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Heat exchange processes and thermal dynamics of a glacier-fed alpine stream

Khamis, K.[1], Brown, L.E.[2], Milner, A.M.[1,3] & Hannah,D.M.[1*]

1. School of Geography Earth and Environmental Science, University of Birmingham, Birmingham, B15 2TT, UK
2. School of Geography/water@leeds, University of Leeds, Leeds, LS2 9JT, UK.
3. Institute of Arctic Biology, University of Alaska, Fairbanks, AK 99775, USA

*correspondence to: d.m.hannah@bham.ac.uk

Abstract:

Glacier-fed river thermal regimes vary markedly in space and time; however, knowledge is limited of the fundamental processes controlling alpine stream temperature dynamics. To address the research gap, this study quantified heat exchanges at the water surface and bed of the Taillon glacier-fed stream, French Pyrénées. Hydro-meteorological observations were recorded at 15-min intervals across two summer melt seasons (2010 & 2011) and energy balance components were measured or estimated based on site-specific data. Averaged over both seasons, net radiation was the largest heat source (~80% of total flux); sensible heat (~13%) and friction (~3%) were sources also, while heat exchange across the channel - stream bed interface was negligible (<1%). Latent heat displayed distinct inter-annual variability and contributed 5% in 2010 compared to 0.03% in 2011. At the sub-seasonal scale, latent heat shifted from source to sink, possibly linked to the retreating valley snowline which changed temperature and humidity gradients. These findings represent the first, multi-year study of the heat exchange processes operating in a glacier-fed stream and, as well as providing fundamental process understanding, the research highlights the direct control antecedent (winter) conditions have on energy exchange and stream temperature during summer months. In particular the timing and volume of snowfall/snowmelt can drive thermal dynamics by: (1) altering the length of the stream network exposed to the atmosphere; and, (2) controlling the volume and timing of cold water advection downstream. Finally, this study highlights the need to develop long term hydro-meteorological monitoring stations to improve understanding of these highly dynamic, climatically sensitive systems.

KEY WORDS: water temperature; snow; ice; energy balance; heat budget; Pyrénées.

INTRODUCTION

Water temperature is a key water quality variable that governs physical, chemical and biological processes in aquatic systems (Caissie 2006; Webb et al., 2008). Over the last century, stream and river temperature has been correlated with rising air temperature (Webb 1996; Lammers et al., 2007; Kaushal et al., 2010) as both respond to fluctuations in atmospheric fluxes (Johnson, 2004). As climatic warming is predicted to continue during the 21st Century (IPCC, 2007); water temperature of lotic systems is also likely to rise (Mantua et al., 2010; van Vliet et al., 2011). Hence, prediction of future thermal patterns is becoming increasingly important for directing mitigation and conservation strategies (Macdonald et al., 2014) but requires an understanding of the fundamental controls (heat fluxes) on river warming and cooling across a variety of river habitat types (Webb et al., 2008).

For rivers and streams, energy transfer occurs at two key interfaces: (1) the atmosphere – water column; and, (2) channel bed – water column (Webb et al., 2008). At the air-water surface interface, energy gains occur through solar and longwave radiation, condensation and sensible heat transfer. Losses may occur through reflection of incident solar radiation, emission of longwave radiation, evaporation and sensible heat transfer (Hebert et al., 2011). At the water-streambed interface conduction and advection, can act as both heat source or sink (Hannah et al., 2004, 2008). While fluid friction of the water column against the bed and banks represents a net gain of energy. Fluxes associated with precipitation and biological are deemed small and often omitted from energy balance calculations (Hannah et al., 2004; Hebert et al., 2011; Garner et al., 2014a). Finally tributary inflows and groundwater- surface water interactions need to be taken into consideration (Webb & Zhang 1997; Hannah et al., 2004; Malcolm et al., 2004).

Alpine river systems are particularly sensitive to warming as here climate-cryosphere interactions control diurnal to seasonal pulses of snow and glacier melt which both regulate river flows (Hannah et al., 1999) and stream water temperature (Hannah et al., 2007). Studies in these systems have focused predominately on climate-stream temperature relationships and spatial/temporal variability of thermal regimes (Brown and Hannah, 2008; Cadbury et al., 2008; Fellman et al., 2014; Malard et al., 2001; Uehlinger et al., 2003). However, shifts in the timing, magnitude and duration of meltwater production are predicted in response to climatic change (Hock et al., 2005; Milner et al., 2009; Stahl et al., 2008), which will have implications for the hydrological and ecological processes in alpine basins (Brown et al., 2007; Muhlfeld et al., 2011; Jacobsen et al., 2012). Hence, an understanding of the energy and hydrological fluxes controlling stream temperatures in these systems is essential for further development of predictive models (Moore et al., 2009; Carrivick et al., 2012).

Our understanding of the deterministic controls of stream water temperature are rooted in research focused mainly on lowland rivers (Wright & Elorrall 1967; Brown 1969; Webb & Zhang 1997, 1999; Caissie et al., 2005) and regulated rivers (Lowney, 2000; Webb and Walling, 1997). To date, few detailed studies of the fundamental processes controlling energy transfer have been carried out in glacier fed rivers with the exception of Chikita et al. (2010) and Magnusson et al. (2012). Despite being at different latitude, both studies identified friction and net radiation as important heat sources. However, not all meteorological variables were recorded above or adjacent to the stream channel and both studies were conducted over single summer melt seasons. These shortcomings are not exceptional as many energy balance studies have either been conducted for short periods (e.g. Evans et al., 1998; Webb and Zhang, 1997) or have used meteorological stations located several kilometres from the stream environment (Caissie et al., 2005). Garner et al. (2014a) highlighted the need for longer term studies which enable characterization of year on year variability in heat flux components; yet, to date no multi-year studies of heat exchange processes for alpine, glacier-fed streams have been found in the literature.

Given the research gaps identified above, this study aims to undertake a detailed inter-annual study of the heat exchange processes and thermal dynamics for an alpine, glacier-fed stream, recording all hydro-meteorological variables at the study location. The specific objectives were twofold: (1) to characterise in channel thermal dynamics and above stream microclimate of a glacier-fed stream in the French Pyrénées, over two melt seasons; and, (2) to quantify the heat exchange process driving thermal variability at seasonal and sub-seasonal scales.

