Estimation of glacial meltwater discharge into Svalbard coastal waters*

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Abstract

During the summer expeditions of r/v 'Oceania' in 1995–1996, oceanographic investigations comprising CTD profiling and suspension measurements were conducted in Svalbard fjords and shelf waters. The freshwater volume was estimated independently from the salinity drop as compared with the assumed background salinity and from the distribution of mineral suspension density in surface waters. Preliminary calculations of the instantaneous freshwater volume based on the distribution of suspended matter (at depths of < 150 m) yielded a figure of 80 km^3 in Svalbard coastal waters in summer. Values for Hornsund and Kongsfjord ranged from 0.4 to 0.7 km^3 of freshwater at the height of summer. This corresponds well with glaciological estimations, which give an annual discharge of 14.6 to 27.5 km^3 of freshwater for Svalbard. The glacial discharge is estimated to make up some 42% of the freshwater budget of Svalbard shelf waters, the remainder being derived from Barents Sea Arctic waters of reduced salinity.

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1. Introduction

Glacial outflow has hitherto been considered negligible in estimations of the Arctic Ocean freshwater budget when compared to riverine discharge (Aagaard and Carmac, 1989). But this opinion has been questioned in recent documents of the ACSYS Project (ACSYS, 1995). However, there are no published accounts stating the numerical proportions of glacial meltwater in the total freshwater balance of the Arctic. Current knowledge of the freshwater influx from rivers and streams in Svalbard was reviewed during the 'Polar Hydrology' conference organised by SINTEF in Trondheim, 29–30 March 1993. Data on glacial discharge were summarised by Jania and Hagen (1996), and the problem of the freshwater volume in Svalbard fjords was presented by Węsławski *et al.*, 1991, 1995. The recently recognised importance of the freshwater volume for the winter formation of the dense bottom waters was a new reason for studying the freshwater balance over the Svalbard shelf. Located in the Svalbard archipelago, Storfjord is believed to be an important regional source of brine-enriched, dense bottom waters (Rudels, 1987; Quadfasel *et al.*, 1988; Gascard *et al.*, 1995; Piechura, 1996). The main objective of the present paper is a preliminary, if only rough, estimation of the freshwater volume derived from glacial meltwater in Svalbard coastal waters.

2. Materials and methods

During several summer expeditions (July–August) in Svalbard fjords, investigations covering CTD, suspension concentrations and light attenuation measurements were carried out on board r/v 'Oceania' (Fig. 1).

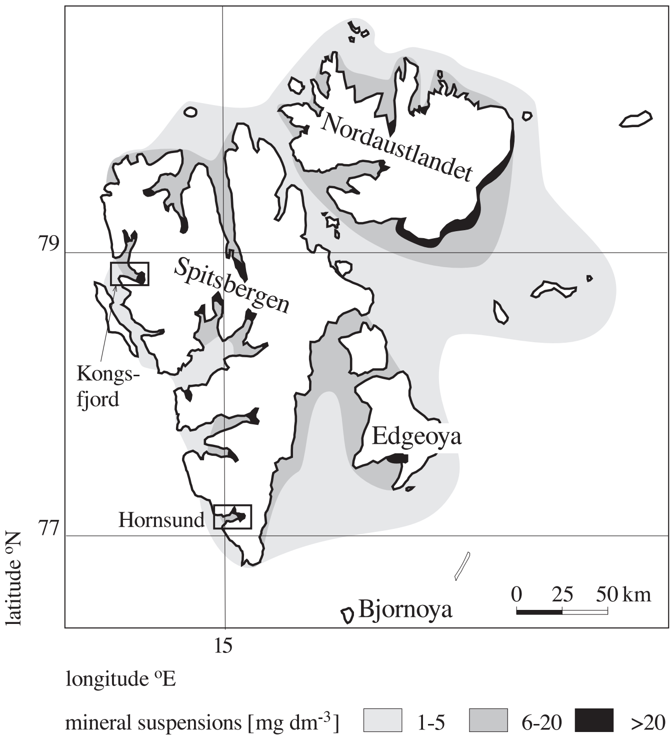

Fig. 1. Study area; the location of high resolution CTD transects is indicated. The framed areas in Fig. 3 show the location of the fjords in the Svalbard archipelago

Additionally, in 1993 and 1996 AVHRR satellite images were collected to support *in situ* measurements (Węsławski *et al.*, 1995; Krężel, 1997). Mineral suspensions were measured from 1 dm^3 samples of water, filtered through weighed 0.45 mm Millipore Filters, dried at 60°C, weighed, combusted at 450°C and reweighed.

