Recent changes in sediment accumulation rates in Adventfjorden, Svalbard*

OCEANOLOGIA, 46 (2), 2004.
pp. 217–231.

KEYWORDS
^{137}Cs
^{210}Pb
Sediment accumulation rates
Fjord
Svalbard

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Manuscript received 19 January 2004, reviewed 15 April 2004, accepted 10 May 2004.

Abstract

Recent sediment accumulation rates in Adventfjorden (Svalbard), a small subpolar fjord, were determined by ^{210}Pb and ^{137}Cs dating. Modern rates in the central basin decrease downfjord from 1.87 to 0.87 cm y^{-1} (2.6 to 1.19 g cm^{-2} y^{-1}). Comparison of the modern values (1986–2001) with older ones (1963–86) reveals a marked increase in sediment accumulation rates in the last ten years. This correlates well with recent climate changes (warming and increase in precipitation).

* The research was funded by the Polish Ministry of Scientific Research and Information Technology (State Committee for Scientific Research), grant No 6PO4 05621.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

Comparison with particulate matter flux data indicates that a portion of the sediment is passed on to Isfjorden.

1. Introduction

Variations in terrestrial material flux to the ocean are among the key characteristics of global change. Climate warming during last the 100 years has caused the retreat of many Svalbard glaciers (Lefauconnier & Hagen 1990, Ziaja 2001, Hagen et al. 2003) and, in consequence, the terrigenous material supply to fjords is expected to increase (Elverhøi et al. 1995, Koppes & Hallet 2002). According to Syvitski & Andrews (1994) and Syvitski (2002), a further rise in sediment flux in the Polar regions over the next 200 years is likely. It is therefore important to document modern sediment accumulation rates and to recognise the effects of recent climate changes on the fluctuations of past rates. Especially valuable for such a study are fjords in high latitudes, where recent global changes have been greatest and sediment accumulation rates are sufficiently fast to provide a high resolution record (Gilbert 2000, Svendsen et al. 2002).

Many chemical contaminants discharged into aquatic environments quickly become attached to sediment particles, so evaluation of their fate and potential effects requires an understanding of sediment transport patterns and accumulation rates. Undisturbed sediment layers of increasing age may preserve a useful history of changes in contaminant concentrations in overlying waters. Adventfjorden is potentially the most endangered fjord in Svalbard with respect to pollution, since Longyearabyen – the largest industrial settlement (coal-mining) – is located nearby (Holte et al. 1996, Siegel et al. 2000, Hop et al. 2002).

The aim of this study is to document the changes in sediment accumulation rate in a small subpolar fjord in relationship to the distance from terrigenous material sources and to trace the changes in sediment accumulation rate in the past 50 years with respect to recent climate change and potential human impact.

2. Study area

Adventfjorden is one of the southern arms of Isfjorden, the largest fjord system on Spitsbergen. 8.3 km long and 3.4 km wide, this fjord is oriented south-east to north-west and located between 78°13′ and 78°17′N and 15°25′ and 15°46′E (Fig. 1). The innermost part of Adventfjorden is composed of a tidal flat with a 0.6–0.9 km wide intertidal zone and a gently falling surface (0.1°). It ends with a steep slope (15–19°) descending to a depth of 30 m. The central basin is 60 to 100 m deep and the depth increases downfjord.