METHODS

Field site

This study was carried out in the alpine Taillon-Gabiétous catchment, Cirque de Gavarnie, French Pyrénées (43°6'N, 0°10'W; Figure 1); see Hannah et al. (2007) for a detailed basin description. Mean daily minimum and maximum air temperatures, recorded at 1390m between 1990 - 2010, were 2.6°C and 12.7°C respectively, and mean total annual precipitation was 1466mm (Météo France 2011). The focus of this study was the Taillon stream, which drains a sub-catchment covering 1.72km^2, of which 5.2% was covered by glacier ice. On north facing slopes, the permanent snowline is located >2700m (Brown et al., 2006). A small cirque glacier, the Glacier du Taillon (0.09 km^2), feeds the Taillon stream. This glacier has downwasted and retreated rapidly (67m) over the last decade (Association Moraine Pyréneénne de Glaciologie, 2009).

Data collection

Microclimate data. Detailed hydro-climatological observations were made during two consecutive melt seasons: 2010 & 2011. Records between 16 June and 2 September (calendar days 166 – 245) are presented herein. An automatic weather station (AWS) was set-up over the main channel of the glacier-fed Taillon stream approximately 1.4 km from the glacier snout (Figure 1; Table 1). All sensors scanned at 10s intervals with 15 min average logged for air temperature (T_{air}), relative humidity (RH), barometric pressure (P), wind speed (ws), incoming solar radiation (K↓), reflected solar radiation (K↑), net radiation (Q*) and bed heat flux (Q_{bhf}). Precipitation (Ppn) data were totalised over 15 min. A miniature datalogger, housed in a radiation shield, was placed at the Taillon Glacier (T_{glac}) to monitor air temperature. It should be noted that during the 2010 sampling campaign, between calendar days 224-228, a sub-set of climate variables (i.e. RH, P, Q*, ws and Q_{bhf}) were not recorded due to a logger malfunction. The retreat of the transient snowline was recorded twice weekly. Fixed position digital images were taken, scaled and then compared to 1:25000 map (Institute Geographique National, 2003). Additional meteorological data were obtained for a Météo France station located in Gavarnie (Figure 1) and used to characterise winters conditions prior to field campaigns.

Water temperature data. Water column temperature (T_w) was recorded using a Campbell CS54A7 deployed 0.1m above the stream bed. Streambed temperatures ($Tb_{0.05m}$, $Tb_{0.20m}$ and $Tb_{0.40m}$) were recorded using Campbell 107T thermistors. All temperature loggers were synchronised (GMT) and recorded at 15 min intervals. Cross-calibration of all temperature sensors was conducted before and after the field season and correction factors were then applied to each logger based on a regression, which related the individual logger reading to the mean reading of all loggers (Hannah et al., 2009).

River gauging. A stream flow gauging station was established next to the AWS. A pressure transducer (Table 1) was placed in a stilling well to provide depth measurements at 15 min resolution, and stage – discharge relationships were estimated using the velocity- area method (Herschy, 1985), to provide a continuous record of river flow.

Calculation of energy budget

The total energy available to a river (Q_n) without tributary inflow can be calculated as follows (Webb and Zhang, 1997):

$$Q_n = Q^* \pm Q_h \pm Q_e \pm Q_{bhf} \pm Q_f \pm Q_a \quad (1)$$

Where Q^* = net radiation, Q_h= sensible heat, Q_e = latent heat, Q_{bhf} = bed heat flux, Q_f = fluid friction at the bed and banks, Q_a = advection. Components of the energy balance were either directly measured (i.e. Q^* and Q_{bhf}) or calculated following Hannah et al. (2004).

Statistical analysis

Temperature duration curves were constructed for both water column and streambed temperature (c.f. Hannah et al., 2009), which provide a graphical depiction of the percentage of time a temperature is equalled or exceeded. All data were tested for normality; discharge, Q_f and net shortwave radiation were square root transformed to meet assumptions of parametric statistics. To understand better, the relationships between hydro-meteorological variables, General Least Squares regression (GLS) was adopted. For all regression models residuals were inspected using ACF (Auto-Correlation Function) plots and QQ (Quantile -

Quantile) plots. If auto-correlation or heterogeneity was identified, auto-regressive integrated moving average (ARIMA) models and variance structures were fitted to successive models (Dickson et al., 2012). The optimum number of auto-regressive parameters (p) and moving average parameters (q), along with the appropriate variance structure, were selected through an iterative procedure which ranked successive models based on the Akaike information criterion (Zuur et al., 2009). All statistical tests were carried out using the nmle and base packages in R 2.14.1.

RESULTS

Micro-climate, discharge and water temperature patterns

Antecedent winter conditions. Snowfall prior to the 2010 season (1.16m) was greater than for the 2011 season (0.85m) and additional snowfall was recorded 2 months later into the 2010 season (0.10 m on 14/05/2010). Mean daily maximum air temperature was comparable in 2010 (9.1 °C) and 2011 (9.5 °C). However, mean daily maximum temperature between March and May was lower during 2010 (11.0°C) than 2011 (12.9°C).

Melt season hydroclimatological context. Mean air temperature for both melt seasons was comparable (Table 2) and the valley AWS was consistently warmer, and diurnal temperature fluctuations less than at the glacier snout. No clear seasonal trend in air temperature was identified during either melt season (Figure 2); however, a notable cold period was apparent between days 166 and 172, 2010 (minimum: T_{AWS} = -1.3°C and T_{glac} = -6.8°C). At the start of the 2010 study period, the seasonal snowpack extended to 2100m on north facing slopes, while patchy snow was present on south facing slopes. During 2010, the snowline retreated rapidly to 2500m between days 172 and 190; however glacier ice was not exposed until day 211 (i.e. snowline altitude >2650m; Figure 2). Air temperature was warmer during the early melt season of 2011 and the transient snowline extended to 2400m on north facing slopes with no snow present on south facing slopes. The snowline retreated rapidly between days 166 and 185 to 2600m and exposure of glacier ice occurred by day 185, 2011. Total precipitation was lower during 2011 than 2010, with events of a higher frequency but lower intensity. For 2010 mean wind speed was lower and relative humidity was comparable to that recorded in 2011(Table 2).

Stream discharge declined across both study periods as the highest flows were associated with the retreat of the transient snowline and episodic precipitation events. However, a characteristic glacier-melt driven hydrograph was evident in the late 2011 melt season (Figure 2) with a greater diurnal discharge apparent for days 230-245 when compared to 2010 (+ 0.07 m^3s^{-1}). The highest mean daily flows and variability (excluding days with ppn > 20 mm) were recorded between days 172 and 190. The peak flows were comparable between seasons (2010 = 0.50 m^3s^{-1} and 2011 = 0.51 m^3s^{-1}) and linked to prolonged, high intensity precipitation events. The average diurnal flow variation during 2010 (0.06 m^3s^{-1}) was lower than 2011 (0.09 m^3s^{-1}). Strong inverse relationships between discharge and snowline altitude were apparent during both 2010 (R^2 = 0.64, $P<0.001$) and 2011 (R^2 = 0.67, $P<0.001$).

