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Alpine proglacial suspended sediment dynamics in warm and cool ablation seasons: Implications for global warming

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Summary Data on suspended sediment dynamics and loads obtained from the Torrent du Glacier Noir, Ecrins Massif, SE France, during the unusually warm 2003 and cooler 2004 ablation seasons are used to indicate the likely future impacts of climate warming on suspended sediment transport processes in temperate Alpine proglacial zones. Suspended sediment concentration (SSC) and discharge (*Q*) were continuously monitored for 16-day periods during July 2003 and July 2004. SSC was monitored by automated pump sampling during diurnal events in each season and supplemented by a 10 min turbidity record. *Q* was monitored at a range of flows and a rating curve used to convert a 10 min water level record into *Q*. Air temperature (AT) was also logged at 10 min intervals throughout the study.

Comparison of the 2003 and 2004 monitoring periods showed that daily mean AT measured at the site was 1.2 °C higher in 2003, mean *Q* was 2.3 times higher, and the suspended sediment load (SSL) was between 3.1 and 4.1 times greater in July 2003 than for the same period in the 2004 ablation season. There is an increase in SSC during the 2004 observation period which is less apparent in 2003, most likely because higher ATs and consequently higher *Q* earlier in the 2003 melt season had removed available sediment before the study took place in July. The rating curve method for estimating SSL produced a total load for the 16-day study period in 2003 which, when corrected upwards to account for statistical bias, was 10314 ± 743 t or 95% of the load estimated from the turbidity record for the same period. In 2004 the corrected

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SSC—Q rating curve estimate was 2504 ± 126 t while the estimate from the turbidity record was 743 ± 112 t though a more sensitive turbidity sensor produced a higher estimate of 3474 ± 302 t. While the different SSL estimation methods in 2004 are not in perfect agreement, the contrast between the two seasons is nevertheless very clear, and is largely attributed to a mean monthly regional air temperature increase of ~2.0 °C over most of the 2003 ablation season. The 2003 SSL record, compared with 2004, can be used to gain an insight into the impact of higher air temperatures resulting from global warming on SSL. Such changes in SSLs have important implications for sediment transfer from mountain to piedmont zones, for stream ecology, for downstream channel stability and flood risk, and for the hydro-electric industry.

Introduction and aims

Global mean surface air temperature has increased by 0.3—0.6 °C over the past 100 years (Jones et al., 1990). The inter-governmental panel on climate change (IPCC, 2001a) indicated that the average global surface air temperature has increased by 0.6 ± 0.2 °C since the late 19th century and is projected to increase by 1.4—5.8 °C over the period 1990—2100. The problem of global warming and its impact on water resources has begun to receive attention in recent years (Hansen and Lebedeff, 1987; Singh and Kumar, 1997; Oerlemans et al., 1998; Jones, 1999; Singh and Bengtsson, 2005). The warming of the Earth-atmosphere system is likely to change both temperature and precipitation (Singh and Kumar, 1997) which may affect both the quantity and quality of freshwater resources. The extent of global snow cover has decreased by 10% since late 1960s (IPCC, 2001a). Long-term records on glacier fluctuations indicating the mass loss and retreat of mountain glaciers, support the change in the climate in the past century (Letréguilly and Reynaud, 1990; Jaubert and Reynaud, 1993). Some glaciers like Nigardsbreen (Norway) and Franz Josef Glacier (New Zealand), on the other hand, have shown an advancing trend (Oerlemans et al., 1998). On the whole, however, a widespread retreat of mountain glaciers has been observed in non-polar regions during the 20th century (Singh and Bengtsson, 2005) and these glaciers and ice caps are projected to continue their widespread retreat during the 21st century.

Since the middle of the 20th century, the areal extent of glacierization in the European Alps has reduced by 30—40%, whereas the volume of ice has been reduced by 50% (Haeberli and Beniston, 1998). IPCC (2001b) indicated that half of Europe's alpine glaciers could disappear by the end of 21st century. Under the warmer climate, the proportion of solid precipitation in the total will reduce, resulting in a decrease in snow accumulation. Haeberli and Beniston (1998) performed simulations of high-resolution climatologies for double-CO_2 situations in the European Alps using regional climate models (RCM) with a 20 km horizontal grid. These predicted generally higher winter temperatures, a more marked increase in summer temperatures, indications that temperature increases more at higher elevations than at lower altitudes, and higher/more intense precipitation in winter, but much dryer conditions in summer. Under such conditions, the Alps would lose major parts of their glacier cover within decades, and lower limits of permafrost occurrence in the Alps could rise by several hundred meters. Pronounced disequilibria in the water cycle, in mass wasting processes, and in sediment flux could ensue, as well as in growth conditions of vegetation.

The response of hydrological systems, erosion processes and sedimentation in Alpine regions could therefore alter significantly due to climate change. Expanding proglacial zones and likely changes in erosion rates, suspended sediment yields (Warburton, 1999; Hodgkins et al., 2003) and sediment storage in such zones (Maizels, 1979; Warburton, 1990; Harbor and Warburton, 1993) may be the most important aspect of fluvial systems for determining response to environmental change (Phillips, 1991). Suspended sediment yields in particular are seen as a sensitive parameter of environmental change (Walling, 1995) since suspended sediment loads in streams and rivers tend to be supply-controlled, whereas bed load is hydraulically controlled. Thus, 'suspended sediment fluxes are likely to be more responsive to climate-driven environmental change, other factors being equal' (Hodgkins et al., 2003, p. 105).

In this study streamflow (*Q*) and suspended sediment concentrations (SSC) in a proglacial stream in the Ecrins National Park, French Alps were monitored in the summers of 2003 and 2004. Summer 2003 was exceptionally hot in France and adjacent countries, and the study uses this as a possible indication of future conditions under global warming. Table 1 presents the melt season temperatures for the region (1997—2005). A lapse rate relationship established during July 2004 between Embrun daily mean temperatures and those at the study site is used to predict daily mean temperatures at the study site, which for June, July and August 2003, can be seen to be substantially higher than both 2004 and the 1997—2005 mean. Since the monitoring for this study took place in July 2003 and 2004, Fig. 1 presents the July data only. The July 2003 and 2004 daily mean averages were 13.8 and 12.6 °C, respectively. A Students' *t*-test showed the difference in daily mean air temperatures for the two months of July 2003 and July 2004 to be statistically significant ($T = 27.3$, $p < 0.01$, $n = 1585$). July and August 2003 were exceptionally hot in France and surrounding countries (Beniston, 2004) with 14802 more deaths than expected in France in August 2003 reported by the National Institute of Health and Medical Research, widespread forest fires and exceptional rock falls in the Alps.

