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Sediment yield decline and climate change in southern Iceland

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Abstract Decreases in instantaneous river suspended sediment loads in the pristine, glacierized, Jökulsá á Sólheimasandi basin in southern Iceland are explored in relation to recent changes in water discharge, precipitation and air temperature. Sediment transport analyses are based on a series of all-year-round depth- and width-integrated suspended sediment samples taken by the Icelandic National Energy Authority from 1973 to 1992. The basin is characterized by very high suspended sediment yields (8990 t km^{-2} $year^{-1}$). Over the 1973-1992 period, however, instantaneous sediment loads have decreased by 48%, although the rate of decline is now slowing. Sediment load reductions are especially marked in spring and autumn. This is related to decreases in spring and autumn water discharges, which are only partly offset by summer melt-season flow increases. These shifts in flow seasonality relate to changes in the seasonal air temperature patterns, especially local cooling trends in March and April, and significant warming in summer. Rising precipitation over much of the period has had limited effects in sustaining sediment loads, possibly because increases are largely confined to the winter season. Climatic trends are shown to be similar throughout the north Atlantic-Scandinavian region, and a call is made for further research into their impact on runoff, sediment delivery and nearshore sediment recruitment across this zone and throughout subarctic latitudes in general.

INTRODUCTION

Studies of *potential* impacts of *projected* climate changes are now well advanced in many fields (e.g. Carter *et al.*, 1991), including hydrological implications (e.g. Gellens, 1991). However, surprisingly few studies have emerged of the influence of recent, rather than future, climate fluctuations on hydrological processes, and impacts on sediment yields have been almost entirely neglected (but cf. Collins, 1991; Lawler, 1994a). Knowledge of the stability of suspended sediment yields from glacierized basins in the face of environmental change is important for studies of erosion rates, geomorphological and glaciological processes, aquatic habitats, sediment-associated pollutant transfer, water potability, HEP generation and downstream siltation. In Iceland, where coastal stability is crucially dependent upon a copious and reliable source of land-derived sediment being recruited to nearshore zones (e.g. Tómasson, 1986), such questions become acutely important from a management perspective. The aim here is to examine recent decreases in instantaneous suspended sediment loads in the Jökulsá á Sólheimasandi glacial river in southern Iceland, in response to runoff changes forced by climate fluctuations. The paper builds on the preliminary examination of *annual* patterns in this basin by Lawler (1994a), by concentrating on *seasonal* signatures of change, by including precipitation variations, and by setting observed climatic fluctuations within a wider spatial and temporal framework.

METHODS

The Jökulsá á Sólheimasandi basin

This glacierized catchment, located at the southern tip of Iceland (19°25'W; 63°30'N), is pristine. Human activity (e.g. industry, cultivation, resource development, recreation) is nonexistent, and buildings and engineering structures are absent. This makes it ideal for the study of climate impacts on hydrological processes, and avoids obfuscation problems caused by concurrent changes in land-use which have affected similar investigations (e.g. Howe *et al.*, 1967). Drainage area at the gauging station, BGS, is around 110 km^2, 68% of which is ice-covered (Rist, 1990). Typical summer melt-season flows range from 20 to 50 $m^3 s^{-1}$, and bankfull discharge is $\sim 100 m^3 s^{-1}$ (Lawler, 1991; Lawler *et al.*, 1992). Annual precipitation (1931-1960) ranges from 1600 mm at BGS (altitude 60 m) to over 4000 mm at the basin head (1493 m) (Eythorsson & Sigtryggsson, 1971 (cited in Björnsson, 1979)). Geology is dominated by hydroclastic and acid volcanic rocks (Carswell, 1983). See Lawler (1991) for a more complete basin description.