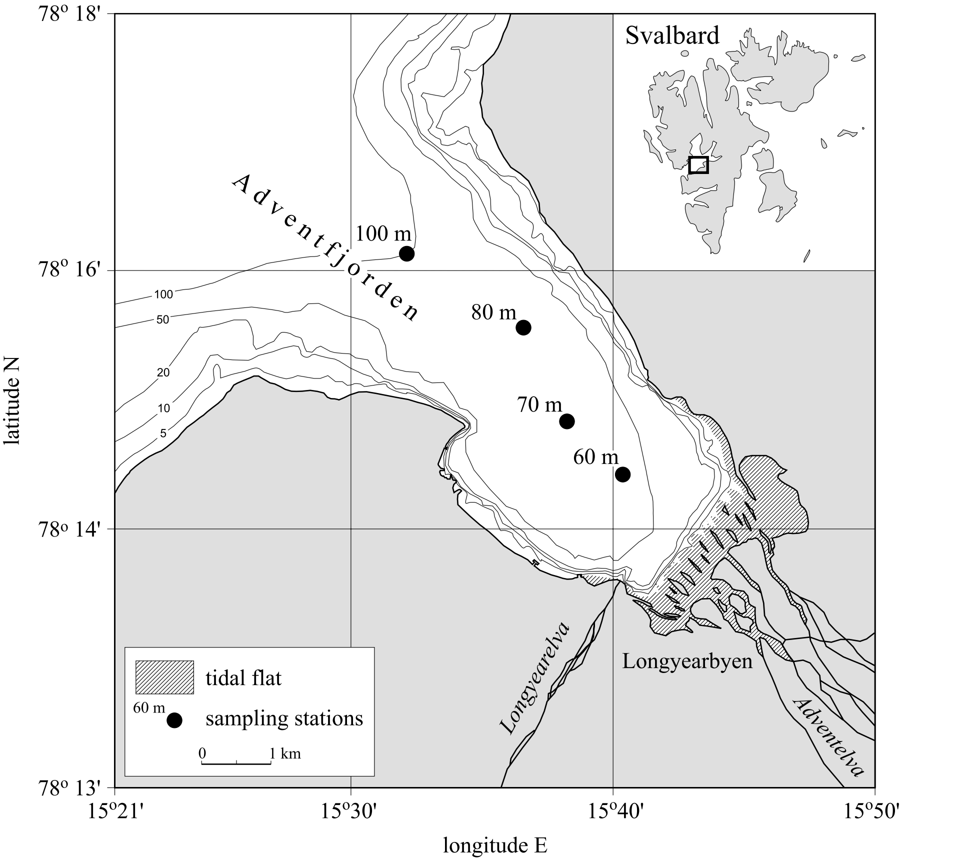

Fig. 1. Locations of coring stations in Adventfjorden

21% of the Adventfjorden basin (total area = c. 694 km^2) is covered with glacier ice (Hagen et al. 1993), which is the most deglaciated area of Svalbard (the average cover is 60%). The last major glacial advances were in the 1890s, at the end of the Little Ice Age (Mangerud & Svendsen 1990, Hald et al. 2001, Ziaja 2001); since that time deglaciation has been continuous. Glaciers contribute most of the sediment to the fjord via the systems of two braided rivers – the Adventelva and the Longyearelva – during approximately four months of the ablation season (Węsławski et al. 1999). The average discharge of the Adventelva reached 3.6 m^3 s^{-1} and the concentration of suspended solids varied between 132 and 486 mg dm^{-3} during the sampling period (summer 2001). The Longyearelva discharged less water (average 2.04 m^3 s^{-1}) but with a slightly higher average concentration of suspended solids (between 149 and 592 mg dm^{-3}). The sediment-laden freshwater enters the fjord as a spreading, turbid surface plume that is subject to considerable modification by semidiurnal tides;

these can reach amplitudes of 159 cm during spring tides (Hasslet 2000). During winter, when the rivers are frozen, the supply of terrigenous material to the fjord is cut off and the surface of the fjord is covered with fast ice.

The climate of the region is much moderated by the warm West Spitsbergen Current (the northernmost extension of the Norwegian Atlantic Current), which makes it very mild, considering its northerly position. The average annual temperature is about −6°C. The warmest month is July (5–6°C), the coldest period is in January–March (about −15°C). Precipitation is very low, about 200 mm annually (Hansen-Bauer et al. 1990). The continuous temperature records started in 1911 in the vicinity of Longyearbyen (the principal town on Spitsbergen) reveal a temperature minimum in 1917, abrupt warming until the 1930s, a cooler period with minimum temperatures in the 1960s and on-going warming till the present day (Nordli et al. 1996). During this last period precipitation has increased by about 2.5% per decade (Førland & Hanssen-Bauer 2003). The changes are well correlated with the NAO index (Nesje & Dahl 2003), and therefore reflect regional patterns of climate variations. Future scenarios predict further increases in temperature and precipitation for this region (Førland & Hanssen-Bauer 2003).