Water column and streambed thermal patterns

Stream water temperature increased over the 2010 melt season, the lowest (3.2°C) and highest (10.7°C) mean daily temperatures were recorded on calendar days 171 and 239. Water column temperature displayed significant positive relationships with distance from the transient snowline (R^2 = 0.69, $P < 0.001$), air temperature (R^2 = 0.39, $P < 0.001$) and negative relationships with stream flow (R^2 = 0.12, $P < 0.01$). A similar pattern was observed during 2011 with the lowest (4.9°C) and highest (10.5°C) daily mean stream temperatures recorded on days 169 and 232. Water temperature displayed significant relationships with the transient snowline (R^2 = 0.64, $P < 0.001$), air temperature (R^2 = 0.80, $P < 0.001$) and stream flow (R^2 = 0.22, $P < 0.01$) in 2011. Both mean seasonal water column and bed temperatures were higher in 2011. During both summers, the water column displayed the greatest temperature range, while in the streambed thermal stability increased with depth (Table 3). Steeper temperature duration curves were apparent for the water column compared to the streambed during both years (Figure 3). The thermal attenuation of the bed was greater in 2011 with an increased separation of curves at the temperature minima (Figure 3).

Heat budget

Seasonal heat budget. Flux partitioning of energy gains was similar during both years with >97% of energy gains occurring at the water column – air interface. Net radiation was the main energy source accounting for 78% of gains. Sensible heat transfer was predominately towards the stream channel and comparable between years (Table 4). However, condensation was lower in 2011 (3% of gains) and represented a smaller heat source than in 2010 (Table 4). Heat gained at the streambed – water column interface was minimal and the bed heat flux accounting for <2% of all gains during both years. Total heat loss was lower during 2010, when evaporation, net radiation and the streambed acted as the main energy sinks contributing 57%, 16% and 22% of losses respectively (Table 4). The amount of energy lost to evaporation and to the streambed was greater in 2011, 64% and 36% respectively, while sensible heat losses were negligible (Table 4).

Sub-seasonal patterns. Daily total gains from net radiation declined across both melt seasons, with the highest clear day values close to the summer solstice on days 188 (24.67 MJ $m^{-2}d^{-1}$) and 177 (23.33 MJ $m^{-2}d^{-1}$) in 2010 and 2011, respectively. Net shortwave radiation acted as an energy source throughout the study period while net longwave radiation was a consistent energy sink (Figure 4). The daily total net radiation flux was negative on two days during the study (calendar days 170 and 245 in 2010); however, these losses were relatively small (-3.40 MJ $m^{-2}d^{-1}$ and -0.84 MJ $m^{-2}d^{-1}$) when compared to average daily total gains. Days when net radiation was an energy sink were characterised by dense low lying cloud cover (i.e. low K↓ during the day) and clear night skies (i.e. strong L↑ losses). Generally, fluctuations in the magnitude of net radiation were inversely related to cloud cover and daily total energy gains ranged widely, but generally contributed >60% and rarely < 50% (Figure 5).

The daily total sensible heat flux tracked changes in the temperature gradient between the atmosphere and water column. The flux was a heat source predominantly; however, on days 171 (2010) and 203 (2011) sensible heat was a sink, (-1.27 MJ $m^{-2}d^{-1}$and - 0.11 MJ $m^{-2}d^{-1}$, respectively). These two events coincided with the lowest mean daily air temperature records of 1.3°C (2010) and 5.8°C (2011). There appeared to be no distinct intra-seasonal dynamic to the sensible heat flux. The proportion of total daily heat gained from sensible heat ranged from 0 - 43%. However, it was generally <30% of the total daily energy gain. The highest proportional gains occurred on days when radiation receipt was lowest (Figure 5). As with the latent heat flux, daily gains were greater proportionally on days of decreased radiation receipt, ranging from <5% on clear sky days >40% on the most overcast days (Figure 5).

In 2010, the latent heat flux acted as both a heat source and heat sink with a clear shift in flux direction apparent as the melt season progressed. Latent heat was predominantly an energy source until day 217 because condensation dominated. Thereafter, latent heat was a sink as evaporation prevailed (Figure 4). In 2011, the sub-seasonal shift in flux direction was not as pronounced as for 2010. The highest latent heat gains were on days 180 (3.33 MJ $m^{-2}d^{-1}$) and 167 (2.59 MJ $m^{-2}d^{-1}$) in 2010 and 2011, respectively (i.e. early in the season).The greatest latent heat losses were observed on days 244 (-2.38 MJ $m^{-2}d^{-1}$) and 234 (-2.53 MJ m^{-}

$^{2}d^{-1}$) in 2010 and 2011, respectively (i.e. later in the season). During 2010, latent heat contributed frequently >10% of the total daily gains during the early melt season (>40% on day 171). During 2011, the latent heat flux generally made up <10% of total daily heat gain; however, episodic events when the flux contribution >10% did occur (Figure 5). During 2010, the bed heat flux was lower consistently than in 2011 and a clear shift from sink to source was apparent as the melt season progresses (Figure 4). However, analysis at the daily time step masks diurnal patterns that illustrate a shift from sink during the day to source during the night. The exception to this is overcast days when the streambed is a source during both day and night. Due to the small heat flux at the water column – streambed interface, contributions were typically <5% to total daily energy gains (Figure 5).

Heat gained from fluid friction rarely exceeded 1.0 MJ^{-2}d^{-1} and tracked discharge variability. The highest gains observed in each season (0.87 MJ^{-2}d^{-1} in 2010, and 1.37 MJ^{-2}d^{-1} in 2011), were during the period high flows associated with peak snow melt (Figure 2). In 2011, gains were higher in the late melt season when a characteristic glacial hydrograph was apparent (Figure 2). The proportion fluid friction contributed to total daily gains ranged from1 - 28 % but generally <5% (Figure 5). The highest proportional gains did not track consistently the days of greatest fluid friction gains, but occurred on days with reduced net radiation receipt and high intensity rain storms that generated high stream discharges.

Energy gains to the water column were always greater than losses; but total energy available to the water column declined after the summer solstice. The highest and lowest values for the 2010 season were on days 185 (30.76 MJ m^{-2}d^{-1}) and 245 (3.22 MJ m^{-2}d^{-1}), respectively and, for 2011, on days 177 (29.68 MJ m^{-2}d^{-1}) and 203 (5.22 MJ m^{-2}d^{-1}). Heat gains at the air water interface dominated energy exchange process; and the highest total energy corresponded to days with the least cloud cover.

