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High Snow Melt Rates in the Cairngorms, N.E. Scotland

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Introduction

In Britain, and in particular, Scotland, snow melt can make a substantial contribution to flood peaks. Perhaps the most well known recent example, the Tay flood of 1993, caused extensive flooding in Perth, and was the result of heavy rain falling upon a melting snow pack that extended across much of the catchment (Black and Anderson 1994). In recognition of the potential snow melt has to accentuate flooding, several attempts have been made to estimate maximum snow melt rates for return periods across Britain. For many years the Flood Studies Report (NERC 1975) figure of 42 mm day^{-1} had been accepted as a design maximum for a return period greater than 50 years. This figure was arrived at after a series of studies examining meteorological data for a selection of predominantly lowland stations across Britain. Melt factors were determined as functions of temperature alone and the maximum melt rate was established by applying a 100 year return period temperature for periods with snow cover (NERC 1975). However, over the last 20 years some authors have questioned this figure, suggesting that the lowland bias of meteorological data makes the figure inappropriate for the whole of Britain (Archer 1981).

Following this, Mawdsley et al. (1991) attempted to estimate the probable maximum snow melt rate (PMSM) for three areas in the UK at 300 metres above sea level, using a technique whereby each component of a snow melt energy balance model is assigned its maximum probable value. Results indicated that maximum melt rates are lower in North East Scotland than in North East England and the Pennines, but may be expected to reach 96 mm day^{-1}.

Similar geographical patterns of potential snow melt rate have been estimated by Hough and Hollis (1995) who, again, used an energy balance model but confined only to periods of recorded snow cover. They found that maximum daily melt rates vary widely across the UK, generally increasing from south west to north east and with increasing altitude and suggest that, rather than air temperature, it is the amount of snow available that restricts melting. From their study, it appears that North East Scotland can expect to have some of the highest melt rates in Britain with a 50 year maximum melt rate at Aviemore (228m AOD) of 65.8 mm day^{-1}.

It therefore seems that large daily melt rates occur when energy supplied to the snow pack is high but, more importantly, when sufficient snow water equivalent is available. The fact that Hough and Hollis's (1995) value of 65.8 mm day^{-1} is lower than that of Mawdsley et al. (1991) may highlight the low probability of snow water equivalents of this magnitude coinciding with maximum values of energy balance components at such altitudes. Naturally, at higher altitudes in Scotland, high snow water equivalents are more frequent, however, what is less clear is whether such high melt rates, as proposed by the authors mentioned above, are likely in the Scottish uplands.

In this paper, meteorological data from an upland automatic weather station are used to calculate potential 6-hour and daily snow melt rates for each energy balance component from January to March 2002. Total predicted melt rates are subsequently compared to hourly estimates of snow water equivalent reduction made using a nearby logging snow plate. The aim of this research is to analyse the energy balances of the highest melt rates within this study period to determine whether such rates could be sustained across the entire catchment elevation range. If it can be shown that high potential melt rates are frequently possible in late spring, at all elevations across an upland catchment, then presumably the main control upon large catchment snow melt runoff in this period is the infrequency of high catchment-wide snow water equivalents. Furthermore, if these high melt rates can be sustained without a significant input from solar radiation then such conditions can occur, albeit infrequently, early in the calendar year when snow water equivalents across the whole catchment are more likely to be high.

The study site is located on the western flank of the Cairngorm plateau, within the River Feshie catchment, with the automatic weather station (AWS) situated on a gently sloping north-westerly aspect in Coire Domhain at an altitude of 680m (figure 1)