The freshwater volume was calculated according to the methods described by Ketchum (1950) and Nutt and Coachman (1956) with some modifications applied to the 1996 data.

The volume of coastal water in the various layers of the fjord was calculated by planimetry, and the salinity averaged from CTD data was applied to each layer. The freshwater fraction (FWF) of each layer was determined according to the formula

$$\mathrm{FWF} = (\mathrm{S}_0 - \mathrm{S})/\mathrm{S} \qquad \text{or} \qquad \mathrm{FI} = \mathrm{FWF} \times 100\%,$$

where

S_0 – is the arbitrary assumed background salinity of the water outside the fjord and S is the actual salinity,

FI – freshwater fraction in %.

The freshwater volume (FWV) was calculated by multiplying FWF by the volume of the layer in question.

The background salinity was taken to represent the source waters, while at the same time disregarding the general reduced salinity of the Arctic Water mass in the calculations. For the 1987 and 1988 data (Węsławski *et al.*, 1991) the background salinity recorded in seawaters outside the fjords (Local Waters) was set at 34.56 PSU for Kongsfjord and 35.23 PSU for Hornsund. For the 1996 measurements, detailed analysis of the relationship between the assumed background salinity and the estimated freshwater fraction revealed conspicuous differences relating to the selected value of S_0. Clearly, the choice of a constant background salinity for the whole water column yields negative values of the freshwater fraction in deep waters where $S > S_0$. This is the effect of the highly saline winter waters; to avoid this effect, the background salinity profile for waters outside the fjord should be assumed in further calculations (Tab. 1).

For the West Svalbard fjords the question arises whether the background salinity profile should be representative of the waters in the West Spitsbergen Current or of the Local Waters found at the mouth of the fjord. Investigations in the West Spitsbergen Current made in 1996 revealed the existence of quite a strong hydrological front separating WSC waters from Svalbard shelf waters; considerable differences between these water masses are visible on the ΘS-diagram (Beszczyńska-Möller *et al.*, in preparation). It is suggested that the salinity profile at the mouth of the

Table 1. Calculations of the freshwater fraction and freshwater volume in Hornsund and Kongsfjord in summers 1987 and 1988 (Węsławski *et al.*, 1991), and 1996 (our own data)

Layer [m]	S_0 [PSU]	FWF	FI [%]	FWV [10^6 m^3]
Hornsund 1987, constant background salinity				
0–10			8.7	216.4
10–20			5.9	136.7
20–30	35.23		5.1	106.5
30–50			3.6	207.9
below 50			1.0	125.0
Total			3.2	792.4
Kongsfjord 1988, constant background salinity				
0–10			9.4	119.6
10–20			7.1	74.2
20–30	34.56		4.7	44.4
30–50			2.4	62.3
below 50			0.5	28.9
Total			2.9	329.5
Kongsfjord 1996, constant background salinity				
0–5		0.0622	6.22	58.3
5–10		0.0445	4.45	41.7
10–20		0.0330	3.30	61.7
20–30		0.0207	2.07	38.8
30–40		0.0103	1.03	19.2
40–50	34.56	0.0064	0.64	12.0
50–70		0.0045	0.45	16.1
70–100		0.0031	0.31	16.2
100–150		0.0011	0.11	6.9
150–200		–0.0015	–0.15	–8.2
200–300		–0.0043	–0.43	–41.4
Total		0.0056	0.56	221.30
Kongsfjord 1996, assumed background salinity				
0–5	33.530	0.0306	3.06	28.6
5–10	33.590	0.0152	1.52	14.3
10–20	33.620	0.0049	0.49	9.1
20–30	34.000	0.0042	0.42	7.8
30–40	34.300	0.0027	0.27	5.0
40–50	34.400	0.0018	0.18	3.3
50–70	34.420	0.0004	0.04	1.6
70–100	34.460	0.0002	0.02	1.0

Table 1. (continued)