DISCUSSION

Water temperature patterns

Seasonal mean water temperature recorded in this study were similar to those reported previously by Brown & Hannah (2008). However, when compared to studies in other glacier-fed systems, the mean and range of water temperature was greater in the Taillon basin. Uehlinger et al. (2003) and Dickson et al. (2012) recorded lower mean water temperature and range (<4°C) during summer melt seasons for glacier-fed rivers in the European Alps. Similarly, Chikita et al. (2010) recorded mean daily temperatures of < 4°C for an Alaskan stream. These differences are likely due to the larger glaciers (>10km^2) in these other systems, which yield summer discharges (range ~ 2 - 46 m^{3}s^{-1}) an order of magnitude greater than those observed in the Taillon basin (range ~ 0.01 – 0.5 m^{3}s^{-1}). This larger glacier flow volume of water generates a low source temperature as well as greater thermal capacity (Poole and Berman, 2001) that may explain the cooler, less variable thermal regimes observed in other rivers.

The streambed was thermally stable (i.e. limited diurnal and seasonal variability) during both melt seasons and had both lower maximum and higher minimum temperatures when compared to the water column. However, the vertical gradient of seasonal mean stream bed temperature differed between years, possibly due to variability in the deposition of fine sediments that altered hydraulic conductivity (Nowinski et al., 2011). In 2010, a small negative gradient was apparent with cooler temperature at depth when compared to 2011; however, intra-seasonal variability was greater in 2010, likely due to increased clear water inputs from the larger snowpack delaying the build up of glacial rock flour at the streambed-water column interface (Cadbury et al., 2008). Alternatively, due to the inherent spatial variability of bed temperature gradients this could have been due to removal and reinstallation of the sensors at a slightly different location. Surface-groundwater interactions and bed substrate properties are also thought to be important controls on bed temperature (Malard et al., 2001; Cadbury et al., 2008). In the case of the Taillon stream, bed sediments are relatively coarse (D_{50} = 0.10 m) and heterogeneous, with hyporehic exchange relatively weak (K.Khamis unpublished data). Hence, spatio-temporal variability in bed temperature gradients, due to varying infilling rates of interstitial spaces, poses the greatest obstacle to the accurate quantification of bed heat fluxes (Westhoff et al., 2010).

Over daily time scales a number of driver of stream water temperature variability were identified for the study reach. Water temperature was directly linked to prevailing metrological conditions (radiation receipt, air temperature, wind speed and moisture content of the atmosphere) and total stream discharge (Brown et al., 2006; Cadbury et al., 2008). Snow cover was a significant driver also as, in this study, it decreased exposure time of the stream to the atmosphere and increased the thermal capacity of stream water through the generation of cold water runoff (Smith 1975; Brown & Hannah 2008; Cadbury et al., 2008). The weaker relationship observed between air and water temperature during 2010 may be attributed to the lower snowline altitude reducing atmospheric exposure for much of the early melt season when radiation receipt was highest.

Heat exchange processes

In this study, the heat budget was dominated by net radiation (>75% of all energy gains) during both melt seasons. Similar findings have been reported from open river channels (Webb & Zhang 1997; Evans et al., 1998; Moore et al., 2005; Hebert et al., 2011) with net radiation contributing >70% of the total heat gain. The dominance of Q* is due to high solar radiation receipt, which is primarily a function of cloud cover, riparian cover and topographic shading (Rutherford et al., 1997; Isaak & Hubert 2001). With regards to this study, as the site is above the treeline and free from extensive topographic shading, shortwave radiation gains greatly exceeded longwave radiation emissions. Hence, net radiation was predominately positive (the flux was towards the stream). It is, however, important to note that although sub-seasonal variability in net radiation gains was pronounced, even under relatively dense cloud daily net radiation gains contributed ~50% of the total daily heat gain.

Although the evaporative flux was the major source of heat loss (>57% during both summers), seasonal losses were exceeded by gains through condensation; hence, the latent heat flux was positive during both field seasons. This is in contrast to other studies when latent heat losses have exceeded gains (Evans et al., 1998; Caissie et al., 2007; Hannah et al., 2008; Hebert et al., 2011); however, these studies have been in lower altitude river environments. Interestingly, Webb & Zhang (1997) found condensation gains important in a regulated river reach, directly below the dam, where reservoir releases cooled water temperature. Chikita et al. (2010) reported similar results from a glacier-fed river in Alaska where the latent heat flux was predominantly a heat source and made up ~6% of all energy gained. The sub-seasonal shift of the latent heat flux observed in the Taillon appeared to be due to changes in meltwater production and distance from the snowpack. Here steep gradients in temperature and humidity were maintained by cold meltwaters released from the snowpack and glacier during early summer.

Sensible heat, displayed no sub-seasonal pattern and was a consistently important energy source during both melt seasons. Values were similar to those reported by other authors (Hebert et al., 2011; Magnusson et al., 2012); however, due to the consistently low water temperature, gradients between air and water temperature were always negative and so no oscillation in the flux direction occurred. Proportionally greater gains (24%) were reported by Chikita et al. (2010) for the sensible heat flux, despite comparable air-water temperature gradients, likely due to decreased contribution of net radiation due to the higher latitude study site (Alaska, USA).

Heat exchanges at the channel bed - water column interface may be an important component of the energy balance both as energy sink (Evans et al., 1998; Hebert et al., 2011) and source (Hannah et al., 2004). However, in this study, heat gains at the channel bed – water column were very small and may be considered insignificant (<1%). During both study periods, the bed heat flux represented an important heat loss (>22%), although the magnitude of loss was small. Fluid friction made a contribution to the energy balance during both years due to the relatively steep channel slope. Notably, the frictional heat flux contribution was lower than that observed by both Chikita et al. (2010) at 38%, and Hannah et al. (2004) at 24%. This may be due to the relatively incised channel at this study reach with a low gradient and hydraulic radius. Inter-annual differences in fluid friction may be attributed to differences in the flow regime (i.e. snowmelt dominated in 2010 cf. pluvial/ glacier melt dominated in 2011). The more rapid retreat of the transient snowline in 2011 led to the earlier exposure of glacier ice and an efficient drainage network for routing melt waters from the glacier developed by the late melt season (Hannah et al., 1999; Hannah and Gurnell, 2001). Consequently, higher flows and, in turn, higher fluid friction energy gains were recorded in 2011.