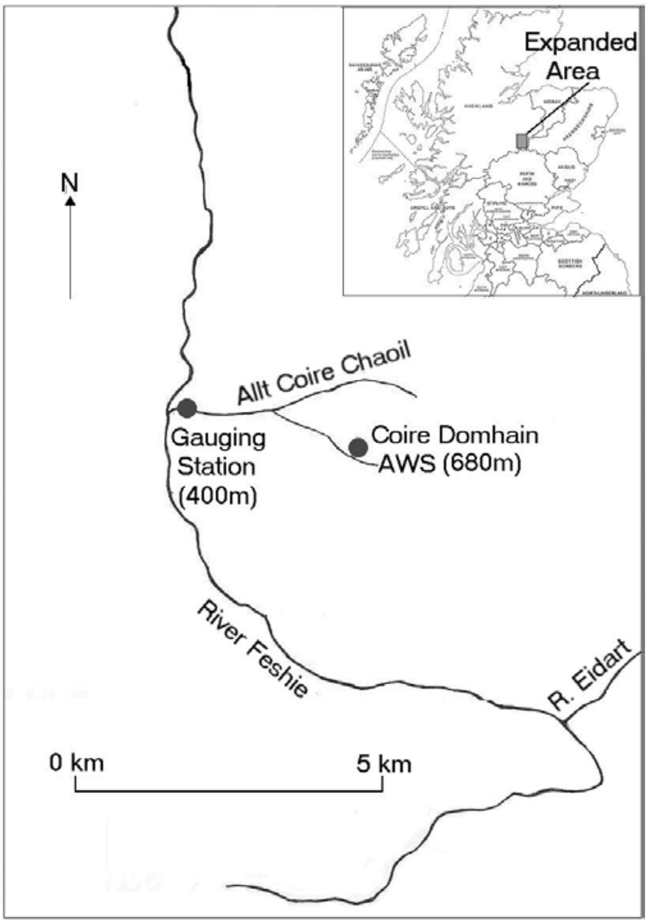

Figure 1. The study site. Inset of Scotland reproduced from Ordnance Survey map data by permission of the Ordnance Survey © Crown copyright 2001.

Methodology

Snow Pack Energy Balance Model

An energy balance model attempts to represent the main energy fluxes to a snow pack with the aim of quantifying their contributions to the overall melt. Snow packs acquire or release energy both at the surface and below, where snow is in contact with the ground. However, measurements of 5cm soil temperature within the catchment have shown that, over this study period, soil did not freeze and consequently there was no negative ground energy flux from the snow pack involved in melting the underlying surface. During periods of snow cover, soil temperature was typically less than $1^{0}C$ and it has been assumed that positive ground energy flux i.e. to the snow pack, is negligible. Similarly, energy acquired by conduction from rain is typically assumed small (Marcus et al. 1985) and in this case is ignored. Consequently, a *surface* energy balance is used to estimate melt energy flux (MF) by attempting to quantify the fluxes of: net long-wave (LWR) and short-wave (SWR) radiation, latent heat of condensation or evaporation (LHF) and turbulent sensible heat (SHF) in the form:

$$MF = SWR + LWR + SHF + LHF$$

To estimate melt energy flux and ultimately snow melt itself, a spreadsheet-based point surface energy balance model has been used, a full description of which can be found in Brock and Arnold (2000). Each hourly energy flux is calculated and converted to a melt rate in mm of water equivalent by dividing by the latent heat of fusion of water, 0.334 MJ kg^{-1}. The result is therefore a potential rate, independent of actual snow depth or density. Minimum data requirements for the model are air temperature, vapour pressure, short-wave radiation, and wind speed. Incoming long-wave radiation flux is estimated using a cloud cover index derived from the difference between potential and actual short-wave radiation, and the snow pack is assumed to radiate as a black body at 0^{o}C. Net short-wave radiation flux has been calculated using albedo directly measured by an albedometer, mounted on the weather station. Turbulent sensible and latent heat fluxes are evaluated using the 'bulk' aerodynamic method, applying the Richardson number for stability correction. Although aerodynamic roughness length varies as the snow cover depletes and hollows form or as vegetation is exposed, for the purposes of this study a single value of 0.001m is used throughout, this value falling within the range of previous estimates for a snow surface (Chamberlain 1983, Brock 1997).

Field measurement of point snow melt yield.

