapid streamflow responses to precipitation under a range of antecedent moisture conditions (Becker and McDonnell 1998). However, the measures of antecedent moisture employed herein are only coarse approximations, as no direct observations of soil moisture or water table levels were collected. Therefore, future studies should aim to incorporate more detailed measures of antecedent moisture to resolve these issues.

Water column and streambed temperature response during the 4-day periods allowed closer inspection of prestorm, concurrent, and poststorm dynamics. Decreased atmospheric energy receipt due to cloud cover was insufficient to account for rapid changes in stream temperature, particularly because reduced incoming shortwave radiation and air temperature usually preceded stream temperature decreases, temperature changes were synchronous with river discharge increases, and stream temperature increases were sometimes observed. Together, this indicates a clear storm-induced stream temperature response. Stream temperature variability associated with storm events was typically greatest in the meltwater-fed Taillon stream (sites A and C) and lowest in the predominantly groundwater-fed Tourettes stream (site B), indicating groundwater contributions may dampen stream thermal fluctuations during storms (Malard et al. 2001; Hannah et al. 2004). Although storm events typically led to a lower temperature compared with preevent conditions (expect for site B during periods 3 and 5 that showed a rise), thermal responses between events varied in magnitude from minimal change (periods 1 and 2) to almost instantaneous, stepped decreases (periods 3 and 4) similar to those reported in two independent South African studies (Chutter 1970; Appleton 1976).

The range of observed water column and streambed temperature responses to precipitation events in the Taillon–Gabiètous basin reflects dynamic relationships between precipitation characteristics and resultant hydrological response. River flow responses to storms appeared to be driven by rapidly routed precipitation (i.e., direct precipitation/channel interception, rapid surface flow over impermeable bedrock/thin alpine soils, and subsurface flow through highly weathered scree) and slower routed water via increased groundwater discharge following recharge. During period 1, stream temperature changes were unapparent, except at site A. Antecedent conditions were wet, with \(\geq\)median and \(\geq\)75 percentile events within the preceding 5 days. The long duration, low-intensity precipitation event on day 196 would have contributed to groundwater discharge into streams, accounting for the similarities between
streambed and water column temperatures at this time (Irons et al. 1989; Hannah et al. 2004). Period 2 had a similar precipitation amount to period 1, but the last ≥75 percentile event was 2 weeks previously and 2 days had passed since a ≥median event. Therefore, the basin would have been drier than period 1, and the relatively short duration event (3.75 h) was probably insufficient to significantly recharge shallow groundwater or contribute to rapid flow generation. Hence, stream thermal (and discharge) change was limited at all sites during period 2.

In contrast, period 3 was characterized by three separate precipitation events (of greater magnitudes and intensities than periods 1 and 2) with only 1 day since the last precipitation event ≥median. Marked increases in stream discharge (concurrent with precipitation peaks) were associated with decreases in temperature of the water column and streambed to 0.05-m depth. Far greater temperature decreases were observed at all sites in period 4 during a very high-intensity hail- and rainstorm that followed dry antecedent conditions (16 days since last ≥75 percentile event and 6 days since last ≥median event). This 99th precipitation percentile event resulted in extensive overland flow (observed in the field), marked increases in streamflow, and major temperature decreases [up to 10.4°C cf. largest reported decrease of 7.5°C; Chutter (1970)].

Although the majority of storms induced stream temperature decreases, water column and upper streambed (to 0.20-m depth) temperature warming was observed during periods 3 and 5. Analysis of all storms across the three sites showed that water temperature increases occurred infrequently but they were associated with short duration, low magnitude, low-intensity precipitation events, and low peak/standardized peak discharges. The largest water column temperature increases represented smaller relative departures from preevent temperatures than the largest decreases (maximum increase = 2.3°C; Site B, day 234, 2003 cf. maximum decrease = −10.4°C; Site B, day 204, 2003). Previous studies have reported temperature increases from between 0.3°C and 0.4°C due to precipitation inputs in temperate basins (Shanley and Peters 1988), and Langan et al. (2001) discussed temperature increases of between 1°C and 3°C in the subarctic Girnock Burn catchment, northeast Scotland, reflecting advection of water from warm riparian seeps and wetlands. Kobayashi et al. (1999) also observed temperature increases of 2°–3°C in a snow-covered basin on Hokkaido Island, Japan, which were attributed to precipitation-driven displacement of warmer groundwater from upper soil layers. The latter of these two processes seems most likely to be responsible for stream temperature warming seen in this alpine stream study, but independent observations of groundwater levels and soil temperatures are needed to support this hypothesis. Warm precipitation did not appear to be the main cause of stream temperature increases because in most cases significant warming was not recorded concurrently across all three sites.