Suspended sediment measurements

All suspended sediment data used in this paper were collected by the Icelandic National Energy Authority (Orkustofnun). The dataset used here for the Jökulsá á Sólheimasandi system runs from 1973 to 1992. It is based on over 1100 depth-integrated samples, and consists of 226 instantaneous values of (a) mean suspended sediment concentration (each value derived from compositing around six samples from different verticals), and (b) water discharge, which is measured using current metering or float gauging techniques (Lawler, 1991; Lawler *et al.*, 1992). Instantaneous sediment loads are calculated as the products of the instantaneous suspended sediment concentration and discharge values. One limitation of the dataset is the low sampling frequency (approximately monthly) which is not designed to detect short-term fluctuations (e.g. Lawler, 1994b; Lawler & Brown, 1992; Lawler *et al.*, 1992). Another is the absence of continuous all-year round flow data, although we have collected considerable continuous *melt-season* data (e.g. Lawler, 1994b; Lawler *et al.*, 1992). The important strengths of the Orkustofnun dataset, however, include: use of depth-integrated, equal transit rate, sampling techniques with recognized samplers such as the US D-49; full-width sampling; *measurement* of discharge when samples are actually withdrawn (not simply *estimation* from rating curves possibly rendered inaccurate in such dynamically-shifting channels (see Lawler *et al.*, 1992)); and some of the longest measurement series for glacierized basins anywhere which, for some Icelandic rivers, start in 1963 (Lawler *et al.*, 1992).

DECREASES IN SEDIMENT LOAD

Figure 1 shows that instantaneous suspended sediment loads are extremely high here, even for glacial rivers (Lawler *et al.*, 1992). Lawler (1994a) found mean annual suspended sediment yields here (1973-1988) of 8990 t km^{-2} $year^{-1}$ (standard error = 1285 t km^{-2} $year^{-1}$ or 14.3%). Figure 1 also shows, however, amidst the strong seasonality in sediment export characteristics of glacierized basins (e.g. Gurnell, 1995), a gradual and statistically significant decline in sediment loads over the 1973-1992 period. The least squares semilogarithmic fit to the trend in Fig. 1 is:

$$\log \text{SSL} = 1.169\,39 - 0.014\,72 \text{ YEAR } (n = 226; p = 0.05) \quad (1)$$

where SSL is suspended sediment load in kg s^{-1} and YEAR is year number (1973 = 0). Instantaneous sediment loads decreased by 48% from 14.6 kg s^{-1} to 7.6 kg s^{-1} between 1973 and 1992 (Fig. 1). The trend also suggests that the rate of sediment yield decline is now slowing: indeed, almost one-third of the decrease took place within the first quarter of the period of record, and some reversal of the overall trend since 1989/90 is also evident (Fig. 1). Annual minima appear to have more strongly declined than the maxima, decreasing by an order of magnitude from around 2 kg s^{-1} to 0.2 kg s^{-1} (Fig. 1).

A combination of factors probably control such decreases, and will relate to changes in glacial erosion processes, the nature, volume and location of fine sediment sources in relation to the glacial drainage network, material entrainment rates and mechanisms, dominant sediment delivery pathways, bulk transport efficiency and depositional opportunities. Disentangling the relative influence of each is beyond the scope of this short paper, especially when so many sediment sources abound (e.g. supraglacial material in the glacial ablation zone; englacial (tephra) debris; subglacial sediments; proglacial and morainic deposits; and exposed hillslope regoliths). The focus here,