3. Material and methods

Sediment cores were collected during the 2001 and 2002 summer cruises of r/v 'Oceania'. The coring stations (Fig. 1, Table 1) were located on a transect from the sources of terrigenous material (the Adventelva floodplain) to the fjord mouth. On each of the stations two cores were taken with a Niemistö corer. The cores were cut immediately into 1 cm thick slices and frozen until further laboratory treatment. Additionally, 50 of near-bottom water were collected from the corer.

Table 1. Coordinates of coring stations and sediment recovery

Water depth [m]	Latitude [°N]	Longitude [°E]	Sediment recovery [cm]
60	78.2402	15.6589	33
70	78.2474	15.6191	30
80	78.2562	15.5915	34
100	78.2687	15.5042	12

^{137}Cs activities were measured using gamma spectrometry. Samples were vacuum-dried and placed in constant geometry dishes. Drop stones were removed from the samples. ^{137}Cs activities were determined with a Canberra HPGe detector and an efficiency of 20%. The duration of measurements varied between 24 and 72 hours.

^{210}Pb activities were determined by alpha spectrometry of the granddaughter nuclide ^{210}Po. Five grams of sediment were chemically leached with hot concentrated HNO_3 followed by 6N HCl (Nittrouer et al. 1979). ^{210}Po was spontaneously electrodeposited onto silver planchets and measured with a PIPS silicon detector.

Mass accumulation rates (MAR) were calculated according to Bruns & Hass (1999):

$$\mathrm{MAR} = \mathrm{DBD} \times \mathrm{LAR}, \tag{1}$$

where MAR is mass accumulation rate [g m^{-2} y^{-1}], DBD – dry bulk density [g m^{-3}], and LAR – linear accumulation rate [cm y^{-1}]. The measured water content, average grain density of 2.7 g cm^{-3}, and mean density of pore water taken to be the mean density of sea water 1.026 g cm^{-3} were used to compute the dry bulk density (DBD).

4. Results and discussion

Sediments

The sediments are composed of homogeneous mud with an average sand content of 5%. Apart from small variations in grain size they do not display any significant textural changeability. This observation is also supported by water content changes, which below the upper few cm are relatively small.

Only in the core from the fjord mouth (100 m) are two sediment types observed: muds in the upper 12 cm and probably glacial till (with abundant angular clasts) below this level. This location is also characterised by numerous settled polychaetes, which cause considerable mixing of the sediments. In the core locations from shallower waters, the number of individuals and total biomass decline significantly (Zajączkowski, unpublished).

^{210}Pb dating

^{210}Pb occurs as a natural product in the radioactive decay chain of ^{238}U, which is nearly ubiquitous in the Earth's crust. ^{238}U decay leads to ^{226}Ra and then ^{222}Rn, an inert gas, which diffuses into the atmosphere and is distributed globally. ^{222}Rn decays via a series of short-lived radionuclides to ^{210}Pb, a solid with a half-life of 22.26 years. Since radon is isolated from its precursor, the natural equilibrium is disrupted. Deposition of ^{210}Pb from the atmosphere takes place on a timescale much shorter than its half-life

(Krishnaswami & Lal 1978); therefore, the ^{210}Pb that settles on the sea is adsorbed by suspended solids and subsequently incorporated in the bottom sediments as excess (unsupported) radionuclide. Excess ^{210}Pb activities are determined by subtracting the average supported activity of a core from the total activities. Supported activity was ascertained by averaging the nearly uniform, low-level ^{210}Pb activities below the region of radioactive decay. Sediment accumulation rates are determined from excess ^{210}Pb activities that decreased exponentially below a zone of uniform activity (surface mixed layer) using a constant sedimentation rate model described by the following equation (Goldberg & Koide 1962, Nittrouer et al. 1979, Harden et al. 1992):

