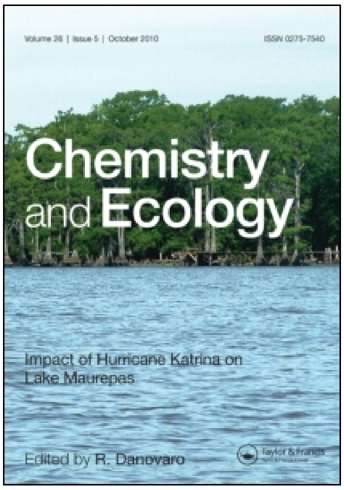

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MULTIDISCIPLINARY INVESTIGATIONS IN THE MARINE ENVIRONMENT OF THE INNER KONGSFIORD, SVALBARD ISLANDS (SEPTEMBER 2000 AND 2001)

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The processes occurring in the marine environment at the interface between sea and glaciers in Arctic fiords are often poorly investigated, mainly due to logistical reasons. Two multidisciplinary campaigns have been carried out in September 2000 and 2001 in the inner part of Kongsfiord to collect late-summer data on oceanographic processes at the peculiar environment close to glaciers front. Warmer oceanic waters enter the inner Kongsfiord across the southern passage of the moraine 20–25 m deep. Surface waters get colder and fresher flowing northward along the glaciers' front and exit across the recently opened passage of Blømstrand. The water column is well stratified with cold lenses of freshwater outflowing from the glaciers at the surface. Sedimentation sharply decreases with distance from the glaciers' front. The inter-moraine depression is the area where preferential sediment accumulation occurs (up to $1.8\,g\,cm^{-2}\,yr^{-1}$), with a residence time of particles in the water column at around 5 days.

Keywords: Svalbard; Oceanography; Sedimentation; Sea–glacier interface; Tracers; Radionuclides

1 INTRODUCTION

The Kongsfiord (Svalbard) is probably one of the most studied glacial fiords in the Arctic and in the last decade great effort has been undertaken to study the Kongsfiord–Krossfiord marine system and adjacent shelf areas. The exchange processes between the open sea and the Svalbard fiords have been studied (Quadfasel *et al.*, 1988) and recently two review papers have described the main physical and biological characteristics of the Kongsfiord marine ecosystem (Hop *et al.*, 2002; Svendsen *et al.*, 2002).

The Kongsfiord is about 20 km long and its width varies from 4 to 10 km (Fig. 1). It is elongated in southeast–northwest direction and exchanges with the open sea occur in the northwestern mouth. In the southeastern part, the shoals of an emerging ancient moraine

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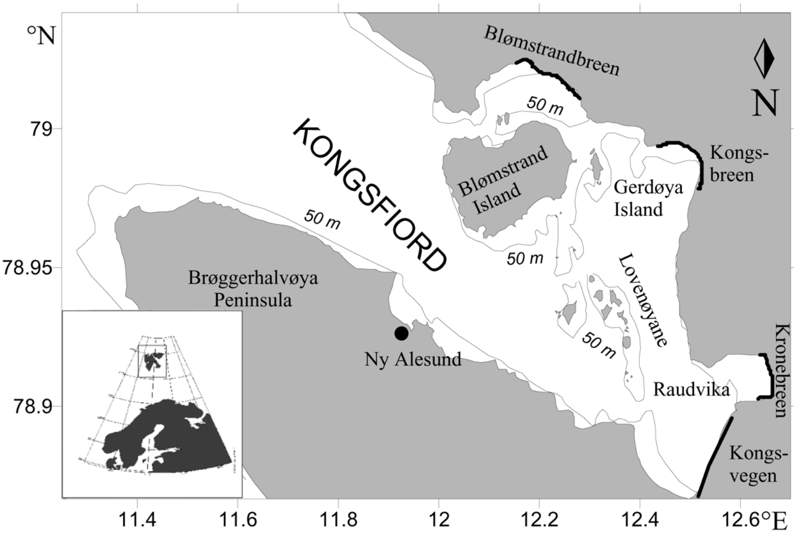

FIGURE 1 Study site: the inner part of the Kongsfiord (Svalbard). Thick lines indicate the fronts of the glaciers.