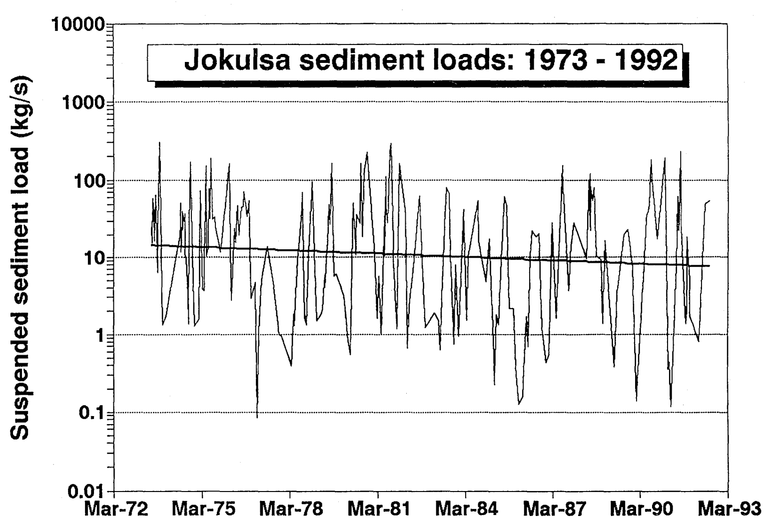

Fig. 1 Changes in instantaneous suspended sediment loads for the Jökulsá á Sólheimasandi system, 1973-1992.

however, is solely on the role of subtle shifts in climate seasonality which appear to have affected runoff and sediment transport regimes.

RECENT HYDROLOGICAL CHANGES

There is no discernible long-term trend in annual runoff in the 1973-1992 period (Fig. 2) (cf. Snorrason, 1990). However, the interpolated seasonal surface in Fig. 3 suggests that summer *melt-season* flows have been increasing over time ($p = 0.05$), at the expense

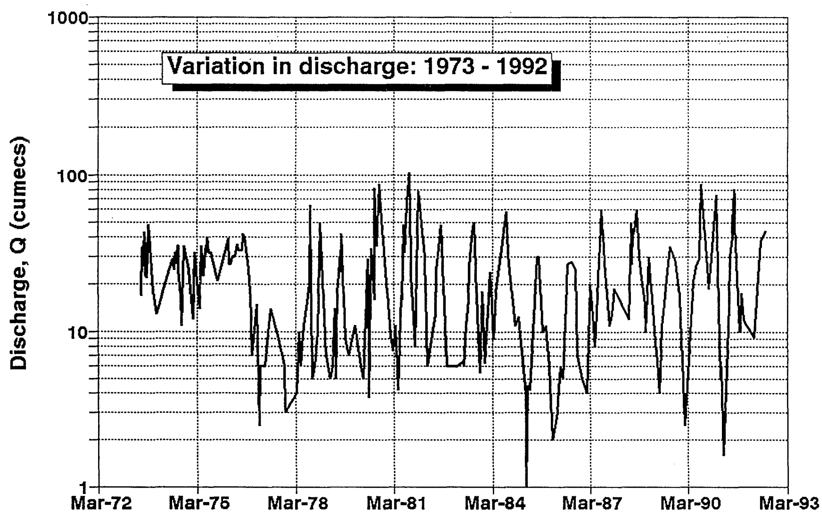

Fig. 2 Time series of instantaneous water discharges for the Jökulsá á Sólheimasandi system, 1973-1992.

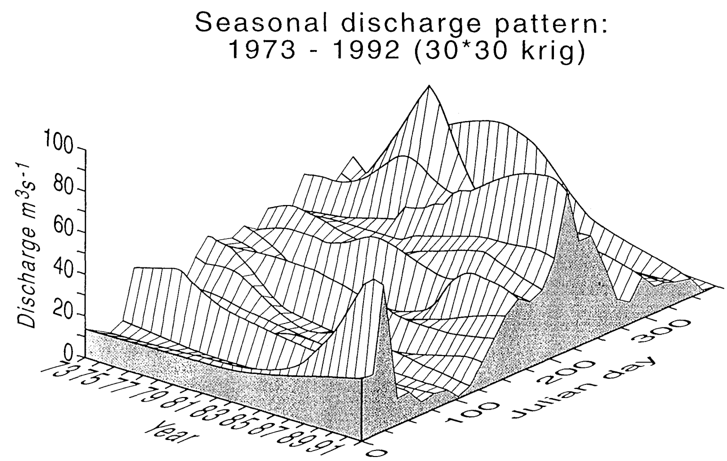

Fig. 3 Changing seasonal pattern of meltwater discharge for the Jökulsá á Sólheimasandi basin, 1973-1992. Note the significant rises in summer flows over time at the expense of decreasing spring and autumn flows.