$$S = \lambda\ z[\ln (A_o\ A_z^{-1})]^{-1}, \tag{2}$$

where S is sediment accumulation rate [cm y^{-1}], λ – decay constant of ^{210}Pb [0.03114 y^{-1}], z – depth in core (distance between A_o and A_z) [cm], A_o – ^{210}Pb excess activity at the particular reference horizon [Bq kg^{-1}] and A_z – ^{210}Pb excess activity at depth z below the reference horizon [Bq kg^{-1}]. In the equation, deep mixing is assumed to be negligible, hence the calculated sediment accumulation rate represents the upper limit to the true sediment accumulation rate (Benninger et al. 1979). The effects of deep mixing can be evaluated, for example, by testing with another radionuclide covering a comparable time scale – ^{137}Cs (Nittrouer et al. 1984, DeMaster et al. 1985).

The studied cores were usually too short to reach the layer where unsupported ^{210}Pb disappears, or the excess ^{210}Pb was too low to be resolved. The reasons for this could be: (1) high sedimentation, which causes a dilution of the isotope, (2) a generally low amount of 210Pb transported to Svalbard (Paatero et al. 2003). Only the core taken at 80 m water depth reveals a profile (Fig. 2) that allows calculation of the sediment accumulation rate. The supported activity in the core was found to be c. 40 Bq kg^{-1}, a slightly lower value than in northern Svalbard, where crystalline rocks support ^{210}Pb activities of 50 Bq kg^{-1} (e.g. Cromack 1991). Numerous variations of the measured values from the idealised exponential decay curve on the presented profile are attributed to variations in the particle size of the sediment (e.g. Smith & Ellis 1982, He & Walling 1996, Cowan et al. 1999). Using eq. (2), the sediment accumulation rate (for the upper 18 cm) was calculated at 0.97 cm y^{-1} at station 80 m. To evaluate the effects of deep mixing the result was used to calculate the expected depth of the 1986 ^{137}Cs peak. The depth obtained (14.5 cm) fits very well with the one obtained for the ^{137}Cs profile (14 cm). This suggests that no deep mixing occurs below the surface mixed layer.

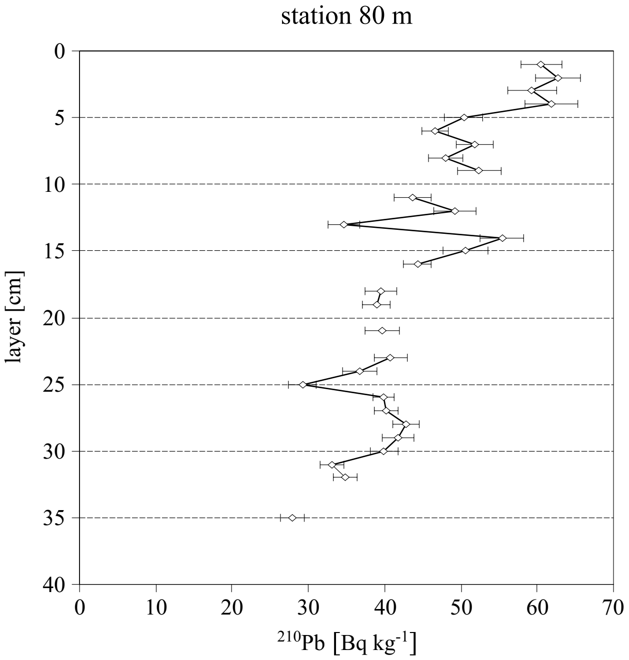

Fig. 2. Total ^{210}Pb activity [Bq kg^{-1}] in the 80 m core; error bars – 2 sigma