Based on this contrast in air temperatures between the 2003 and 2004 melt seasons, this study aimed to quantify the differences in streamflow, sediment load, and sediment

Table 1 Melt season daily mean temperatures in the French Alps (1997—2005)

	1997	1998	1999	2000	2001	2002	2003	2004	2005	1997—2005 Mean
Embrun, 44°34′ N, 6°30′ E, altitude 871 m										
April	9.6	8.1	8.6	9.3	8.1	10	9.9	9	9	9.1
May	14	14.6	15.7	15.5	15.2	13.1	14.7	12.6	14.4	14.4
June	16.3	17.7	16.6	18.5	17.1	19.7	21.5	18.2	19.1	18.3
July	18	20.6	19.9	17.9	20.2	19.9	22.5	20.2	19.7	19.9
August	20.4	20.8	19.9	20.6	21.7	19	23	19.9	18.5	20.4
September	17.9	15.2	17.5	16.5	12.9	14.7	15.8	16.5	15.9	15.9
Study site, Glacier Noir Bridge 44°55′ N, 6°25′ E, altitude 1908 m										
April	7.0	6.2	6.5	6.8	6.2	7.2	7.2	6.7	6.7	6.7
May	9.3	9.6	10.2	10.1	10.0	8.9	9.7	8.6	9.5	9.6
June	10.5	11.3	10.7	11.7	11.0	12.4	13.3	11.6	12.0	11.6
July	11.5	12.8	12.5	11.4	12.6	12.5	13.8	12.6	12.4	12.4
August	12.7	12.9	12.5	12.8	13.4	12.0	14.1	12.5	11.7	12.7
September	11.4	10.0	11.2	10.7	8.7	9.7	10.3	10.7	10.3	10.3

All temperatures at study site predicted from Embrum data using a lapse rate equation based on July 2004 daily means $y = 0.53x + 1.19$ $R^2 = 0.69^{***}$ ($n = 16$).

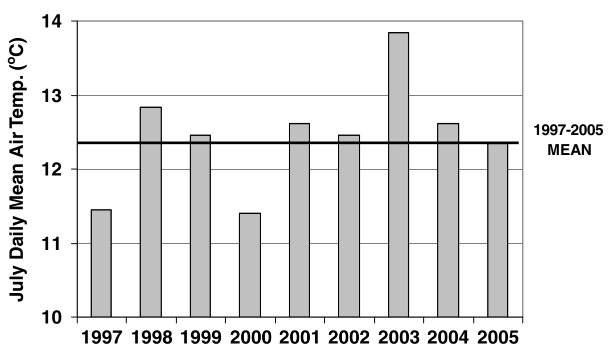

Figure 1 July daily mean air temperatures at Torrent du Glacier Noir Bridge monitoring site (44°55′ N, 6°25′ E, altitude 1908 m) for 1997—2005 (predicted from lapse-rate relationship using data from Embrun (44°34′ N, 6°30′ E, altitude 871 m).

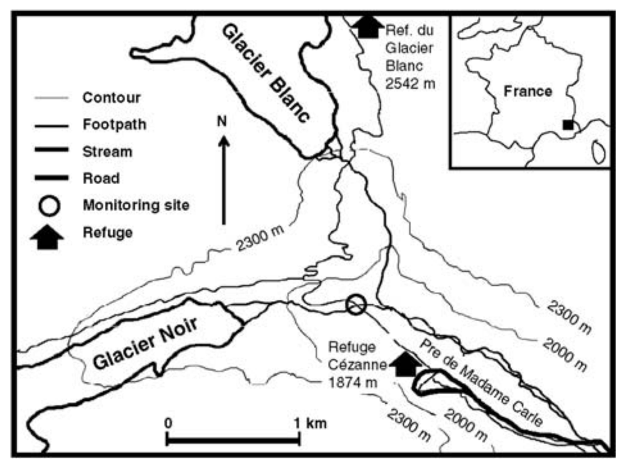

Figure 2 Location of the Glacier Blanc and Glacier Noir with monitoring station at Torrent du Glacier Noir Bridge indicated.

dynamics between a 'future' warmer scenario, as witnessed in 2003 and 'present' conditions, as in 2004.

Study area

The Torrent du Glacier Noir is one of two major watercourses flowing onto the Pre de Madame Carle (Fig. 2). The torrent emerges from the Glacier Noir (Fig. 3A), a debris covered glacier, via two major sub-glacial conduits which meet 0.5 km from the snout, and then flow over coarse moraines for a further 0.6 km to where the torrent joins the Torrent du Glacier Blanc. The gradient is steep (average is 0.18 m m^{-1} over this 1.1 km, compared to the average gradient of the Pre de Madame Carle which is 0.04 m m^{-1}), it has a boulder bed and step-pool sequences in its long profile. The catchment area draining to the monitoring station is ~15 km^2, approximately 37% of which is ice covered.

Figure 3A View of the Glacier Noir in July 2004 showing the main sub-glacial conduit from the snout and the smaller stream flowing from the snow patch on left.

Methods

A monitoring site was established at a stable cross-section where a bridge crosses the Torrent du Glacier Noir (Fig. 2) and rock filled gabions form a stable channel margin (Fig. 3B). A stage board, a High Range Partech IR15C Turbidity Sensor (0—10 000 mg/L range), a Druck pressure transducer, and an air temperature thermistor (placed in Stevenson screen 1.25 m above ground level) were installed in the same location in both seasons. Data from all sensors were logged at 10 min intervals from 9 to 24 July 2003 (16 days) and from 7 July to 4 August 2004 (29 days) by Grant and Sentry data loggers.

Stage and mV were noted during site visits so that linear mV to stage rating relationships were established ($r^2 = 0.96$, $n = 16$). A linear stage versus discharge (Q) rating relationship was achieved using the velocity—area method (Herschey, 1978). Velocity was gauged from the bridge using a Braystoke impellor type flow meter at 0.6 depth at six verticals (1 m apart) at 11 different stage values on 19 July 2003 (between 07:00 and 16:00) and checked again on several occasions in July 2004 ($n = 11$, $r^2 = 0.94$). The highly turbulent nature of the flow in these channels led us to repeat velocity readings 10 times at each vertical at the same stage based on which standard error estimates ranged from 0.07 to 0.21 (mean = 0.13) m s^{-1}. The errors in our cross-section area estimates are likely to be lower than these, suggesting that discharge values may be associated with errors in the range 0.1—0.3 $m^3 s^{-1}$.