(Lovenøyane) separate the inner fiord east of Ny Ålesund into two parts. This inner part is where the glaciers (Kongsvegen, Kronebreen, Kongsbreen, Blømstrandbreen) reach the sea. Oceanic water from the outer part of the fiord can pass through some narrow passages across the shoals and, recently, across the passage between Blømstrandbreen glacier and the facing island of Blømstrand. Water circulation in the outer part of the fiord is well known and typical of broad fiords (Svendsen *et al.*, 2002) depending on the morphology as well as on offshore geostrophic circulation and wind patterns (Klinck *et al.*, 1982). During along-shore winds (i.e. across the fiord), net transport is in and out of the fiord resulting in flooding and emptying of the basin; during across-shore winds (i.e., along the fiord), there is a tilt in the free surface and pycnocline but the total volume of water into the fiord remains constant. Less is known about the inner part of the fiord because research vessels cannot pass through the shoals of the moraine and also the morphology of the glaciers' front is very dynamic with rapid changes. The circulation in the inner part was necessarily inferred by mathematical models (Svendsen *et al.*, 2002) but numerical simulations refer to the period when the Blømstrand passage was closed by the glacier reaching Blømstrand island. Following the opening of this new passage, few data have been gathered so far, on high resolution water mass distribution and circulation in the inner fiord, as well as on their relationship to particle dynamics and sedimentation/resuspension processes.

The questions addressed were:

- To what extent does the outflow of freshwater from the glaciers influence the circulation pattern in the area, following the huge retreat of the glacier front?
- To what extent do the particles released by the glaciers (mainly Kongsbreen and Blømstrandbreen) influence the sedimentation regime?

The article aims to illustrate the main oceanographic processes occurring in the inner part of the Kongsfiord close to the glaciers and the possible importance of the 'recently-opened passage' in influencing the hydrographical, sedimentary and biological processes in the inner fiord. Special focus is given to (i) small-scale interactions of water masses with different characteristics, from the ice fronts to the outer fiord and (ii) identify the areas of maximum sediment accumulation.

2 MATERIALS AND METHODS

The investigations were carried out in September 2000 and 2001 in the inner marine part of the Kongsfiord at the glacier–sea interfaces, eastward to 12° E.

2.1 Hydrology and Water Currents

Small aluminium dinghies provided by the Ny Ålesund Large Scale Facility were equipped with a custom-made crane, electric winch and Global Positioning System (GPS). These arrangements allowed to deploy oceanographic equipment and record accurate positions. Sea water temperature and conductivity were measured by a Conductivity Temperature Depth (CTD) probe IDRODAC-316 (Idronaut). Calibrations were done regularly. Daily surveys into the inner part of Kongsfiord and the recently opened Blømstrand passage were performed in the periods September 5–9, 2000 and September 5–11, 2001. About 50 CTD casts were performed each year. A self-recording Aanderaa RCM7 current metre was deployed at 17 m depth in one of the northern opening of the moraine (GPS 78° 56′ 58″ N 12° 15′ 55″ E) where major outflows of fresh water toward the fiord was expected.

2.2 Suspended Solids and Sedimentation Processes

1. Total suspended solids (TSS), were determined after filtration of 1–4 l of seawater on pre-weighted cellulose acetate filters (0.45 nm).

2. Chlorophyll *a* and phaeopigments concentrations were determined on the residue obtained by filtration of seawater. Samples for pigment analysis were filtered (1–2 dm^3) through Whatman GF/F glass-fibre filters ($\Phi = 25$ mm) and then extracted in 10 cm^3 of 30% acetone for 24 h in the dark at 4 °C. Total chlorophyll (*a*, *b*, *c1* + *c2*) concentrations were determined using spectrophotometric procedures (trichromatic method) detailed in 'Standards Methods' (1999).