^{137}Cs dating

The artificially produced radionuclide ^{137}Cs (half-life 30.17 years) is introduced into the hydrological cycle during nuclear weapons testing and as a result of accidental releases from nuclear installations. In most sedimentary environments, ^{137}Cs is deposited as fallout, which is rapidly and strongly fixed by sediment (particularly clay) particles (Livens & Rimmer 1988). Further, ^{137}Cs redistribution occurs in association with sediment particles. Dating with ^{137}Cs data is based on assumptions of certain ages for particular parts of its depth profile (Ritchie & McHenry 1990, Ely et al. 1992, Pinglot et al. 1999). The deepest occurrence of ^{137}Cs activity corresponds to the first significant atmospheric releases in 1952–53, the depth of maximum ^{137}Cs activity in the sediment relates to the maximum atmospheric production in 1963, and the second maximum of radiocaesium (only in part of the northern hemisphere) is associated with the 1986 Chernobyl accident.

The ^{137}Cs activities were above the detection limit in all the samples analysed. The average surface layer activities were 3 to 8 Bq kg^{-1}, similar to the values recorded on the Svalbard shelf, but higher than those in Barents Sea sediments (Heldal et al. 2002). The respective maximum measured activities were 21 and 19 Bq kg^{-1} in the 70 m and 80 m cores.

The depth profiles shown on Fig. 3 reveal a characteristic pattern with one (60 m) or two (70 and 80 m) evident peaks. Since the isotope was measured throughout all the cores, it is inferred that all the sediment was deposited after 1952. The 80 m core profile is the best documented one. It shows two distinct peaks (Fig. 3) that are assumed to represent the 1986 and 1963 ^{137}Cs fallout maxima; this interpretation is supported by independent ^{210}Pb dating (Fig. 2). The very similar profile of the 70 m core suggests that its upper peak represents the year 1986. The limited length of the core does not resolve the full 1963 peak, so the core base and the computed values must be treated as only minima. The 60 m core has only one peak, and since the station where it was taken lies closest to the river mouths, it is expected to display the highest accumulation rate, an assumption indirectly supported by ^{137}Cs activities. The observed peak is assumed to represent the 1986 maximum. The radiocaesium profile in the deepest core (100 m – Fig. 3) has no distinct peak and its relatively