Layer [m]	S_0 [PSU]	FWF	FI [%]	FWV [10^6 m^3]
Kongsfjord 1996, assumed background salinity				
100–150	34.540	0.0005	0.05	3.1
150–200	34.620	0.0002	0.02	1.3
200–300	34.720	0.0003	0.03	2.5
Total		0.0020	0.20	77.6
Hornsund 1996, maximum value within each layer assumed as background salinity				
0–5	33.306	0.0291	2.91	14.3
5–10	33.479	0.0234	2.34	11.5
10–20	33.740	0.0098	0.98	9.6
20–30	34.014	0.0060	0.60	5.9
30–40	34.207	0.0036	0.36	3.4
40–50	34.328	0.0027	0.27	2.4
50–70	34.435	0.0026	0.26	4.6
70–100	34.558	0.0035	0.35	9.3
100–150	34.690	0.0041	0.41	11.2
150–200	34.737	0.0023	0.23	3.5
Total		0.0056	0.56	75.7

fjord should be representative of the water mass outside the fjord and that it should be applied in calculations of the freshwater volume. The method of calculation involving maximum salinities within particular layers as background was considered, but the freshwater volume obtained represented not only the water mass produced directly in Kongsfjord but also those arising during earlier processes. The salinity profile assumed at the mouth of the fjord contains a freshwater fraction from the Arctic Water mass, derived from Siberian river discharge. The salinity profiles in the central and inner part of the fjord are characteristic of the Local Waters, which are freshened by glacial discharge while entering the fjord. This proportion in the freshwater balance was the subject of our calculations.

3. Results

3.1. Freshwater volume estimated by direct salinity measurements

The freshwater fraction in Horsund and Kongsfjord was assessed in detail during two summers and, in view of the differences in the methods of calculation, the data obtained are very different (Tab. 1). The freshwater volumes calculated against a constant background salinity are probably somewhat overestimated but to a certain degree are a reflection of the amount of freshwater of fjord origin. A drop in salinity to 26 PSU in the surface waters of the innermost fjord basins and to 34.4 PSU in the deeper layers and outer fjord waters corresponded to a freshwater fraction of 10 to 0.6%. For the fjords in question, the instantaneous volume of freshwater in summer was estimated at 0.79 km^3 in Horsund and 0.33 km^3 in Kongsfjord. The second method yields results nearly one order of magnitude lower (0.076 and 0.078 km^3 respectively), which are thus underestimated. The assumed background salinity profile probably represented not only the water mass outside the fjord but also included layers where fjord water was carried out through the mouth, which resulted in lower differences between S and S_0.

3.2. Freshwater volume estimated by density of suspended matter in surface waters

For surface waters (0 to 0.5 m) the correlation between the suspended mineral load and the drop in salinity was calculated (Fig. 2). The squared

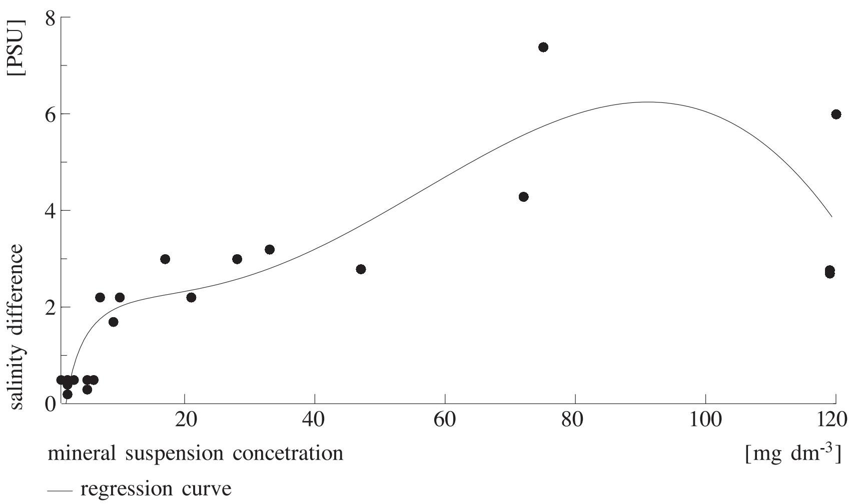

Fig. 2. Relation between quantity of suspensions and freshwater in surface fjord waters

correlation coefficient R^2 for a nonlinear regression curve is $R^2 = 0.443$ and allows approximate classes of surface waters to be defined, *i.e.* those where the salinity drop range varies with the suspension load (Tab. 2). The satellite

Table 2. Calculation of the freshwater volume according to the suspension loads in particular surface water types and their extensions as shown in Fig. 3