3. The disequilibrium ^{234}Th/^{238}U technique has been used to trace scavenging processes (Buesseler *et al.*, 1992). ^{234}Th is a particle-reactive, naturally occurring radionuclide, produced in the water column by the decay of its soluble parent ^{238}U. After production, thorium can be scavenged onto particles and removed from the water column in association with them. The extent of the disequilibrium between ^{234}Th and ^{238}U is an effective tracer of scavenging processes and particle residence times in coastal waters and in the upper ocean. Due to its short half-life (24.1 days), ^{234}Th can be used to trace scavenging processes on time scales varying from a few to about 100 days.

Particulate and dissolved ^{234}Th were pre-concentrated by filtration of large volumes of water (700–1000 l) through a prefilter (1 μm, polypropylene) and two identical polypropylene MnO_2-impregnated cartridges, in series, to extract dissolved thorium. The cartridges were ashed in the laboratory at 450 °C, sealed in plastic containers and measured for ^{234}Th activity by gamma counting using a low background HPGe detector on 63.3 keV emission peak. The accuracy of the results was checked by analysing standard reference materials. ^{238}U concentration was calculated from salinity using the following relation: $^{238}U = 1.17 \times \text{sal}\ Bq\ m^{-3}$ (Ku *et al.*, 1977).

A box model was used to estimate the rate of thorium scavenging and removal by sinking particles. Assuming that (i) thorium profiles are in steady state and (ii) advection and diffusion are negligible, the flux of dissolved thorium onto particles J_{Th} and the flux of particulate thorium P_{Th} can be written as:

$$J_{Th} = \lambda(A_U - A_{Th}^d),$$
$$P_{Th} = \lambda(A_U - A_{Th}^d - A_{Th}^p),$$

where A_U, A_{Th}^d, A_{Th}^p are the activities of ^{238}U, ^{234}Th in the dissolved form and ^{234}Th in the particulate form and λ is the decay constant of ^{234}Th ($0.0288\,d^{-1}$). The particle flux was determined by multiplying the particulate ^{234}Th flux by the ratio TSS/^{234}Th on suspended particulate matter.

The residence time of dissolved (τ_{diss}) and particulate (τ_{part}) ^{234}Th with respect to scavenging onto particles and particle sinking are given by:

$$\tau_{diss} = \frac{A_{Th}^d}{J_{Th}} \quad \text{and} \quad \tau_{part} = \frac{A_{Th}^p}{P_{Th}}.$$

4. Surficial sediments were collected using a box-corer and a Niemistö corer, and immediately sectioned in 1-cm horizons for ^{210}Pb and ^{137}Cs determinations via gamma-spectrometry. Particulate organic carbon (POC) and particulate organic nitrogen (PON) were analysed using CHN elemental analyser Perkin-Elmer 2004.

3 RESULTS AND DISCUSSION

3.1 Hydrology and Water Currents

In late-summer (2000 and 2001) the intrusion of the salty (>33 psu) and warm (4.5 °C) water into the inner fiord was visible all along the Southern coast as far as Kongsvegen (Fig. 2).

The warm core was at about 25 m depth. Flowing anticlockwise along the glaciers front, the water became progressively colder and less saline: a layer of very cold fresh water produced by ice melting (5–10 m from the surface) was observed, and its northward outflow was visible out of the passage between Blømstrand Island and Blømstrandbreen (Fig. 3). This cold surface layer produced in the inner fiord affected the surface water temperature in the outer fiord which dropped from 3.6 °C in the southern part to about 2.4 °C in the northern part where outflow occurs. Lenses of dense cold water (1.8 °C) occupied the deep intermoraine depressions in front of Kongsbreen.