A snow plate has been designed to log, at hourly intervals, the mass of snow resting on a flat surface adjacent to the automatic weather station. The instrument consists of a rectangular aluminium plate suspended by cables from a load cell mounted beneath a tripod. The plate is suspended over a natural hollow such that it is flush with the surrounding ground surface, and covered with wire mesh to increase surface roughness. The output has been calibrated to Newtons in the field using weights, and subsequently converted to millimetres of water equivalent using a water density 1000kg m^{-3} and the plate surface area of 1.922 m^{2}. Verification of the snow plate measurements has been carried out using snow core sampling throughout the study period and indicates that differences in measured snow water equivalent between the two techniques are random and within a range of +/- 5%. An exception to this was a measurement taken on 15 March when heavy snowfall and accumulation from drifting had created a snow bridge between the plate edges and the surrounding ground surface, leading to an under-estimation of mass. Data from the period of onset of this snowfall (11 March) to the subsequent removal of the bridge (18 March) have been ignored in the analysis. Additionally, data was unavailable for the period of 22 February to 3 March due to the instrument being blown down in high winds.

To reduce the effect of a time lag between the onset of melt and release from the base of the snow pack (snow melt yield), all hourly values have been aggregated into 6 hour and daily totals. Data from the snow plate logger and energy balance estimates of melt have been summed to produce consecutive 6-hour totals for 0300, 0900, 1500 and 2100 hours GMT each day. Daily totals have been produced for 0900 hours GMT to conform to standard practice of precipitation recording in the UK.

Results

Comparison of measured and modelled melt rates.

A visual check on performance indicates that the energy balance model produces 6 hour and daily melt rates that correspond well to reductions in snow water equivalent as measured by the snow plate. (Figures 2 and 3). Modelled melt is significant to the 99 % level in explaining the variation in decrease of snow water equivalent for both 6 hour ($R^2 = 0.60$) and 24 hour ($R^2 = 0.87$) time periods. Root mean square errors are 1.66mm and 3.01 mm for 6 hour and 24 hour values respectively.

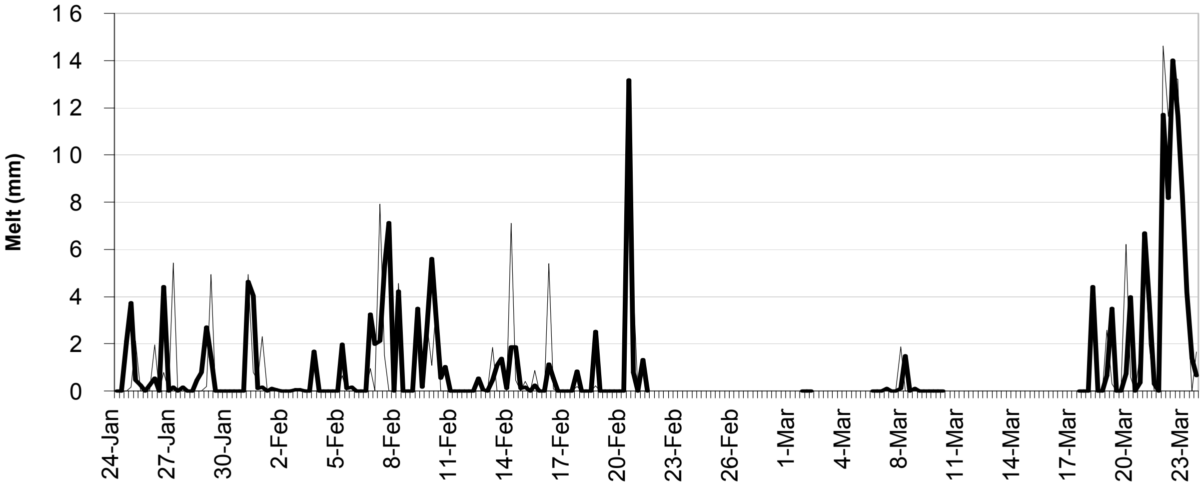

Figure 2. Measured (thick lines) and modelled (thin lines) 6 hour accumulated snow melt at Coire Domhain.