	Mean FW [%]	Minimum FW [%]	Maximum FW [%]	SD	Number of observations	Area [km^2]	Surface water volume 0–20 m [km^3]	FWV in surface layer [km^3]
range of minimum suspension amount [mg dm^{-3}] in 0–20 m water layer								
1–5	1.0	0.6	1.4	0.2	23	40000	800	8.0
6–20	6.0	6.3	8.5	1.5	4	18000	360	21.6
> 20	13.0	6.3	21.0	6.9	10	1600	32	4.2
Together						59600	1192	33.8
FWV								
layer 0–20 m							1192	33.8
layer 20–150 m	0.6						7748	46.5
Together 0–150 m						59600	8940	80.2

imagery of surface suspensions was correlated with *in situ* measurements, and the general layout of the three delimited water classes is shown in Fig. 3. Calculation of the water volume representing these classes (Tab. 2) gives an instantaneous freshwater volume of 34 km^3 in the surface (0–20 m) layer and 46 km^3 in the lower layers (20–150 m) at the height of summer (late July).

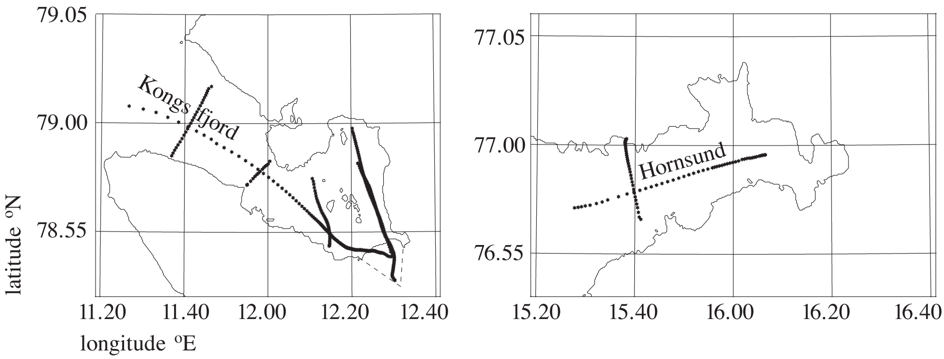

Fig. 3. Extrapolated view of surface suspension distribution in the Svalbard shelf area. AVHRR imagery corrected with *in situ* measurements (compilation from Węsławski *et al.*, 1995; Krężel, 1997 and our own data)

4. Discussion

The volume of glacial ablation from Svalbard was recently compiled by Jania and Hagen (1996). They give a range of 40 to 75 g cm^{-2} y^{-1} (400 to 470 mm of water) and a glaciated area of 36 600 km^2. In view of these figures, the volume of freshwater discharged annually into coastal waters fluctuates from 14.6 to 27.5 km^3. This figure corresponds well with our calculations based on the satellite-suspension data (Tab. 2). A more detailed freshwater balance for Horsund (Węsławski *et al.*, 1995) shows the annual freshwater input to be *ca* 1 km^3, which is nearly twice the instantaneous freshwater volume estimated on the basis of the salinity profiles presented here (0.7 km^3). Certainly, the amount of freshwater discharged annually should be greater than that the instantaneous value owing to the dynamic processes of mixing and advection. There are sources of freshwater other than glacial ablation, like precipitation (rain, snow and snow melt), pack ice and fast ice melt, and riverine discharge (to a large extent of glacial origin). These sources make up less than 10% of the freshwater in Hornsund (Węsławski, 1995). Another source of freshwater in the seas around Svalbard is the Arctic Water mass of low salinity carried by the East Svalbard and

Barents Sea currents. If we take the salinity of core Atlantic Waters from the West Spitsbergen Current to be 35.5 PSU, and are mindful of the fact that practically 75% of Arctic Basin waters are derived from Transformed Atlantic Water (Swift, 1986; Pfirman *et al.*, 1994), we can assume the salinity difference between 35.5 (characteristic Atlantic Water) and 34.5 (Local Svalbard Waters) to be due to freshwater imported from the Arctic Basin. Furthermore, the glacial discharge is detectable on CTD profiles only within the 0–20 m layer (Beszczyńska-Möller *et al.*, in preparation). The proportion by volume of freshwater of local origin to that imported from the Arctic Basin is from 42 to 58%. Taking 4 PSU to be the average salinity of the ice pack, and the average ice thickness to be 1 m, the volume of freshwater from seasonal pack ice melt makes up about 1.1 km^3 and comes from a 1 mln km^2 area of the ice-covered Barents Sea (Sakshaug *et al.*, 1992). In such a comparison, glacial discharge plays an important role in the regional freshwater balance in Svalbard.

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