of spring and autumn discharges. The melt season, therefore, has become shorter, but more intense, over time, which corresponds well with the seasonal pattern of sediment load decreases noted by Lawler (1994a). He found that the *summer* peak in sediment loads had been maintained or even enhanced: however, during *spring* (Julian day 60-150), lower suspended sediment loads had become more common, and high values in *autumn* (Julian day 250-330) had become rarer. It appears, then, that *summer* flow and sediment concentration increases are insufficient to offset completely the "losses" of sediment transport in *spring* and *autumn*. A greater concentration of flow into a shorter melt season may also have increased the spring and autumn stability of the glacial drainage system, resulting in fewer occasions when the subglacial sediment bed is eroded by switching channels (e.g. Collins, 1979; Gurnell, 1995).

CLIMATE CHANGE IMPACTS ON RUNOFF

These hydrological changes seem to be climatically driven. The decline in spring flows correlates well with a statistically significant lowering throughout this period of March and April air temperatures at Vík (25 km to the southwest) (e.g. Fig. 4(a)): this is likely to reduce energy available to produce meltwater in spring. Furthermore, the increase in summer flows (Fig. 3) may be a response to significant warming in the months June-September (Fig. 4(b)). The schematic summary shows that the annual picture (Fig. 5(a)) is one of decreasing suspended sediment loads despite reasonably stable discharge and temperature trends. However, this apparent stability is simply the balancing out of two conflicting seasonal patterns: river flows and temperatures are declining in spring and autumn (Fig. 5(b)), but increasing in summer (Fig. 5(c)). This demonstrates the importance of seasonal or subseasonal breakdowns in climate impact analysis. Intriguingly, annual precipitation at Skógar (5 km to the west of BGS) shows a slight *upward* trend since 1977 (Fig. 6). The seasonal picture is again important, however, and shows that most of this increase is in winter (Fig. 6), when much precipitation falls as snow. Enhanced winter snow storage probably has limited *direct* impact on sediment production or delivery rates. However, the high albedo of an enlarging snowpack (Röthlisberger & Lang, 1987, p. 220) may help to account for a delayed onset to the melt-season flow peak, while the greater volumes of accumulated snow could explain increasing summer discharges (Fig. 3) (see also McGregor *et al.*, 1995).

CLIMATE-CHANGE CONTEXTS

Air temperature trends

The current rate of summer air temperature increase at Vík (0.27°C per decade, Fig. 4(b)) is reflected elsewhere in Iceland and in other arctic and subarctic environments (e.g. Alexandersson & Dahlström, 1992; Farmer (1989) (cited in Kullman, 1992); Jónsson, 1992; Nordli, 1991). Einarsson (1991) found Icelandic warming to be more marked in winter with a rise of $\sim 0.75°C$ since 1972. Compared to south and west Iceland, however, recent warming has been more pronounced in northern and eastern Iceland (Einarsson, 1991), and it may be that even more significant