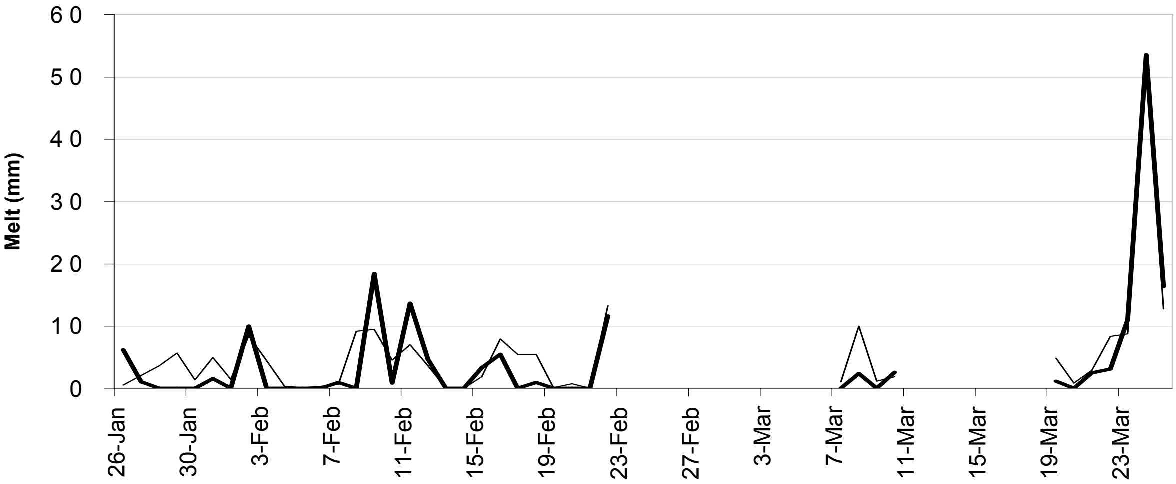

Figure 3. Measured (thick lines) and modelled (thin lines) daily snow melt at Coire Domhain

High Melt Rates

The three largest 6-hour melt rates have been identified, occurring on the 21 February, 23 March and 24 March. The last two of these events contributed to the total depletion of a deep snow pack, the initial depth of which was unknown due to bridging. However, snow core measurements taken above the snow plate on the 15 March, a few days prior to the onset of melt, indicated a snow water equivalent of 233mm.

Table 1 presents the energy fluxes responsible for these three melt events along with the estimated (M_E) and measured (ΔSWE) 6-hour melts in millimetres. All energy fluxes are in W m^{-2} with positive values indicating a net flux directed towards the surface of the snow pack. The values in parentheses show these values expressed as the number of standard deviations from the mean.

Table 1. Mean energy balance components for the 3 highest recorded 6-hour melt rates

Date	*Time*	*ΔSWE*	M_E	*LHF*	*SHF*	*LWR*	*SWR*
21 Feb	2100	13.2	8.0	56 (1.9)	91 (2.2)	-26 (1.6)	2 (-0.5)
23 Mar	1700	15.5	16.3	31 (1.3)	102 (2.5)	-33 (1.3)	153 (3.6)
24 Mar	0500	14.9	12.2	84 (2.7)	126 (3.0)	-22 (1.8)	0 (-0.6)

Table 2. Mean energy balance components for the largest daily melt

Date	*Time*	*ΔSWE*	M_E	*LHF*	*SHF*	*LWR*	*SWR*
24 Mar	1100	57.7	52.8	67	119	-25	43

Both the 21 February and 24 March melts occurred mostly after sunset, and consequently, turbulent sensible and latent heat fluxes provide virtually all of the melt energy. This energy was supplied as a result of a combination of relatively high mean temperatures (5.1 and 4.7 ^{o}C respectively) and high mean winds speeds (6.0 and 8.5 m s^{-1}), associated with warm fronts travelling over the region. The melt period ending 17:00 on the 23 March contrasts sharply to these periods in that the short-wave radiation flux dominates. This period immediately preceded the passing of the warm front during the night of 23-24 March and, as indicated by the AVHRR image at 13:18 received by the Dundee satellite receiving station, was mainly cloud free. Combined with this, the albedo of the snow pack had been in decline from a peak of 0.87 on the 15 March to 0.51 on the 23 March. Wind speeds were still high over this period (mean 8.2 m s^{-1}) although lower temperatures and vapour pressures explain the lower contributions of latent and turbulent sensible heat fluxes compared to later on that night.