CONCLUSIONS

As reductions in snow and glacier cover are expected to continue, reduced summer discharge and increased stream exposure will result in greater sensitivity of glacier fed streams to climatic change/variability (van Vliet et al., 2011). Hence, a detailed understanding of the fundamental controls on stream temperature across a range of environments is required urgently to provide a robust basis for further development of process based models and mitigation scenarios (Garner et al., 2014a). This study, over two summers, provides insights into the heat exchange processes operating in an alpine, glacier-fed stream. Net radiation, sensible heat exchange and latent heat were identified as important energy sources for warming the stream. Net radiation was consistently the dominant energy flux to the stream due to the open nature of the site. Latent heat was particularly important during early summer when rapid melting of the snowpack created steep temperature and humidity gradients between the water and air. Interestingly, latent heat also displayed the greatest inter-annual variability, which appeared to be directly linked to snow line altitude and prevailing meteorological conditions. In contrast to findings from other stream systems heat exchanged between the water column and streambed was small (Evans & Petts 1998, Hannah et al., 2008) suggesting this interface is of reduced importance for warming and cooling the water column in this system.

Antecedent meteorological conditions were an important control on both stream water temperature and the heat exchange process. In particular, the timing and volume of winter snowfall and spring snowmelt dictated: (1) the length of stream channel exposed to the atmosphere; and, (2) the volume and timing of cold water advection downstream. However, it is important to remember the small size of the Glacier du Taillon and other Pyrenean glaciers means that they represent an ‘end member’ along a gradient of glacier size. The glacier scale effect is particularly important when considering the predicted shrinking of the cyrosphere (Barnett et al., 2005) and subsequent reduction in summer discharges (Jansson et al., 2003). In particular, the current thermal patterns observed in the Taillon stream (i.e. limited glacier buffering and sensitivity to winter snow accumulation) may be considered a future analogue for rivers and streams presently fed by larger glaciers (Milner et al., 2009).

Further field based studies investigating heat exchange at the surface water - riparian interface (Leach and Moore, 2014) and the nature of in-stream advective fluxes (Garner et al., 2014b) are required to provide a robust knowledge base for the future development of physically based models. We suggest that detailed process understanding of well-chosen test catchments is required so scenario based, deterministic modelling can be used to improve understanding of how sensitive, glacier-fed river systems will respond to future climate conditions.

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Table 1: Metrological and hydrological variables measured and instrumentation used.

Variable	Instrument	Location	Instrument error
Water temperature (at river gauges)	Campbell CS54A7 temperature probe	0.1m above the stream bed	0.2°C
Water temperature (at other sites)	Gemini Tinytag Plus and Aquatic	0.1m above the stream bed	0.2°C
Bed temperatures	Campbell 107 thermistor	Stream bed 0.05m, 0.2m 0.4m depth	0.2°C
Air temperature	Skye SKH 2013	1.75m above the stream surface	0.1°C
Incoming and outgoing short-wave radiation	Kipp and Zonen CM3	1.75m above the stream surface	10% (of daily sum)
Net radiation	Campbell NR-Lite	1.75m above the stream surface	5% (of reading)
Relative humidity	Skye SKH 2013	1.75m above the stream surface	1-3% (of reading)
Precipitation	Campbell tipping bucket rain gauge	On the river bank	0.05mm
Wind speed	Vector A100R 3 cup anemometer	1.75m above the stream surface	$0.25 ms^{-1}$
Atmospheric pressure	Skye SKPS 820 barometer	1.25m above the stream surface	1.0 mBar
Bed heat flux	Hukseflux thermal sensor	Stream bed 0.05m	5-15% (of daily sum)
River stage	Druck PDCR-830 pressure transducer	0.1m above the stream bed	0.6% (of reading)

Table 2: Descriptive statistics for selected hydro–meteorological variables, over the 2010 and 2011 monitoring periods. All values are based on 15 minute averages except incoming shortwave radiation (daily totals) and precipitation (seasonal totals). The coefficient of variation is provided in parentheses.

Variable	**Mean**		**Range**		**Max**		**Min**	
	2010	**2011**	**2010**	**2011**	**2010**	**2011**	**2010**	**2011**
T air (°C)								
Glacier	9.3 (0.53)	8.5 (0.40)	29.9	22.8	23.1	22.3	-6.8	-0.5
AWS	13.1 (0.40)	12.9 (0.36)	27.2	24.2	25.9	26.4	-1.3	2.2
Precipitation (mm)	308.8*	221.8*	-	-	11.2	13.0	0	0
Shortwave radiation ($MJm^{-2}d^{-1}$)^	21.04 (0.36)	20.42 (0.42)	29.21	27.35	31.11	34.20	2.90	8.60
Wind speed ($m\ s^{-1}$)^	0.87 (0.66)	1.60 (0.59)	4.22	5.39	4.22	5.39	0	0
Atm. pressure (mb)^	822 (0.004)	819 (0.004)	21	19	832	826	811	807
Humidity (%)^	72.1 (0.28)	72.3 (0.27)	80.0	66.4	100.0	99.8	20.1	33.0
Discharge ($m^{-3}s^{-1}$)	0.15 (0.50)	0.16 (0.50)	0.45	0.46	0.50	0.51	0.01	0.04

*total for whole study period; ^ due to data logger failure during 2010 the calendar days 224-228 are omitted from calculations

Table 3. Summary statistics for water column and stream bed temperatures (°C) at AWS (lower site). Standard deviations are displayed in parentheses.

Variable	Mean		Range		Max		Min	
	2010	2011	2010	2011	2010	2011	2010	2011
T_w	7.0 (2.6)	7.8 (2.4)	12.4	12.6	14.6	14.3	2.3	1.7
$T_{b0.05}$	7.0 (2.3)	8.1 (1.8)	10.4	9.4	12.9	12.2	2.5	2.8
$T_{b0.20}$	6.9 (2.0)	8.1 (1.5)	8.8	8.0	11.3	11.6	2.5	3.6
$T_{b0.40}$	6.9 (1.9)	8.0 (1.5)	7.1	7.7	10.2	11.4	3.2	3.7

Table 4. Summary statistics for energy fluxes (MJ $m^{-2}d^{-1}$) towards (heat gain) and away (heat loss) from the stream channel during summer 2010 and 2011 (SD = standard deviation). Due to logger failure in 2010 calendar days 224-228 are omitted from the calculations for both seasons.