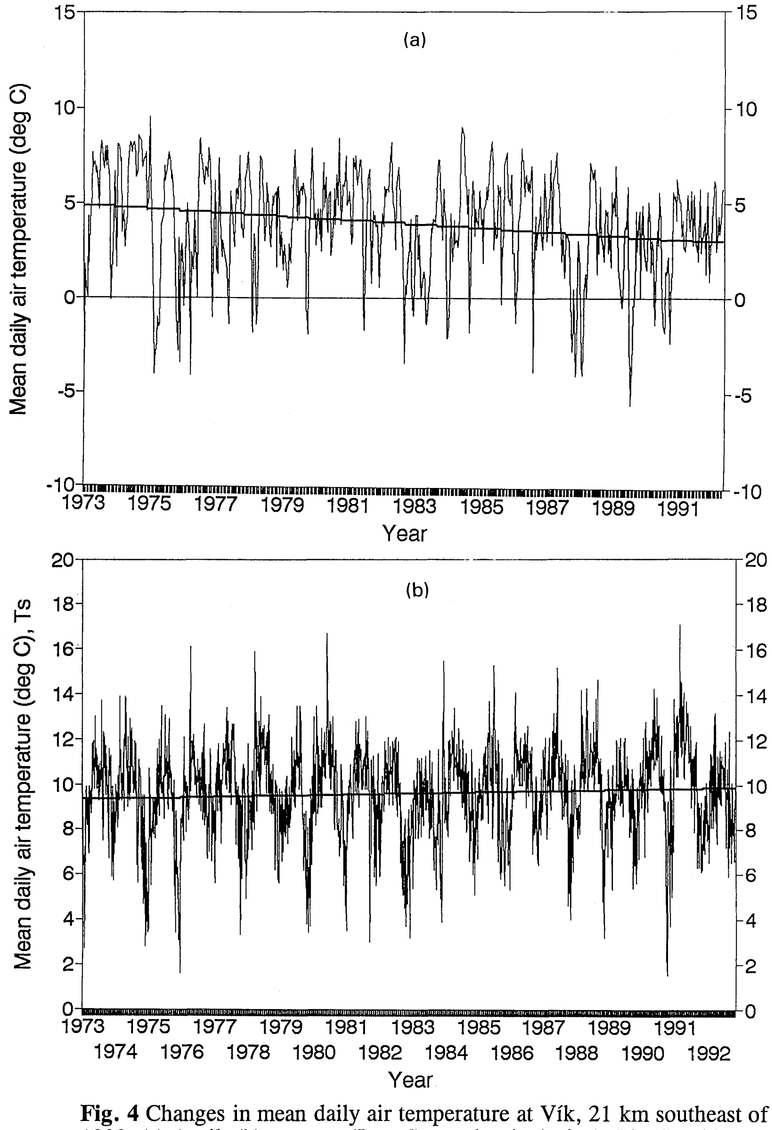

Fig. 4 Changes in mean daily air temperature at Vík, 21 km southeast of BGS, 1973-1992: (a) April; (b) summer (June-September inclusive). The fitted least squares trend to the April temperature values (T_A), in °C, against time, D (number of days from 1 January 1900) is: $T_A = 12.1 - 0.00027\,D$, equivalent to a decline of 0.99°C/decade over the study period. For the summer temperature values (T_S), the fitted linear trend is: $T_S = 7.35 + 0.000075\,D$, equivalent to a rise of 0.27°C/decade. Both trends are significant at $p < 0.0001$.

hydrological effects may be found here. Warming since the early 1970s is also evident across the north Atlantic-Scandinavian zone (e.g. Sweden (Alexandersson & Dahlström, 1992)). Decadal rates for warming since 1970 have been 0.26°C for all Arctic land areas (65°N-85°N) (Kullman, 1992) and 0.30°C for latitude 65°N (Weber, 1995).

It is important, however, to stress that this recent warming has not been continuous over the last 130 years. Although western Iceland has been *generally* warming since