Discussion

It is clear then that the greatest daily melt over the study period, 57.7 mm ending at 11:00 24 March, consisted of two distinct phases. During the afternoon an approaching warm front led to rising air temperatures and gradually thickening cloud. Over this period, short-wave solar radiation was high during the middle of the day and dominated the melt process. This type of melt is probably only possible late on in the snow season when midday solar elevation achieves mid-range values. As the sun began to set, net short-wave radiation flux fell away but this coincided with the arrival of the warm front and with it, seasonally warm and windy conditions. What followed was a second phase of melt characterised by high latent and turbulent sensible heat fluxes. Combined over the full 24 hours, it can be shown that the sensible heat flux dominated the melt process (Table 2) accounting for more energy than latent heat and net short-wave radiation combined. Although contributing to high melt rates during the middle of the day, the effect of short-wave radiation is short lived. High sensible heat fluxes on the other hand, are less limited in their period of influence, depending, as they do, upon the time taken for a warm and windy sector to pass over the region. In this case, warm air remained to the end of the data record on 25 March, after the snow pack had fully melted.

Snow melt contribution to stream level

Snow water equivalents tend to vary greatly across a catchment, not only with altitude, but also in relation to slope, aspect and curvature of the land surface. Wind redistribution, in particular, leads to a high spatial variability in snow depth with preferential accumulation in gullies and hollows and scouring over more exposed areas. Based upon field observations, the site used within this study is expected to be fairly neutral in terms of the net effect of blowing snow, and, assuming an even balance between accumulation and ablation areas of wind redistributed snow across the catchment, can be held as fairly representative of this elevation as a whole. In terms of melt, the results presented above refer to point rates at 680m and say little, directly, about snow melt across the entire catchment. Nevertheless, if it can be assumed that rates of melt at altitudes lower than 680m are at least as high as those at 680m, due to a temperature lapse with altitude, then some inference of spatially averaged potential melt rates in the middle and lower parts of the catchment can be made. To assess the influence of catchment–wide snow melt, data has been collected from a water level recorder (Figure 5) operating in Allt Coire Chaoil into which the Coire Domhain catchment drains. Although a rating curve has yet to be established, stage measurements give a visual indication of the contribution snow melt has to stream flow. The catchment is approximately $4km^2$ so lag times between precipitation or snow melt inputs and resultant stream flow are assumed to be no more than a few hours.