A Sigma 900 portable water sampler was deployed at hourly and half-hourly sampling rates for 24 h and 12 h periods in each season retrieving 144 samples (72 in each season). The intake tube of the sampler was fitted with a stainless steel filter which admitted sediment of a maximum size of 2 mm. The sampler was set to flush the intake tube once prior to pumping a 0.5 L sample into each of 24 bottles. The intake nozzle was fixed to the stage board next to the turbidity sensors, 0.15 m above the bed, so as to remain within the flow at all times. The highly turbulent nature of the flow leads us to believe that suspended sediment is extremely well mixed and that values sampled at the stream margin will be representative of the whole cross-section (see Gurnell et al., 1992). Water samples were filtered through Whatman GF/D 8 μm filters in the field and filters were returned to the laboratory in Liverpool JM University for standard gravimetric analysis. Repeat weighing of filters suggests that standard errors are around 0.15 mg. We therefore estimate that suspended sediment processing is likely to be associated with errors of ±10 mg, and the measurement of volume ±5 ml, giving overall error of about 3%.

Some fine particles (<8 μm) may have passed through the filters. A sample of ten filters ranging in SSC from 75 to 1426 mg/L were analysed for their particle size distribution using a Malvern Mastersizer. The proportion of fines <8 μm ranged from 0% to 24% with a mean of 11.5%. This suggests that at least 10% of the suspended sediment is finer than the 8 μm pore size of the filters used, though it is not possible to estimate how much of this passed through filters compared with how much is trapped, but this analysis shows that some is certainly trapped. In low flow conditions, these fines could make up a reasonable proportion of the total suspended sediment load, and this should be borne in mind when examining the results which follow.

Figure 3B View of the monitoring site under the bridge (foreground) looking at the Torrent du Glacier Noir upstream towards the Glacier Noir. The northern lateral moraine of the glacier can be seen on the right.

Results

Air temperature and discharge at the Torrent du Glacier Noir

Air temperature and discharge time series are compared for the July 2003 and July 2004 study periods in the Torrent du Glacier Noir (Fig. 4). While the dataset spans a slightly longer period in 2004, Table 2 presents comparative data for air temperature (AT) and discharge (Q) for the same parts of the ablation seasons for 2003 and 2004. The large number of values means that estimates of standard error of the mean are small and we are confident that there are real differences in AT ($T = 27.3$, $p < 0.01$, $n = 1585$) and Q ($T = 102.9$, $p < 0.01$, $n = 1585$) between these periods. Mean daily AT measured at the site was 1.2 °C higher in 2003 and mean Q was 2.3 times higher. Both Q records reveal a pronounced diurnal flow pattern that is entirely temperature driven in 2003 (there was no rainfall) and predominantly temperature driven in 2004 (when ~5 mm of rain fell on 8 July 2004 and a further 5 mm fell on 16 July 2004). The early part of the 2004 record, until 15 July 2004, was significantly cooler than the second half of July 2004, with correspondingly lower discharges. The considerably lower discharges recorded in July 2004 are likely to be a result of lower temperatures early in the season (Table 1) and possibly less snowfall over the previous winter (see discussion). However, even though temperatures on the afternoon of 15 July 2004 peaked at 25.6 °C, the discharge peak 2:30 h later remained low (4.8 $m^3 s^{-1}$). In contrast, on 23 July 2004 the temperature at 15:30 h that afternoon also peaked at 25.6 °C but on this occasion the discharge peak at 18:10 h was 7.3 $m^3 s^{-1}$. Thus, discharge seemed to be more responsive to increases in air temperature later in the 2004 ablation season. Air temperature in the previous days, weeks and months is likely to have an impact on discharge as the snow line rises, the snowpack extent shrinks, glacial storage increases and sub-glacial drainage conduits begin to develop (Rothlisberger and Lang, 1987).