From 5 September, 2000, to 9 September, 2000, at the northern passage of the Lovenøyane moraine, velocity components of currents at 17 m in E–W direction were higher than in N–S direction by about 1 order of magnitude to indicate possible exchange of water across the passage. Despite of eastward pulses up to $20\,cm\,s^{-1}$, progressive diagram showed very poor net water transport with distances of about 2 km covered in 3 days (Fig. 4).

3.2 Suspended Solids and Pigments

In selected stations of the inner fiord and in a reference area in the outer fiord euphotic depths, total suspended solids (TSS), chlorophyll and phaeopigments concentrations were determined (Fig. 5).

The southern part of the fiord (Stations KO2 and KO1) is mainly influenced by oceanic water (low TSS, high values of photosinthetically active radiation (PAR) penetration and

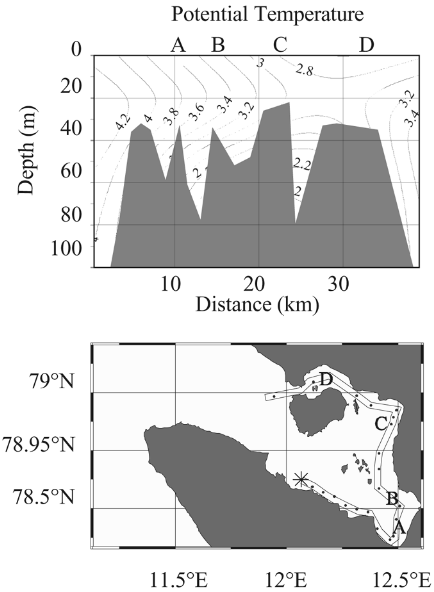

FIGURE 2 Potential temperature and salinity along the showed path (*, starting point; A, Kongsvegen; B, Kronebreen; C, Kongsbreen; D, Blømstrandbreen). Salty water intrusion is at about 20 m depth across the southern passage of the moraine. Fresh surface water lens is in the northern part and along the recent Blømstrand passage.

high chlorophyll *a* concentrations, but contributions from land are also evident: the presence of chlorophyll *b* and *c*, and of a lens of freshwater (evidenced by CTD profiles) suggest inputs from Brøgger halvøya. In the inner part of the fiord, the glacier melt water is also marked by specific indexes characterising inputs of terrigenous origin: (i) chlorophyll *b* and *c*, which are common in fresh water, (ii) high values of suspended solids and, consequently, (iii) strong attenuation of PAR penetration in the first few metres of the water column. The euphotic depth ranged from 2 to 10 m.

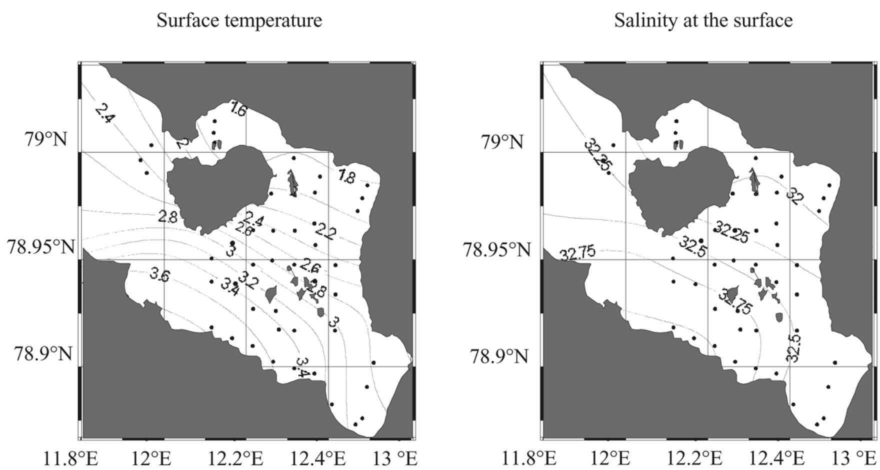

FIGURE 3 Map of temperature and salinity at the surface.