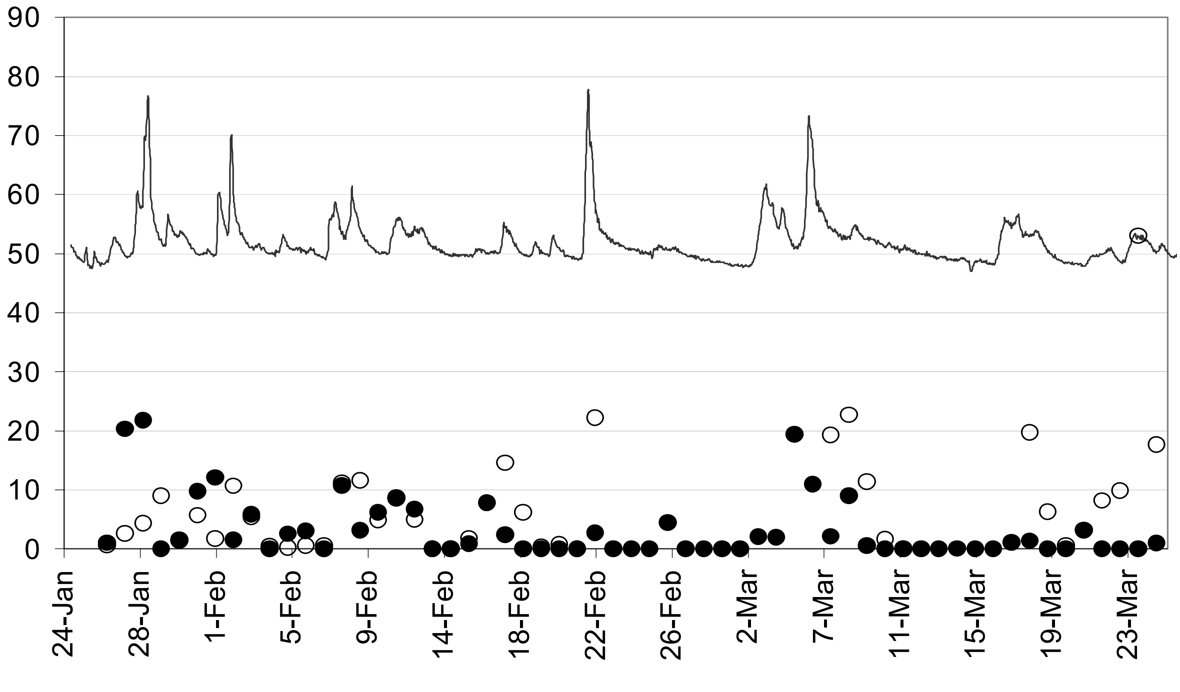

Figure 4. Hourly water level (continuous line) of Allt Coire Chaoil (400m) compared with calculated daily melt (light circles) and rainfall (dark circles) at Coire Domhain (680m). Stream level is in centimetres; melt and rainfall are in millimetres.

Using regression analysis of daily rainfall data for 13 stations located within 25km of Coire Domhain, an altitude correction factor of 1mm per 100m has been applied to non-zero daily precipitation values acquired from Meteorological Office records for Aviemore to estimate precipitation in Coire Domhain. These values have then been partitioned into rain and snow fractions depending upon air temperature. Below 0^{o}C all precipitation is counted as snow and above 1^{o}C, it is assumed to be entirely rain. Between these thresholds precipitation is divided into rain and snow linearly depending upon temperature i.e. at 0.5 ^{o}C, precipitation is half rain and half snow. Thresholds were estimated, from observations made during several ascents within the catchment during snowfalls, and conform to values used in previous research (Moore and Owens 1984, Barringer 1989). The resultant rainfall amounts can be used to assess whether increases in stream level can be attributed to rainfall or snow melt (Figure5).

Peak stream level during this study period occurs at 23:00 on the 21 February and does not coincide with high rainfall that day (2.8mm). During the previous day however 13.9 mm of snow water equivalent has been estimated at 680m and, with an average air temperature of −1.0 ^{o}C at 680m, it may be assumed that much of the catchment above the stream recorder (400m) was snow covered. It is likely, then, that the peak stream level at this point was largely a result of rapid melting occurring across a large part of the contributing area during the evening of 21 Feb. In contrast, the melt event of 23 and 24 March produces a much less prominent peak. For several days leading up to this time, moderate rates of melt had been occurring, having the effect of reducing the overall catchment snow pack. Indeed, field observations made on 15 March indicated that whilst the snow pack was deep in the vicinity of the snow plate, overall cover was patchy at this altitude and no snow was observed below 500m.

Implications for estimating snow melt contribution to flood peaks.

It is possible to draw some conclusions from this analysis which may have wider implications for the understanding of snow melt contributions to river flows in Scotland. Firstly, it is clear that, given suitable meteorological conditions, melt rates greater than 50 mm day^{-1} are possible at high altitudes in N.E. Scotland. A combination of relatively warm temperatures, high winds and high vapour pressures produce large latent and turbulent fluxes which are sufficient on their own to produce high melt rates. It should be expected that under these conditions of stability, temperature will decrease with altitude and with it, presumably so would these heat fluxes. However, it is also fair to say that wind speeds tend to increase with altitude in high relief catchments and may offset some of this decrease.

Figure 6 illustrates the potential melt from latent and sensible heat fluxes under a hypothetical scenario within the catchment using averaged hourly lapse rates of temperature and increases of wind speed with altitude for 1999/2000 derived from Meteorological Office station data at Aviemore (228m AOD) and Cairngorm (1090m AOD). Valley conditions at 400m AOD of 8^{0}C and a wind speed of 5 ms^{-1} are extrapolated upslope using the rates of -0.0068 ^{0}Cm^{-1} and 0.0042 ms^{-1}m^{-1} respectively. Although hypothetical, the meteorological conditions within this scenario are at least plausible and the exercise indicates that under warm, windy conditions, there may be a potential for high melt rates to be sustained across the entire catchment elevation range.