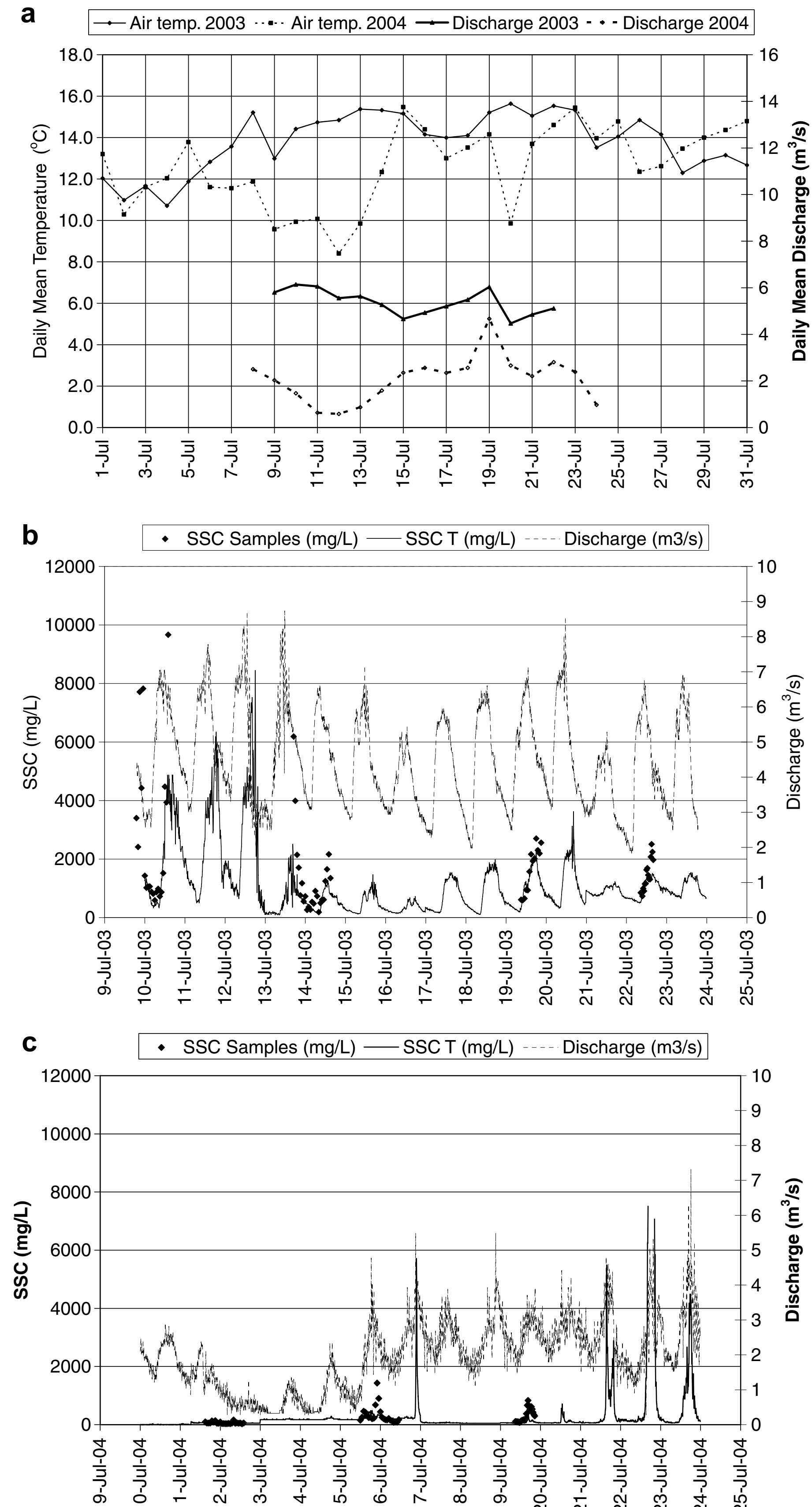

Figure 4 Air temperature, discharge and suspended sediment concentration time series compared for July 2003 and July 2004 study periods in the Torrent du Glacier Noir. NB. Data points in Fig. 4b and c show sampled suspended sediment concentration (SSC), lines show 10 min SSC predicted from turbidity measurements (SSCT) and 10 min discharge for July 2003 and 2004 observation periods.

Table 2 Seasonal comparisons between air temperature and discharge parameters for 10—23 July 2003 and 2004, Torrent du Glacier Noir

	10—23 July 2003 $n = 2016$	10—23 July 2004 $n = 2\,016$
Mean air temperature (°C)	13.8 ± 0.1	12.6 ± 0.1
Max air temperature (°C)	28.8	26.4
Min air temperature (°C)	6.4	3.4
Mean discharge ($m^3\ s^{-1}$)	4.5 ± 0.03	2.0 ± 0.02
Max discharge ($m^3\ s^{-1}$)	8.7	7.3
Min discharge ($m^3\ s^{-1}$)	1.8	0.3

Suspended sediment, discharge and turbidity

Summary statistics for SSC and Q (Table 3) highlight the variability within, and differences between, the 2003 and 2004 study periods. The SSC versus Q relationship (Fig. 5) in 2004 (all samples) shows less scatter ($R^2 = 0.66$, $n = 72$) than in 2003 ($R^2 = 0.33$, $n = 72$). In the 2003 melt season air temperature (Table 2) and corresponding discharge (Fig. 4) was considerably higher. The higher 2003 air temperatures early in the observation period (8—15 July) caused higher discharge which seems to have flushed through readily available sediment rendering the system relatively more supply limited for the remainder of the 2003 observation period. Discharge early in the 2004 melt season was significantly lower, so that when it did begin to rise in mid-July 2004, there was a plentiful supply of in-channel and channel margin sediment available for transport, making SSC more sensitive to changes in Q as indicated by the slopes of the SSC versus Q regressions in Table 4 and Fig. 5, and the apparent departure from the power-law model during the highest flows in each season (Fig. 5).

When the SSC data sampled over four and three separate 24 h periods in 2003 and 2004, respectively are plotted separately, the relationships are generally stronger, especially in 2003 (Table 4) suggesting that combining data into one seasonal rating relationship fails to take account of the individual characteristics of each diurnal flood event. Indeed,

Table 3 SSC and Q comparisons by sampling events for the 2003 and 2004 ablation seasons

	2003 ablation season				2004 ablation season		
Sampling date (s)	9—10 July 2003	13—14 July 2003	19-July 2003	22-July 2003	11—12 July 2004	15—16 July 2004	19 July 2004
No. samples	20	23	13	16	24	24	24
Mean SSC (mg/L)	2784	1267	1631	1430	64	321	308
Max SSC (mg/L)	9664	6188	2700	2506	160	1426	830
Min SSC (mg/L)	592	188	600	736	28	82	74
Mean Q (m^3/s)	5.4	6.1	5.9	6.1	1.0	1.9	2.6
Max Q (m^3/s)	8.1	8.7	7.4	7.7	1.7	3.2	3.7
Min Q (m^3/s)	3.5	3.9	3.5	2.6	0.3	0.9	1.5

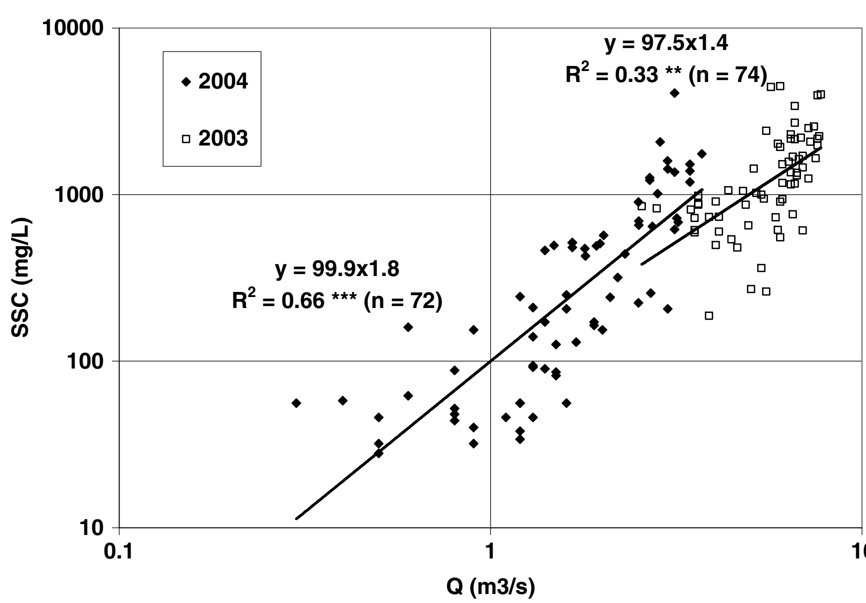

Figure 5 Suspended sediment concentration v discharge rating curves for the 2003 and 2004 ablation seasons.

Table 4 Event based and seasonally combined rating relationships for SSC and *Q* and SSC and *T* for 2003 and 2004 ablation seasons in Torrent du Glacier Noir

Sampling date (s)	Sampling frequency (min)	SSC versus *Q* rating				SSC versus turbidity rating			
		a	*b*	R^2	Corr. fact.[a]	*a*	*b*	R^2	*n*
2003									
9–10 July 2003	60	1.42	2.67	0.58	1.53	4276.30	0.18	0.02	20
13–14 July 2003	60	0.94	2.61	0.54	1.48	4137.60	1.04	0.80	23
19-July 2003	30	1.34	2.39	0.76	1.20	9014.20	1.46	0.59	13
22-July 2003	30	2.47	0.85	0.57	1.09	18642.00	1.58	0.72	17
All 2003		*1.93*	*1.59*	*0.29*		*2877.00*	*0.5*	*0.19*	*74*
2004									
11–12 July 2004	60	1.77	0.26	0.06	1.13	545221.00	3.67	0.11	24
15–16 July 2004	60	2.06	1.24	0.32	1.30	58598.00	2.31	0.15	24
19-July 2004	30	1.45	1.56	0.66	1.37	600006.00	3.74	0.96	24
All 2004		*1.92*	*1.23*	*0.56*		*800000.00*	*5.5*	*0.54*	*72*

[a] Corr. fact = Correction factor applied to overcome load underestimation due to statistical bias (Ferguson, 1986).