Stream temperature response to storm events was typically dampened into the streambed reflecting the attenuation of bed conductive and advective processes with depth (Hondzo and Steffan 1994). Streambed temperature response to precipitation was found to 0.40-m depth, which is considerably greater than some Alaskan streams affected to 0.10-m depth (Irons et al. 1989). In these Alaskan streams, water column and streambed temperature convergence was attributed to precipitation-driven groundwater recharge and subsequent upwelling into the riverbed. However, in our study, storm events typically resulted in water column and streambed temperature decreases concurrent with increased river stage, suggesting downwelling of channel water into the streambed. Streambed cooling by surface water also penetrated to a much greater depth than the 0.20 m reported by Hannah et al. (2004). This difference may be due to the coarse sediment caliber and large interstitial voids allowing water to infiltrate the streambed more readily in Pyrenean alpine streams.

The wide spatiotemporal variability in water column and streambed temperatures detailed herein is in contrast to many stream energy budgets that negate precipitation effects (e.g., Evans et al. 1998). Because direct precipitation falling into the river channel is estimated as only 1%–2% of streamflow for basins without lakes or swamps (Ward and Robinson 2000) and precipitation-induced runoff entering the channel should be accounted for by advective heat transport from upstream, this assumption of negligible reach-scale precipitation heat flux may remain valid. Nevertheless, this study indicates that storm events may have considerable influence on stream temperature. It is most likely that stream temperature response to storms resulted from advected energy inputs, primarily from surface and near-subsurface hillslope pathways and by groundwater, rather than direct heat flux by falling precipitation.

Overall, spatiotemporal differences in water column and streambed temperature dynamics reflect basin hydrological functioning (i.e., groundwater versus meltwater system), storm event characteristics (precipitation total, peak intensity, and stream discharge peak), and antecedent conditions. Runoff response to precipitation in this alpine basin is probably enhanced by rapid surface (overland flow) and near-subsurface flux of water (enhanced by heavily weathered, permeable debris/
scree slopes). Alternatively, preevent water may be displaced by “new” water, a process enhanced by shallow soil depths and water routing through weathered bedrock on steep slopes (Becker and McDonnell 1998). However, it is clearly difficult to infer basin hydrological functioning using only streamflow and temperature data. To understand accurately how storm events influence stream thermal conditions, further studies are necessary to unravel the influence of factors, such as soil permeability, water table depth, and basin topography (McDonnell 2003). The wider importance of basin characteristics influencing event-driven thermal variability can only be speculated upon at present because temperature data are not routinely collected in studies of runoff generation processes. Hydrologists studying rainfall-runoff processes in river systems (e.g., Uhlenbrook et al. 2002; Kirchner 2003) could greatly contribute to understanding of the processes influencing thermal variability by incorporating stream temperature measurements alongside stream discharge and tracer investigations of streamflow generation. Notwithstanding lack of data about these parts of the system, it remains a challenge to explicitly identify direct storm event effects against changes in “background” meteorological conditions (driving river energy exchange) and stream discharge (modifying thermal capacity and, in turn, responsiveness of river equilibration with the environment). With improved knowledge of links between flow generation processes and thermal variability, stream temperature could potentially be used to understand streamflow permanency when access to ungauged basins is difficult (Brown et al. 2006b).

5. Conclusions and further research needs

This study reveals how storm event characteristics (most notably precipitation total, peak precipitation intensity, and stream discharge peak) and antecedent conditions (which together determine the nature and rapidity of hydrological response) play an important role in driving thermal dynamics at subdiurnal time scales. Previous research in the Taillon–Gabiétois basin has identified proximity to source, prevailing meteorological conditions, variable water source contributions (snowmelt, glacier icemelt, and groundwater), and aspect and channel width:depth ratios to be key controls on melt season and year-round alpine stream thermal dynamics (Brown et al. 2005, 2006a,b). In the Taillon–Gabiétois basin, precipitation event-driven temperature dynamics are nested within these diurnal, seasonal, and interannual stream thermal regimes.

Detailed studies of storm event thermal response of other river systems are needed to determine the generality of the findings presented herein. Further research is also required in alpine areas to understand the influence of storm events on water column and streambed temperature during autumn, winter, and spring when precipitation falls mostly as snow. Patterns of glacial retreat, such as those occurring presently in the Taillon–Gabiétois basin (Hannah et al. 2006), may also lead to further variation in stream thermal responses to storm events because changes in the timing and magnitude of meltwater generation and duration/amount of snow cover may provide different “background” conditions upon which storm events are superimposed (Hannah et al. 1999). Overall, interdisciplinary research over longer time scales and for multiple locations is needed to enhance understanding of climate–hydrology–stream temperature relationships in alpine and indeed other environments.

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