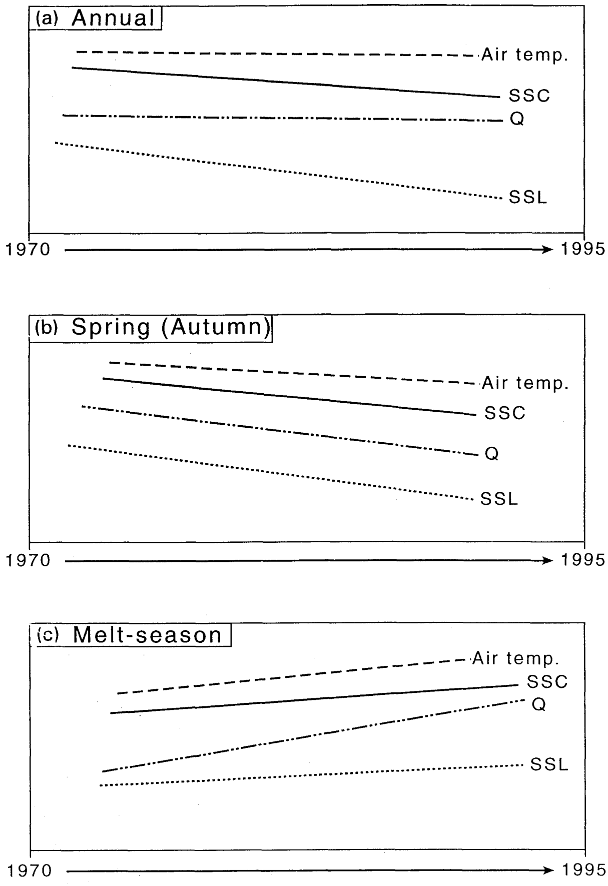

Fig. 5 Schematic summary and seasonal breakdown of main trends in temperature, discharge (*Q*), suspended sediment concentration (SSC) and suspended sediment load (SSL): (a) annual; (b) spring and autumn; (c) summer.

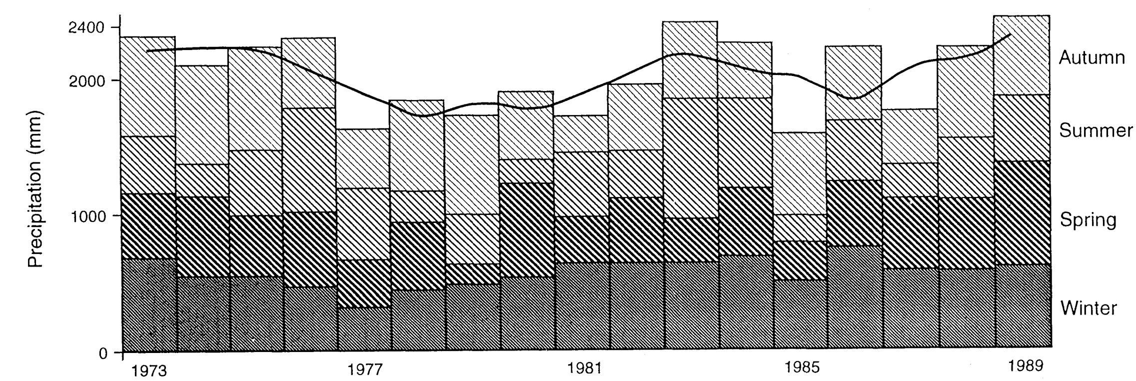

Fig. 6 Changes in seasonal and annual precipitation at Skógar, 5 km west of BGS, 1973-1989. A three-year running mean for annual precipitation is also added.

around 1860, a strong cooling since the 1940s has occurred, a trend which has only been reversed over the last 20-25 years (Jónsson, 1991). This serves to create uncertainties regarding global warming (Kullman, 1992, 1994; Weber, 1995) and highlights the difficulty in detecting longer term temperature trends.

Precipitation changes

Annual precipitation also shows an overall increase since the 1970s throughout Iceland. In southern Iceland, average annual precipitation for 1961-1990 has increased by ~10% on the 1931-1960 period (Jónsson, 1991), most of this occurring in the first half of the year (Jónsson, 1991). As with temperature, there is a positive correlation between Scandinavian and Icelandic precipitation time series, with 1970-1990 precipitation increases of some 2.5% to 4.5% in Sweden and 9.0% at Samnanger in Norway (Alexandersson & Dahlström, 1992). Climate fluctuations identified in Iceland, therefore, appear to be widespread, and their hydrological, geomorphological and glaciological implications in these other regions need to be researched.