Variable	**Mean**		**SD**		**% of heat loss/gain**	
	2010	**2011**	**2010**	**2011**	**2010**	**2011**
Heat gain						
Q *** (Net radiation)**	14.78	12.90	7.67	7.21	78.4	77.8
K* (Net SW)	17.42	17.35	8.41	7.16	-	-
Q_h (Sensible heat)	2.43	2.24	1.48	1.28	12.8	13.6
Q_e (Condensation)	1.16	0.49	1.14	0.66	6.1	2.9
Q_{bhf} (Bed heat flux)	0.06	0.15	0.12	0.31	0.3	1.6
Q_f (Friction)	0.44	0.68	0.21	0.31	2.3	4.1
Heat loss						
Q *** (Net radiation)**	0.04	-	0.14	-	15.9	-
L* (Net LW)	3.89	4.42	1.79	1.84	-	-
Q_h (Sensible heat)	0.02	0.00	1.14	0.01	5.2	0.02
Q_e (Evaporation)	0.20	0.48	0.44	0.77	56.9	71.5
Q_{bhf} (Bed heat flux)	0.08	0.27	0.16	0.34	22.0	24.4
Total energy						
Q_n	15.84	15.71	6.51	5.51	-	-
Air-water interface	15.84	15.14	6.54	5.65	100	96.3
Water-streambed interface	-0.04	0.22	0.19	0.31	-	3.7

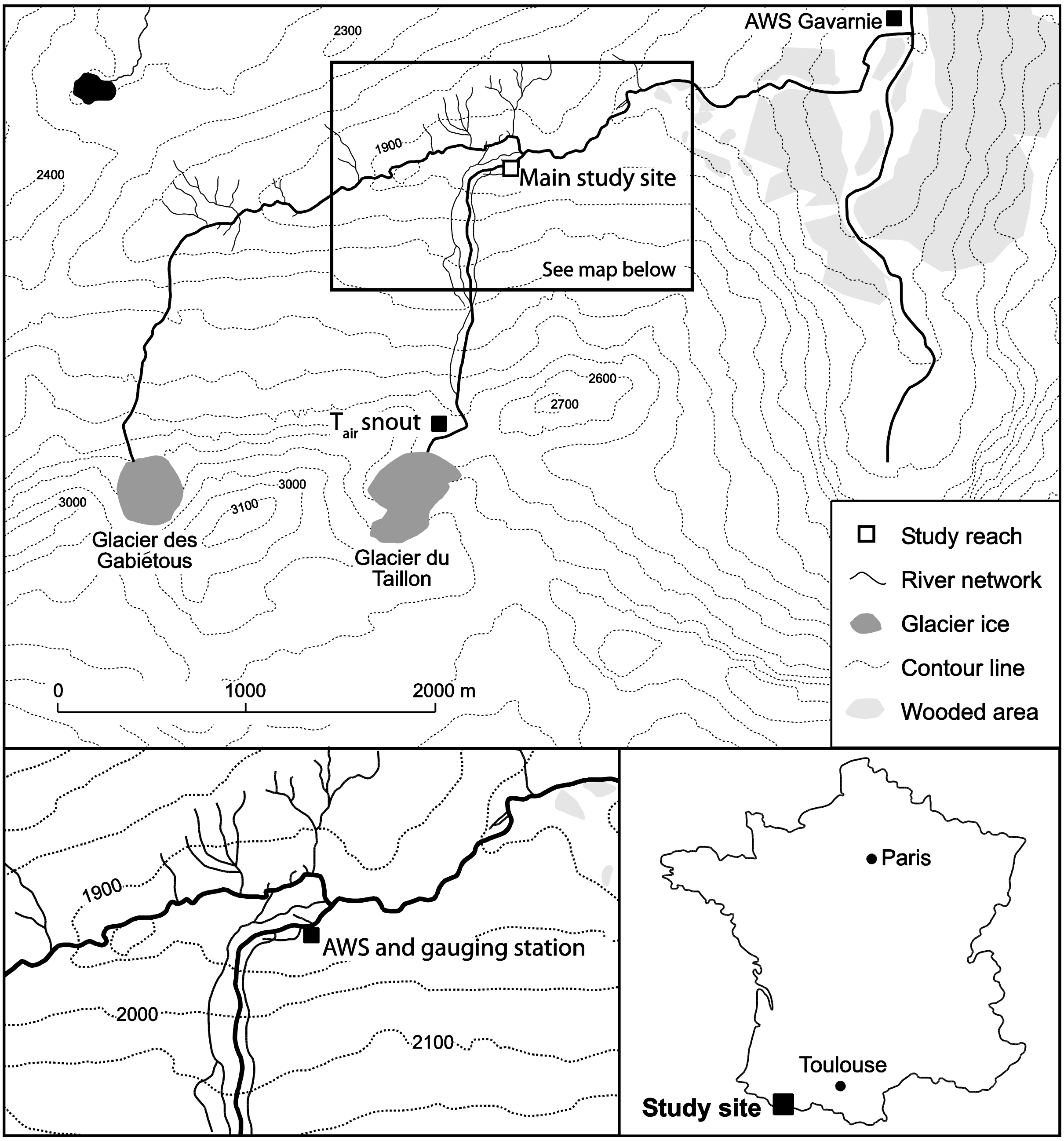

Figure 1. Location of the Taillon-Gabiétous catchment. The study reach, Gavarnie meteorological station (AWS Gavarnie) and glacier snout air temperature station (T_{air} snout) are highlighted.