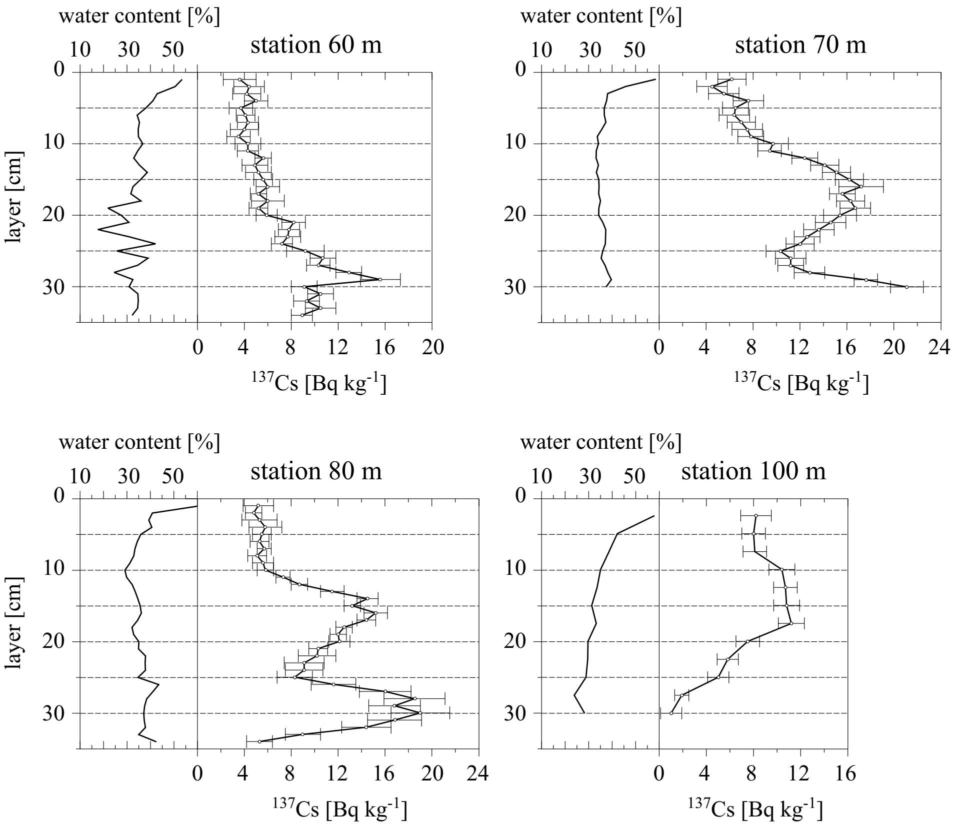

Fig. 3. The distribution of ^{137}Cs [Bq kg^{-1}] and water content [weight %] in sediment depth profiles. The two sigma error bars are included

uniform depth distribution points to the possible occurrence of mixing and redeposition. Mixing is probably largely related to bioturbation caused mostly by numerous polychaetes. Furthermore, the underlying glacial till deposits are probably of Late Pleistocene age, so there must have been a hiatus between these and the overlying marine sediments.

Sediment accumulation rates

The sediment accumulation rates are calculated on the basis of the age reference layers interpreted from ^{137}Cs profiles (for 1963 and 1986) (Table 2). To avoid any influence of sediment compaction on the results, the rates are given as mass accumulation rates [g cm^{-2} y^{-1}].

Post-1986 accumulation rates decrease downfjord from 2.6 g cm^{-2} y^{-1} at the 60 m station and about 1.2 km from the tidal flat to 1.34 and 1.19 g cm^{-2} y^{-1} at 70 and 80 m, respectively (correspondingly 2.5 and 3.6 km from the tidal flat). For the 100 m station, the accumulation rate (from 1963 to the present day) might be about 0.09 g cm^{-2} y^{-1}, but this value should be treated with caution.

Comparison of the sediment accumulation rates for two periods – 1963–1986 and 1986–2001 – shows remarkable variation. The record from the 80 m core demonstrates noticeably higher rates in the more recent period (1.19 g cm^{-2} y^{-1}) than in the older one (0.83 g cm^{-2} y^{-1}). A similar relation is observed in the 70 m core: from 1.34 g cm^{-2} y^{-1} to = 0.79 g cm^{-2} y^{-1}.

The change in sediment accumulation rate is linked to particulate matter flux, which in subpolar fjords is governed by glacial meltwater discharge (Syvitski 1989). The discharge is mainly a function of climatic conditions – precipitation and temperature – which control glacial ablation. Precipitation has increased in the last two decades over Svalbard (Førland & Hanssen-Bauer 2003); nevertheless, because it is still very low (about 200 mm y^{-1}), its contribution to the total discharge to the fjord is considered to be minimal. A very pronounced increase in temperature has been observed over the last 50 years in central Spitsbergen (Nordli et al. 1996, Førland & Hanssen-Bauer 2003). As a result, glacial ablation is enhanced, so the discharge of meltwater and suspension flux to the fjord is also expected to increase. The warming is also associated with the retreat of glaciers, which has left unconsolidated and easily eroded sediments, which and through this can increase the particulate matter flux to the fjord.

In recent decades anthropogenically induced changes in fluxes to fjords have been reported from several locations, e.g. Schafer et al. (1983), Colman & Bratton (2003). In Longyearbyen, however, mining is in decline

Table 2. The sediment accumulation rates in relation to distance from the tidal flat. The rates are calculated from reference layers (1963 and 1986 peaks) in ^{137}Cs activity profiles (Fig. 3). The credibility of the rates for the 100 m core is discussed in the text

Station	Distance from tidal flat [km]	Depth of 1986 peak [cm]	Depth of 1963 peak [cm]		Accumulation rates		
					1986–2001	1963–86	1963–2001
60 m	1.2	29	NA	LAR [cm y^{-1}]	1.87	NA	NA
				MAR [g cm^{-2} y^{-1}]	2.60	NA	NA
70 m	2.5	16	30	LAR [cm y^{-1}]	1.00	• 0.58	• 0.74
				MAR [g cm^{-2} y^{-1}]	1.34	• 0.79	• 1.00
80 m	3.6	14	28	LAR [cm y^{-1}]	0.87	0.61	0.71
				MAR [g cm^{-2} y^{-1}]	1.19	0.83	0.97
100 m	6.0	NA	7 (?)	LAR [cm y^{-1}]	NA	NA	0.07 (?)
				MAR [g cm^{-2} y^{-1}]	NA	NA	0.09 (?)