Climate drivers

The synoptic context underlying recent climate changes needs to be understood before reliable future predictions can be made. Iceland is located in a climatological boundary zone associated with the atmospheric polar front and the oceanic polar front, which lies between the cool Arctic Ocean and warm Atlantic waters (Bergthorsson, 1988). This boundary situation explains the great variability of the Icelandic climate, and makes trends difficult to detect and predict. Warming phases, such as the last 20 years, are characterized by displacement of the Icelandic Low northwards, and the establishment of more northerly cyclone tracks (Jónsson, 1992). Westerly weather types have become more dominant in Iceland, bringing warmer and wetter conditions (Jónsson, 1992; Snorrason, 1990). Warming has been shown to be associated with reductions in average pressure (Jäger, 1988): indeed, mean surface pressure has fallen from 1007 to 1004 mb since the early 1970s (Jónsson, 1992). Lower pressure conditions correlate well with sea ice retreat northwards, which may promote some feedback as high pressure is further reduced immediately north of Iceland (Bergthorsson, 1988). At mid-tropospheric 500 mb levels there have also been changes in the circumpolar zonal index. The westerly index is now stronger, and this has also been associated with milder and wetter conditions in Scandinavia, particularly in recent winters (Alexandersson & Dahlström, 1992).

Future climate prospects

It is uncertain whether these recent climatic trends are indicative of anthropogenically induced global warming, or are related to natural climatic recovery from the Little Ice Age. Latest GCM temperature predictions have been reduced as more variables are integrated: for example, the incorporation of the effects of sulphate aerosols has lowered projected warming to accord much better with observed warming to date (Mitchell et al, 1995; Wigley, 1995). Nevertheless, possible changes still appear significant. Warming to 2050 (Mitchell *et al.*, 1995) is projected to be less in southwest Iceland (1.0°C) and more marked in the extreme north and northeast (almost 2.0°C). The Jökulsá á Sólheimasandi region might experience warming in the range of 1.1°C to 1.3°C by 2030-2050, giving a decadal warming rate to 2040 of 0.24°C to 0.29°C: this is very close to the observed summer warming rate for Vík of 0.27°C shown in Fig. 4(b). Most models also suggest continued increases in annual precipitation for Iceland, perhaps by a further 15% by 2050, with the greatest increase in winter. Again this is in line with *observed* short term trends (Fig. 6). Such climatic changes might also be expected to impact *directly* on, for example, glacier mass balance, advance/retreat patterns, rock weathering rates and sediment supply (e.g. Church & Ryder, 1972; Lawler, 1994a). If so, this could have considerable impact on water and sediment output from glacierized basins and, by implication, coastal stability in southern Iceland and the recruitment of clastic material to the north Atlantic circulation system which is thought to be sensitive to Icelandic contributions (Boulton *et al.*, 1988).

CONCLUSIONS

Suspended sediment loads in the Jökulsá á Sólheimasandi basin appear to have declined semilogarithmically over the 1973-1992 period, from an average of 14.6 kg s^{-1} to 7.6 kg s^{-1}. Some recovery is now evident, however. Decreases are restricted to spring and autumn periods. This corresponds well with a strengthening of summer discharge dominance at the expense of spring and autumn flows. Furthermore, tendencies for summer warming and spring and autumn cooling since the early 1970s appear to be driving these hydrological changes. Although suspended sediment yields will also be influenced by glacial behaviour and supply shortages, they do appear to be extremely sensitive to subtle shifts in climatic seasonality. Given that similar climatic fluctuations are evident across much of the Scandinavian region, research is needed into their impact on river flow, sediment transport and channel and coastal stability across this zone, and throughout subarctic latitudes in general. Comparisons with alpine environments (e.g. McGregor *et al.*, 1995), with their very different patterns of glacier energy balance, temperature and precipitation, would also shed light on the complexity of glaciofluvial responses to gross climate controls. Given also the often episodic nature of sediment fluxes, a focus on finely-resolved analyses of change at the event timescale would be additionally illuminating (e.g. Howe *et al.*, 1967; Lawler, 1987). With so much uncertainty surrounding regional climate scenarios – and likely hydrological, glaciological and geomorphological responses – it is not yet possible to predict future sediment yields with any certainty. However, should present trends prove to be widespread and continuing, patterns and controls of sediment supply and their impacts downstream and in coastal zones need to be closely monitored.

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