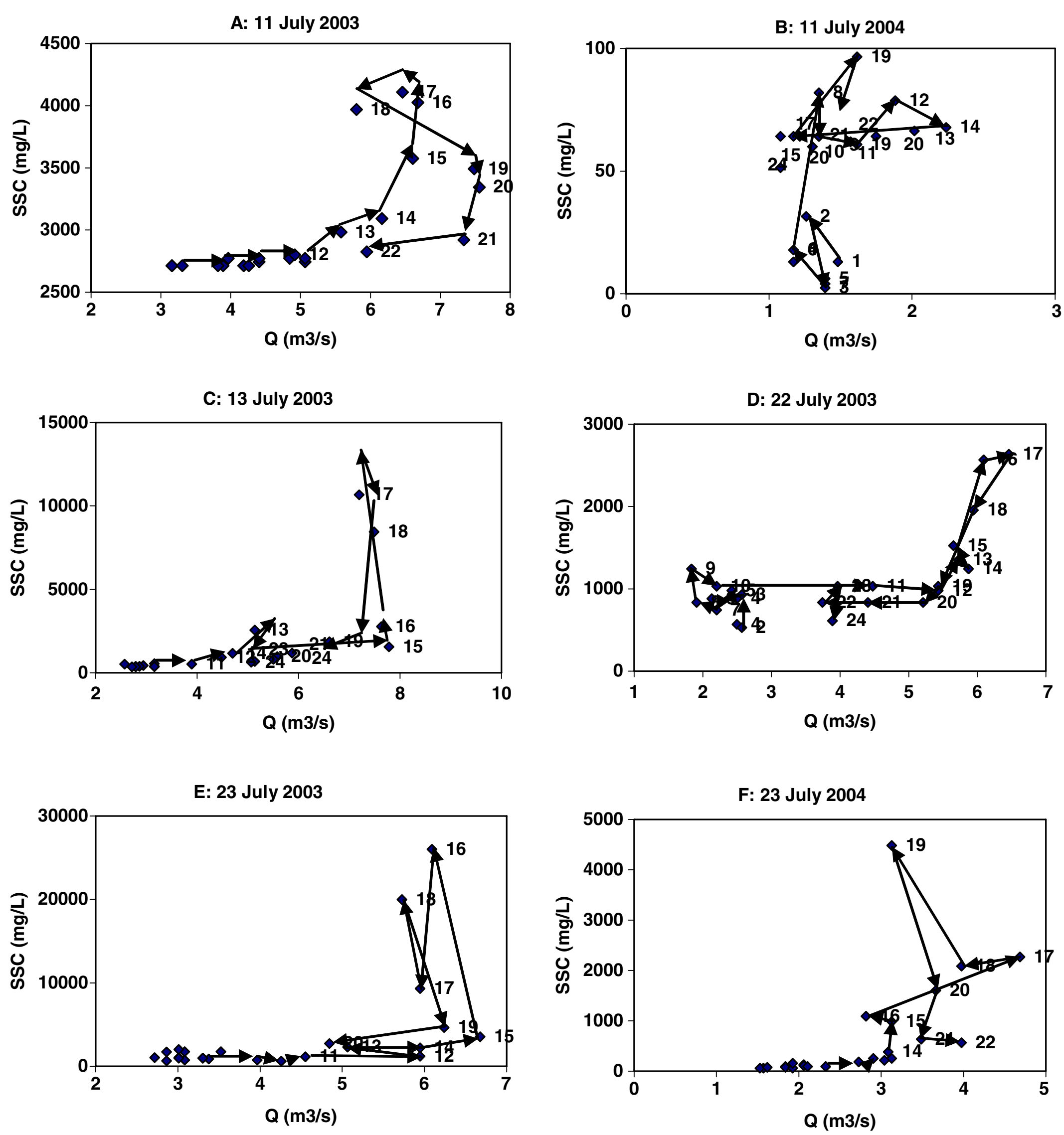

Figure 6 Hysteresis loops for selected diurnal flood events from 2003 and 2004. Point numbers refer to the hour of the day. NB. Different scales on both *x*- and *y*-axes.

scatter in SSC versus Q relationships is widely recognised (Østrem, 1975; Collins, 1979; Bogen, 1980; Klein, 1984; Richards, 1984; Williams, 1989; Hodgkins, 1996) and this presents difficulties when combining the SSC versus Q rating curve with Q time-series to predict un-sampled SSCs for the purpose of computing suspended sediment loads (SSLs). When SSC and Q are non-synchronous, hysteresis loops will be clockwise (when SSC peaks before Q) and anticlockwise (when Q peaks before SSC). Strong clockwise hysteresis suggests very short sediment travel distances (e.g., Orwin and Smart, 2004) while anticlockwise hysteresis (Klein, 1984) suggests the sources are more distant or that sediment is supply limited. Hysteresis loops for six diurnal flood events from both seasons of the study (Fig. 6) show no dominant clockwise or anticlockwise hysteresis and the patterns early and later in the study period do not seem to be significantly different. These patterns suggest that the suspended sediment sources are highly variable. We suggest that as Q rises, fine sediment stores within the fluvio-glacial gravels at the channel margins are mobilised at different rates and at different times giving rise to highly non-synchronous SSC and Q time-series and the attendant scatter in Fig. 5. The deployment of turbidity sensors can help to overcome this problem, but we experienced a similar issue when calibrating the sensor. Fig. 7 shows how the SSC versus T rating relationships for each season also exhibit considerable scatter, particularly in 2003 when the R^2 value (0.19) is not significant, even though three of the four flood event relationships are significant (R^2 values of 0.80, 0.59, 0.72, respectively, but the event of 9—10 July 2003 is not). The SSC samples, SSC record predicted using the turbidity sensor, and Q are shown in Fig. 4B/C. In 2003 the first event sampled on 9—10 July gave the highest SSCs which showed little dependence on Q. The highest SSC reached 9664 mg/L, but the samples and turbidity record show SSCs frequently exceeding 2000 mg/L throughout the observation period. With the exception of a spike on 17-July, the 2004

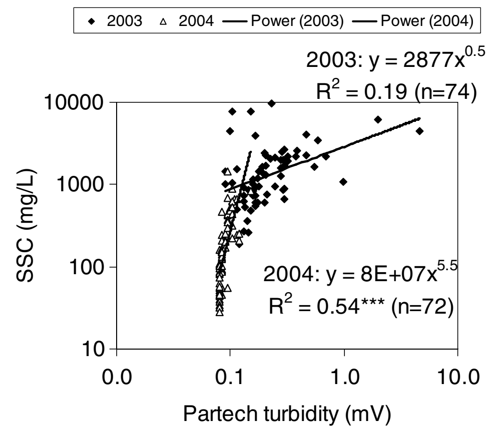

Figure 7 Suspended sediment concentration versus Partech turbidity relationships for 2003 and 2004 monitoring seasons.