Symbols: LAR – linear accumulation rate, MAR – mass accumulation rate, NA – not available.

(Dallmann et al. 2001); if these activities were responsible for an increase in accumulation rates in the fjord, this would probably have occurred much earlier.

A significant rise in sediment accumulation rates has also been observed in fjords supplied by surge-type glaciers (Jaeger & Nittrouer 1999, Gilbert et al. 2002). This type of glacier is also common on Svalbard (Hamilton & Dowdeswell 1996). However, no surging has been recorded on the glaciers in the Adventfjorden catchment area since the 1930s (Hagen et al. 1993). Cowan et al. (1988) showed that intensive rainfall can significantly raise sedimentation in temperate fjords. However, such phenomena are rather rare in this part of the Arctic, hence summer rainfall is low and weak in intensity (Førland & Hanssen-Bauer 2003).

Elverhøi et al. (1983) surveyed Adventfjorden with high resolution acoustic profiling and estimated the thickness of the Holocene sediment cover. The calculated long-term average sediment accumulation rates for the central basin are in the range of 0.1–0.3 cm y^{-1}, i.e. almost one order of magnitude smaller than the modern rates reported here. This is consistent with previously published reports on changes in accumulation rates in Spitsbergen fjords during the Holocene (Elverhøi et al. 1995, Hald et al. 2001).

Sedimentation versus accumulation rates

There are several data from sediment traps in Adeventfjorden (Węsławski et al. 1999, Zajączkowski 2002, unpubl.) which report a particulate matter flux to the fjord bottom from suspension. It is difficult to perform a detailed comparison between these rates and sediment accumulation rates, as sediment trap data refer only to short exposure periods (usually 1–2 days) and significant computation errors occur in estimates of the duration of the ablation season from one year to another. Even so, a rough calculation points to the dominance of particulate matter flux over accumulation rates. If this is correct, some other mechanisms will be needed to restore the balance. Near-bottom sediment transport in the form of grain flows, turbidity currents (Prior et al. 1981), and resuspension of the nepheloid layer have all been suggested as having transported some portion of the supplied material downfjord and even further to Isfjorden. Indirect confirmation of this type of transport is the ^{137}Cs profile at the 100 m station (probably on a kind of small sill).

5. Conclusions

In this paper the authors have provided data documenting changes in sediment accumulation rates in relation to distance from the source of terrigenous material over time (the last 50 years). Modern rates in the central basin of Adventfjorden decrease downfjord from 1.87 to 0.87 cm y^{-1} (2.5 to 1.14 g cm^{-2} y^{-1}). Comparison of the modern values (1986–2001) with older ones (1963–86) reveals a marked increase in sediment accumulation rates in the last ten years. This correlates well with recent climate changes, particularly with the increase in average temperatures and precipitation. Confrontation with particulate matter flux data indicates the possibility of sediment passing on to Isfjorden. With the forecasts of continuous warming (Førland & Hanssen-Bauer 2003), a further increase in the particulate matter flux is predicted, which could raise the suspended matter concentration in the fjord water, reduce the dimensions of the euphotic zone (impact on primary production) and further increase sediment accumulation rates.

The ^{137}Cs dating method was found highly suitable for studying accumulation rates in Svalbard fjords and could be very useful in high-resolution studies of the global change record in fjord sediments during the last 50 years.

Acknowledgements

The authors appreciate the assistance of Maria Włodarska-Kowalczuk, Łukasz Wysocki and the crew of r/v 'Oceania', particularly Roman Obuchowski.

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