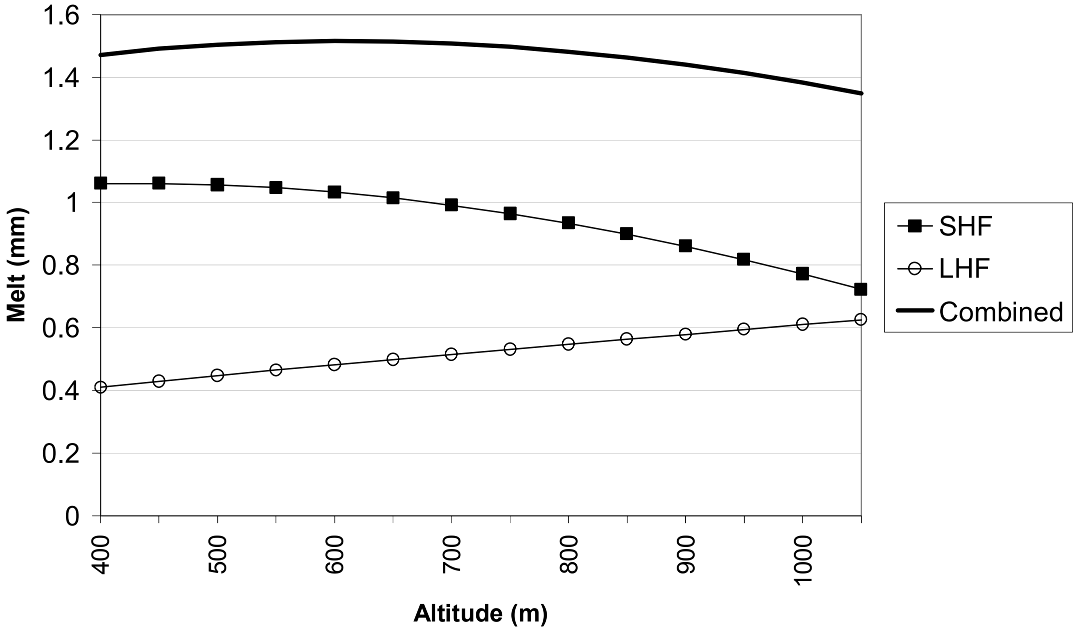

Figure 5. Turbulent sensible (SHF), latent (LHF) and combined heat fluxes across an upland catchment under hypothetical meteorological conditions. Vapour pressure is constant.

For both melt events highlighted in this study, the total amount of melt was ultimately limited by a full depletion of the snow pack. In these cases at least, the amount of available snow water equivalent was the main control upon maximum melt rates. Although no estimate can be made of the return periods of the meteorological conditions experienced during the two melt events, from the authors' experience, these conditions are not exceptionally rare during the early part of the year. The rarity of such melt rates therefore, occurring over an *entire* catchment covered with sufficient snow, probably reflects the fact that a rapid switching from cold, snowy to warm and windy conditions is necessary. However, such conditions do from time to time occur, a recent example being just prior to the Tay flood in January 1993 when a succession of deep Atlantic depressions brought both heavy rain and high temperatures to a catchment with extensive snow cover (Black and Anderson 1994). If little or no short-wave radiation is necessary to produce high snow melt rates, it may not be surprising to find episodes such as this occurring very early in the year when full snow cover is more likely.

Conclusion

The use of an energy balance model has demonstrated the valuable facility to identify the most important causes of snow melt and has shown, for the Cairngorm Mountains, the capacity for high air temperatures and high wind speeds to create melt rates in excess of 50 mm d^{-1}. Previous studies have shown that it is possible to estimate return periods for these meteorological conditions at a point, typically at low altitude, but have stopped short of extending this analysis across the full altitudinal range. An understanding of how temperature and wind speeds vary with height under a range weather patterns should make such an analysis possible.

These results have also highlighted the point that sufficient *effective* snow water equivalent is essential for snow melt to have any great impact upon river flows. The daily contributing volume of snow water equivalent is an irregular polyhedron stretched across the catchment with a depth equal to either the daily melt or snow water equivalent at that point, whichever is the smaller. On the 21 February this polyhedron was shallow but broad and caused a sharp rise in stream flow in contrast to the deeper but much less extensive volume of 23-24 March. Using empirical and/or theoretical spatial relationships within a GIS environment, it should be possible to identify return periods for both potential maximum snow melt rates and snow water equivalent depths across an entire catchment. It may then be possible to establish the maximum probable contributing volume i.e. the snow melt yield, for a particular return period.

Acknowledgements

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