Table 5 Suspended sediment load estimates for Torrent du Glacier Noir in 2003 and 2004

		2003			2004		
		SSL *QR* (t)	SSL *QR* (t) corrected	SSL *T* (t)	SSL *QR* (t)	SSL *QR* (t) corrected	SSL *T* (t)
(1)	10-July	1097 ± 77	1678 ± 118	1370 ± 37	12 ± 0.2	14 ± 0.2	1 ± 0.04
	11-July	1275 ± 91	1951 ± 139	1383 ± 44	8 ± 0.2	9 ± 0.2	7 ± 0.3
	12-Jul	1364 ± 117	2087 ± 179	1419 ± 53	3 ± 0.1	3.4 ± 0.1	3 ± 0.07
(2)	13-Jul	324 ± 32	480 ± 47	900 ± 167	4 ± 0.4	5 ± 0.4	9 ± 0.4
	14-July	249 ± 15	369 ± 22	800 ± 121	11 ± 1	14 ± 1	15 ± 1
	15-July	214 ± 16	317 ± 24	639 ± 85	42 ± 4	55 ± 4	39 ± 3
	16-July	115 ± 6	170 ± 9	157 ± 8	79 ± 5	103 ± 5	104 ± 21
(3)	17-July	315 ± 22	378 ± 26	140 ± 10	221 ± 9	303 ± 9	15 ± 0.4
	18-July	405 ± 30	486 ± 36	534 ± 122	204 ± 16	280 ± 16	9 ± 0.3
	19-July	442 ± 31	530 ± 37	471 ± 27	221 ± 9	303 ± 9	20 ± 2
	20-July	576 ± 43	691 ± 52	397 ± 29	247 ± 11	338 ± 11	26 ± 3
(4)	21-July	296 ± 9	323 ± 10	476 ± 38	267 ± 18	366 ± 18	148 ± 25
	22-July	379 ± 20	413 ± 22	438 ± 30	195 ± 20	267 ± 20	*125*[a]
	23-July	405 ± 20	442 ± 22	1697 ± 262	325 ± 32	445 ± 32	222 ± 34
Totals (t)	7456 ± 529	10 314 ± 743	10 821 ± 1033	1840 ± 126	2504 ± 126	*743 ± 112*	
Mean daily yield (t km^{-2} d^{-1})	32	44	47	8	11	3	

SSL *QR* = Suspended sediment load estimated by predicting SSC from the SSC versus Q rating curves, one for each period 1—4.
SSL *T* = Suspended sediment load estimated by predicting SSC a 0—10 000 mg/L Partech turbidity sensor, different rating curves used, one for each period 1—4.
*SSL *QR* (t) corrected = Correction factor applied to overcome load underestimation due to statistical bias (Ferguson, 1986).
[a] On 22-July 2004 the Turbidity Sensor grossly overpredicted SSCs (where turbidity readings were considerably higher than the calibration range). The SSL for that day is interpolated from the relationship between SSL *QR* and SSL *T* and entered in italics as 125 t so that the column total has more meaning.

record shows significantly lower sampled SSCs and lower SSCs predicted from the turbidity record right up until 21-July when the turbidity record again predicted SSCs in the 6000–8000 mg/L range on two days at the end of the period which were not sampled.

Suspended sediment loads

Suspended sediment loads (SSL) were estimated in two ways (Table 5). First was the rating curve or duration curve method using a log–log rating curve, where unmeasured SSCs are estimated from Q using least squares regression (e.g., Walling, 1977; Walling and Webb, 1981; Carling, 1984; Fenn et al., 1985). Statistical considerations show that the SSL is likely to be underestimated by as much as 50% using this method and so a correction factor exp $(2.65\,s^2)$ (Ferguson, 1986) was applied to the SSLs estimated in this way. It is clear that the individual, event-based relationships (Table 4) are usually stronger than the combined rating curve for the whole 16-day record. Therefore, four separate rating relationships (Table 4, left) were used in 2003, and three in 2004 which were applied to the 3–4 day periods (identified in Table 5) within which the samples were collected. These 3–4 day periods within the record spanned 1–2 days either side of the 24 h period when water samples were retrieved at hourly intervals. SSC was predicted from Q using the regression relationships. In the second method, 10 min SSC was predicted from the 10 min turbidity record. Again four separate rating relationships were used in 2003, and three in 2004 (Table 4, right). Once 10 min SSC had been predicted by each method, loads ($Q \times$ SSC) for each 10 min period were computed and the daily totals were converted into tonnes. Standard errors (SE = $s/\sqrt{n}$, where s = standard deviation and n = 144) for each daily load were calculated from the 144 instantaneous loads per day (computed for each 10 min period) and appear in Table 5.

Discussion

Suspended sediment loads (SSL) were estimated for the two methods deployed in this study. Their reliability and representativeness is discussed by Gurnell et al. (1992). Table 5 reveals that the corrected loads obtained by the rating curve method ('SSL *QR* Corrected' in Table 5) produced a total load for the study period in 2003 which is 95% of the load estimated from the turbidity record (SSL *T*). However, in 2004 the rating curve method computes a considerably higher load than SSL *T*. There is some uncertainty in the 2004 turbidity record when on 22-July it grossly overpredicted SSCs (see note[a] in Table 5) when the sensor may have become buried at some point, then flushed clear later. Due to the low turbidity observed in the Torrent du Glacier Noir in early July 2004, a Low Range Partech Turbidity sensor (0–750 mg/L) was also deployed at the same site since there was concern that the 0–10 000 mg/L range sensor may not be sensitive enough to record the low SSCs observed. The load computed from the Low Range Turbidity sensor record was 3474 ± 302 t which is higher than that estimated by SSL QR for 2004, even when corrected for bias. In future work a turbidity probe with range of somewhere between these two extremes (e.g., 0–2500 mg L_1) may be more appropriate for work in this environment, but calibration using hand or pumped samples will still be necessary throughout the monitoring period since this analysis demonstrates how the SSC versus Q and SSC versus T relationships change considerably throughout a 16-day period (Table 4).