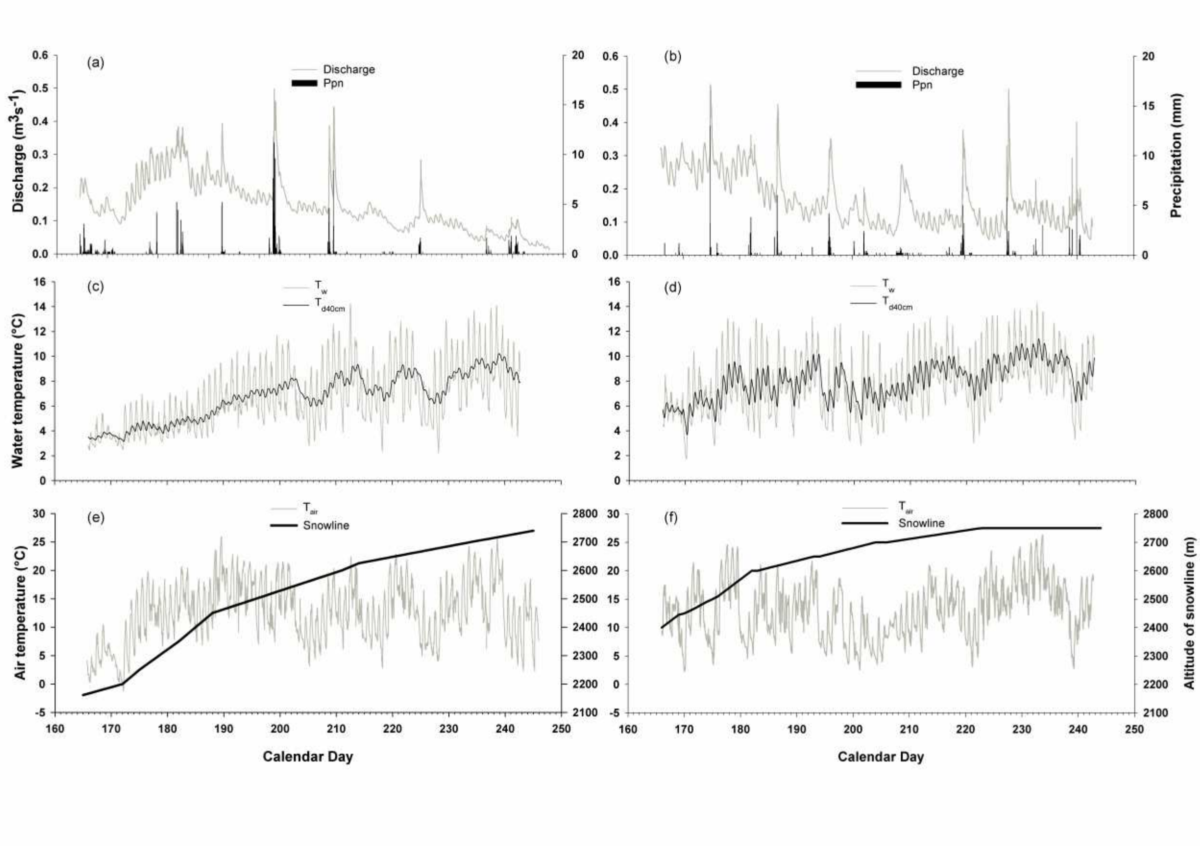

Figure 2. River discharge and precipitation time-series for (a) 2010 and (b) 2011;water column and stream bed temperature recorded for (c) 2010 and (d) 2011; and air temperature and snowline altitude for (e) 2010 and (f) 2011.

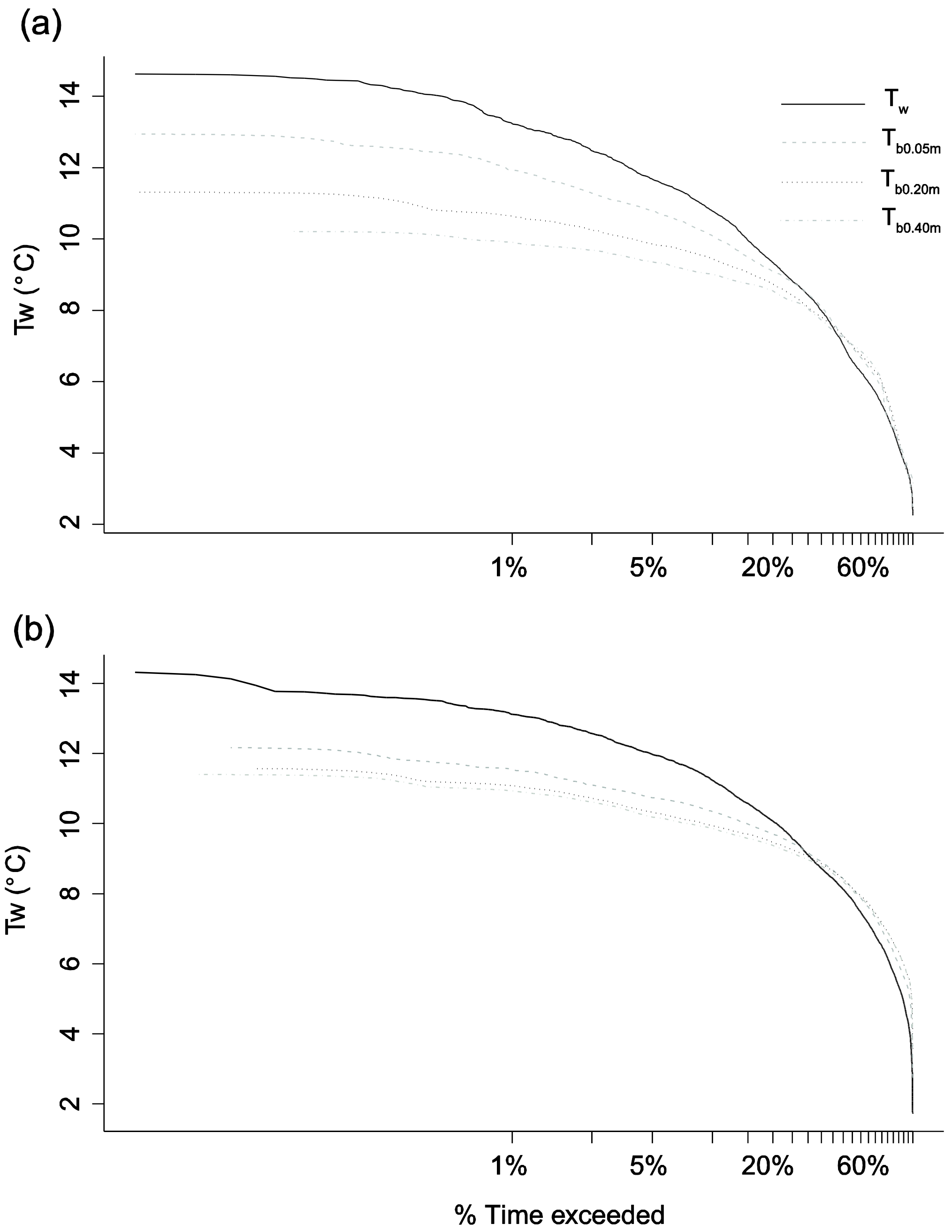

Figure 3**.** Temperature duration curves of the water column and stream bed temperatures for the (a) 2010 and (b) 2011 study periods.