The SSLs estimated from the 10 min turbidity record in this study are perhaps less likely to underestimate SSLs than by using the hourly and half-hourly pump sampling strategy used to derive the SSC versus Q rating curves (Olive and Reiger, 1988; Gurnell and Warburton, 1990). Experiments undertaken by Gurnell and Warburton (1990) at the Glacier de Tsidjiore Nouve and Bas Glacier d'Arolla in Switzerland, reported that SSC series derived from 1.5 min turbidity records were characterised by frequent short flushes which form an important component of the SSL (46% and 37%, respectively for the two aforementioned glaciers). Even the 10 min record used in this study may well have 'missed' important information and could result in underestimates of SSL by this method also. However, for the purposes of this study, we are confident that by applying the same techniques to both the 2003 and 2004 datasets, we are making a fair comparison and we assume that the errors and limitations apply equally to both seasons since the monitoring, sampling and analysis techniques have been deliberately kept consistent for both the 2003 and 2004 datasets. Tables 4 and 5 clearly demonstrate the seasonal differences which we attribute to the exceptionally warm air temperatures in April–July 2003 (Table 1). Not only was the mean monthly air temperature for July 2003 at Embrun 1.2 °C higher than for July 2004, but the preceding months of the ablation season were also much warmer than the 1997–2005 average and warmer than in 2004. In contrast, the April–July 2004 ablation season was cooler than the same months in 2003, and in April, May and August was cooler than the 1997–2005 average.

The 2003 SSL record, compared with 2004, can usefully be used to gain an insight into the impact of higher ATs and ensuing Q on SSL. Even when the error estimates in Table 5 are considered, there are still clear differences in the SSL (as estimated by two methods) between each season. Daily mean AT measured at the site was 1.2 °C higher in 2003, mean Q was 2.3 times greater and the suspended sediment load (SSL) was between 3.1 and 4.1 times greater in July 2003 than for the same period in the 2004 ablation season. Thus, there is a real difference in the SSLs between the seasons.

Parallels may be drawn between the results from this study and the likely impacts of higher alpine summer temperatures as a result of global warming. Global climate models (GCM) such as the Hamburg climate model (Timmreck et al., 1999) typically adopt changes in temperature and precipitation in the range 1–3 °C and −10% to +10%, respectively. In the Himalayan Spiti River, Singh and Kumar (1997) used the UBC watershed model to simulate the hydrological response of the basin under the changed climatic scenarios indicated above. For example, an increase of 2 °C in air temperature enhanced annual snowmelt runoff, glacier melt runoff and total streamflow in the range 4–18%, 33–38% and 6–12%, respectively, whereas the effect of change in precipitation (P − 10% to P + 10%) suggests a linear increase in snowmelt runoff and total streamflow, while glacier melt runoff is inversely related to changes in precipitation. Under a warmer climate scenario, Singh and Kumar conclude that snowmelt runoff and glacier melt runoff cause an earlier response of total streamflow and a change in flow distribution.

In the Ecrins, a mean monthly regional air temperature increase of ~2.0 °C over most of the 2003 ablation season is shown to increase mean discharge by 2.3 times during the 16-day study in July as compared with the same period in 2004, and to increase SSLs by between 3.1 and 4.1 times in this 16-day period. Clearly there are a number of factors which can affect this pattern. First, the amount of winter snowfall higher up in the catchment will influence summer meltwater discharges. As a crude indicator, January–July precipitations totals for Embrun (44°34′N, 6°3′E, altitude 871 m) were 341 mm in 2003, 247 mm in 2004 and 271 mm in 2005. While totals up on the Glacier Noir above the study site are likely to be considerably higher, with a greater proportion falling as snow, these figures do give some indication that the higher precipitation in January–July 2003 may have resulted in a greater availability of snow for melting by the higher 2003 ablation season temperatures. This needs to be borne in mind when interpreting these findings, as does the fact that much of the lower Glacier Noir is covered in a thick layer of debris (Fig. 3A) which may result in different melt responses in the two seasons. Second, suspended sediment supply is of major importance. It could be that the high SSLs in July 2003 resulted in removal of the available sediment in sub-glacial, ice marginal and proglacial storage zones, so that the SSLs in July 2004 were substantially lower because the sediment supply had been exhausted in the previous season (Gurnell, 1987). It could take several 'normal' seasons for this sediment supply to be replenished. It is also important to note that this study has only examined a part of the total melt season, and so it is not possible to comment on how these findings might scale-up to the whole melt season. Clearly, in a global warming scenario where mean monthly temperatures rose by $T + 2.0$ °C year-on-year, the system would be unlikely to be able to sustain the sorts of *Q*s and SSLs seen in the Torrent du Glacier Noir in July 2003. Caution should therefore be exercised in extrapolating the differences in SSLs reported here to multiple future seasons in a warmer climate. Thirdly, there is a question about suspended sediment storage between the glacier snout and the monitoring site, a distance of around 1 km.

Warburton (1999) suggests that proglacial river systems provide the key link between glacial processes and the wider environment and addresses the question of sediment storage. Warburton (1990) found that 23% of the sediment yield of Bas Glacier d'Arolla, Switzerland, was eroded from the proglacial zone, whereas Maizels (1979) reported that 16% of the fluvial sediment from Glacier des Bossons, France, was redeposited in the proglacial valley sandur. Hodgkins et al. (2003), working on the Finsterwalderbreen proglacial zone in Svalbard, showed a net increase in suspended sediment storage in the proglacial area (aggradation) in the 1999 ablation season while in contrast the 2000 ablation season showed a net decrease in storage (denudation). Orwin and Smart (2004) found that the proglacial area was the source for up to 80% of the total sus-