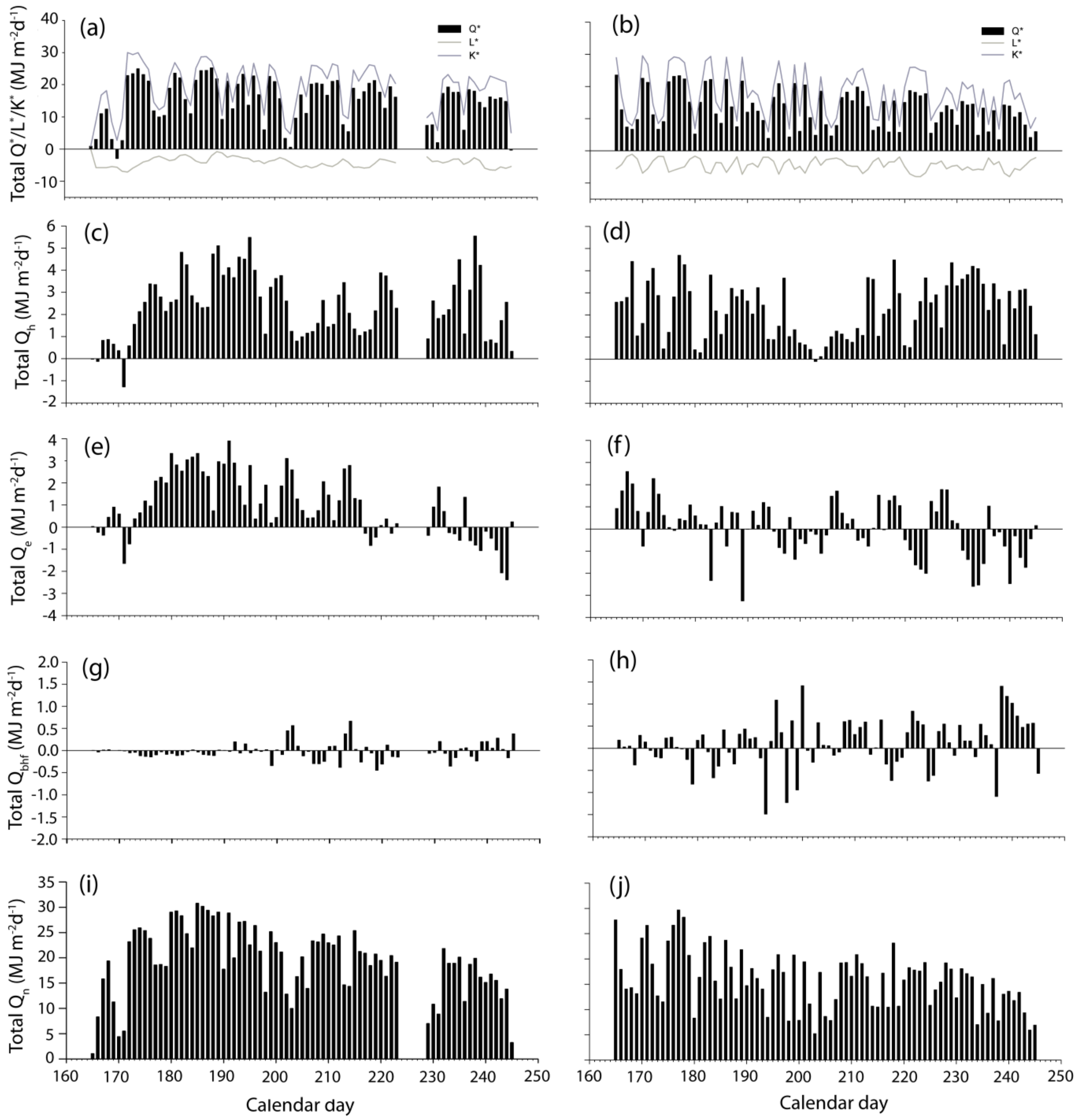

Figure 4. Daily total; net radiation, net shortwave radiation and net longwave radiation in (a) 2010 and (b) 2011, sensible heat in (c) 2010 and (d) 2011, latent heat in (e) 2010 and (f) 2011, bed heat flux in (g) 2010 and (e) 2011, and daily total energy available for the water column in (i) 2010 and (j) 2011. For 2010 data is missing between calendar days 224-228.

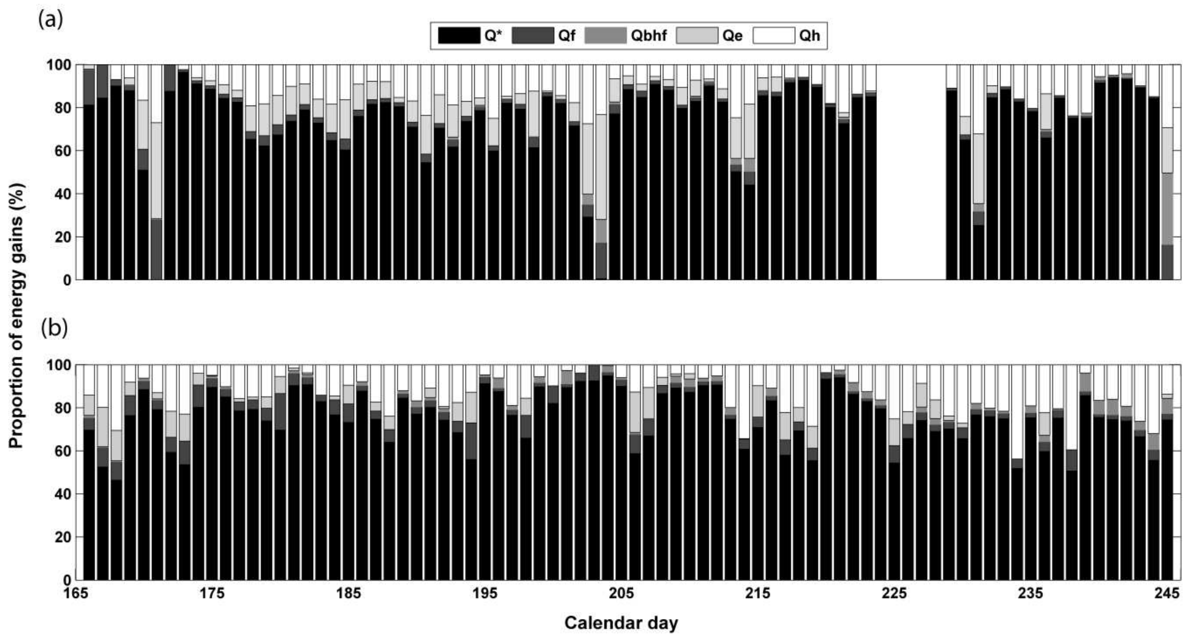

Figure 5. Proportion of all energy gains for (a) 2010 sampling period and (b) 2011 sampling period. For 2010 data is missing between calendar days 224-228.