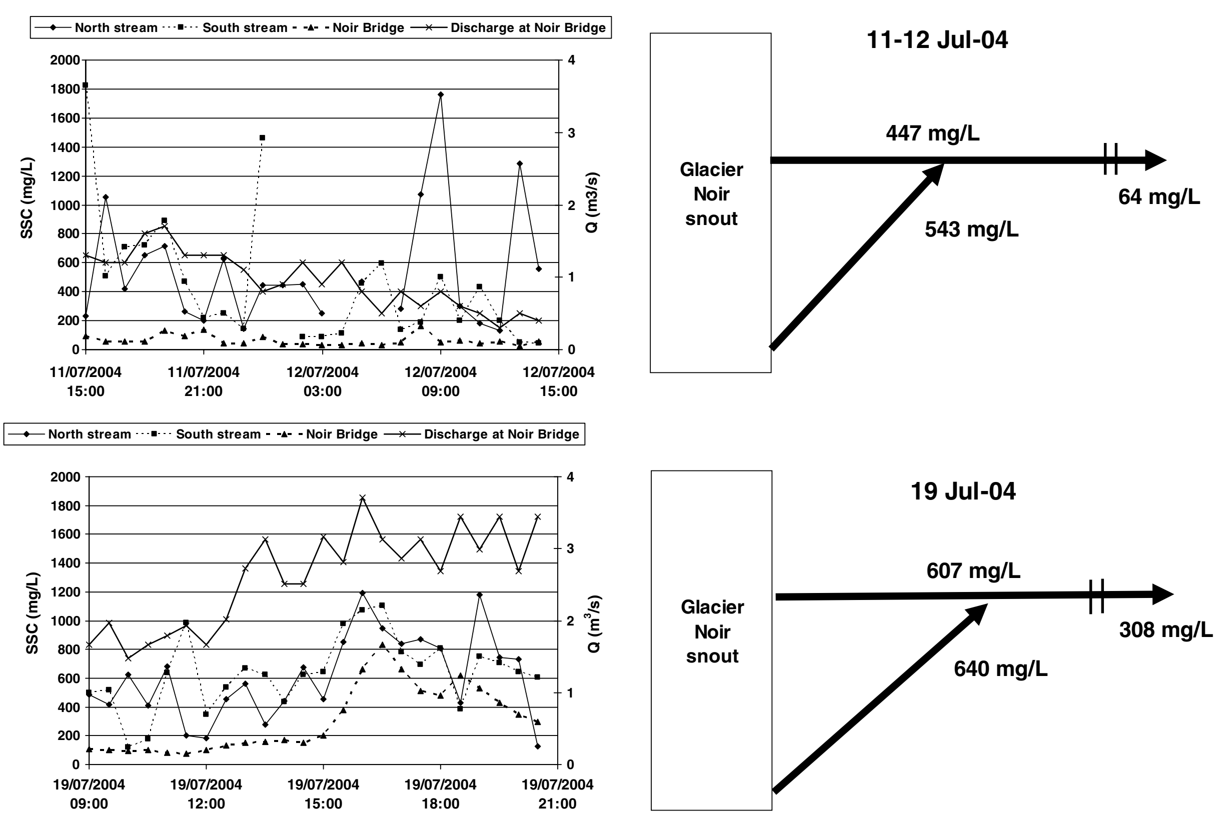

Figure 8 Results of upstream and downstream synchronous SSC sampling on Torrent du Glacier Noir for 11–12 July and 19-July 2004 (upstream data from Patton, 2004). NB. Figures on right schematics are mean SSCs ($n = 24$).

pended sediment yield transferred from the Small River Glacier basin in Canada. Distinguishing the proportion of sediment load derived from contemporary erosion, as opposed to that reworked from stored sediments (Harbor and Warburton, 1993), is clearly important. In glacierised basins, where sediment transport often takes place in large, discontinuous events at diurnal and seasonal timescales (Bogen, 1980; Fenn, 1989; Gurnell et al., 1994; Hodgkins, 1996; Stott and Grove, 2001), quantifying transport rates of sediment entering proglacial zones is particularly important for an understanding of sediment transfer across such zones.

In order to gain some insight into sediment transport dynamics between the glacier snout and the monitoring point in this study, data from another study (Patton, 2004) are considered. Patton collected samples in the north and south glacier Noir conduits (see Fig. 2) some 300 m from the snout and 20 m from their confluence. Samples were collected by dipping a 0.5 L bottle into the flow, and were processed by filtration using the same method as described earlier. Sampling was synchronous with the Sigma automatic sampler deployed at the monitoring site on 11–12 July 2004 and 19 July 2004. Fig. 8 presents the findings which clearly show much higher mean SSCs near to the glacier snout than at the monitoring site. The difference is greatest during the low discharge 11–12 July 2004 period, when SSCs at the monitoring site were only 13% of those sampled closer to the snout. During higher discharges on 19 July 2004, this difference was 49%. Thus, during these two sampled periods, suspended sediment must have been entering storage somewhere in the channel between the upstream and downstream sampling points (0.5 km apart). In the longer term, presumably, at least some of this sediment is flushed out during high discharge events, as witnessed during a rainstorm which coincided with high temperatures on 18 July 2005. So, it remains a possibility, though we consider an unlikely one, that the differences in SSLs between the July 2003 and July 2004 observation periods in this study could be due to changes in sediment storage in this 1 km reach between the glacier snout and monitoring station.

Nevertheless, we believe that the dataset presented here provides a real field-based example of how global warming could impact upon suspended sediment loads in European Alpine proglacial environments. These data could be useful in future calibration of models of sediment transfer from mountain to piedmont zones, improved inputs to scenario models of glacial retreat following global warming, and better planning of sediment flushing events by the hydro-electric industry. Further work to examine the nature of sediment storage and transport over the proglacial plain of the Pre de Madame Carle, to which the Torrent du Glacier Noir is a major sediment input, is planned.

Conclusions

Comparison of 16-day monitoring periods in July 2003 and July 2004 showed that mean daily AT measured 1 km from the snout of the Glacier Noir was 1.2 °C higher in 2003, mean *Q* of the Torrent du Glacier Noir was 2.3 times greater and the SSL was between 3.1 and 4.1 times greater in July 2003, than for the same period in the 2004 ablation season. The rating curve method for estimating SSL (SSL *QR*) produced a total load for the 16-day study period in 2003 which, when corrected upwards to account for statistical bias, was 10 314 ± 743 t or 95% of the SSL estimated from the turbidity record (SSLT) for the same period. In 2004 the corrected SSLQR estimate was 2 504 ± 126 t, while that from the 0–10 000 mg/L range turbidity probe was tentatively 743 ± 122 t, and the estimate from a low range (0–750 mg/L) Partech turbidity probe deployed at the site was 3474 ± 302 t. While the two SSL estimation methods in 2004 are not in perfect agreement, the contrasts between the two seasons is nevertheless very clear and is largely attributed to a mean monthly regional AT increase of ~2.0 °C over most of the 2003 ablation, perhaps combined with greater winter snowfall. The July 2003 SSL record, compared with July 2004, can be used to gain an insight into the impact of higher air temperatures on SSL. It invites parallels to be drawn between the results from this study and likely impacts of higher alpine summer temperatures as a result of global warming. Such changes in SSLs have important implications for sediment transfer from mountain to piedmont zones, for stream ecology, for downstream channel stability and flood risk and for the hydro-electric industry.

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