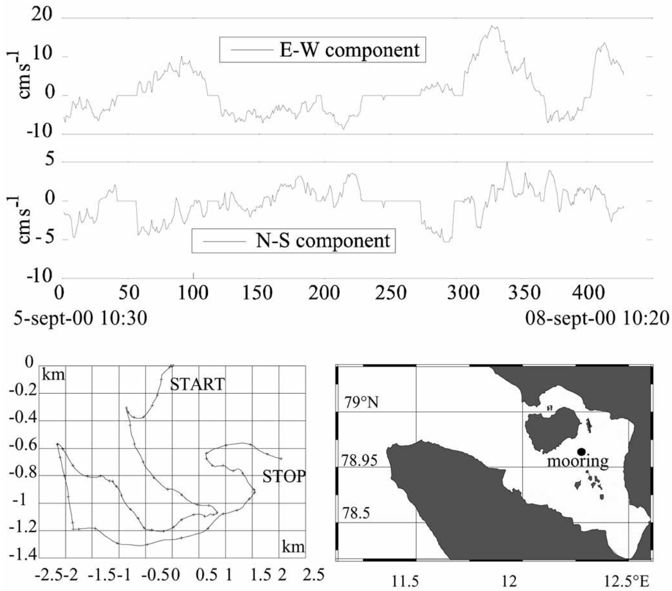

FIGURE 4 The reported time series of water current at 17 m depth in the northern passage of the Lovenøyane moraine (above) and the reported progressive diagram indicating poor net transport in kilometre from 5-Sept-00 at 10:30 to 8-Sept-00 at 10:20 (below on the left). Marks in the line indicate the distance between two consecutive sampling (10 min) and the black dot in the map shows the mooring position.

3.3 Sedimentation Processes

The highest concentrations of TSS (up to 100 mg l^{-1}) were found near Raudvika and Kongsvegen, while they significantly decreased in the Blømstrand passage. Data derived from the disequilibrium $^{234}Th/^{238}U$ (Fig. 6) indicated, in these areas, particle fluxes in the

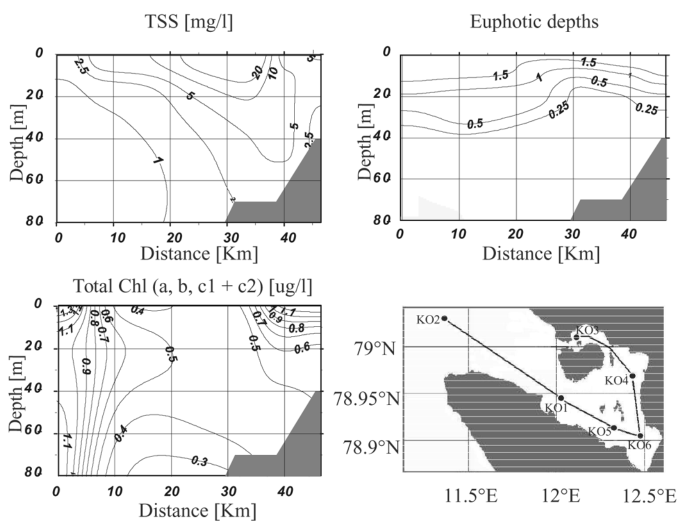

FIGURE 5 Total suspended solids, euphotic depths (1% surface photosinthetically active radiation—PAR 400–700 nm), chlorophyll *a*, *b* and *c* concentrations, along the path showed in the map.

range 5–8 g m^{-2} d^{-1} and very short particle residence times in the water column (around 5 days), suggesting a fast sedimentation regime when approaching the glacier–sea interface. In contrast, the outer fiord was characterised by lower particle fluxes (2–4 g m^{-2} d^{-1}) and longer residence times (12–30 days), (Papucci *et al.*, 2002). In the sediments of the inner fiord, the low POC/PON ratios (4–8) evidenced the input of fresh organic matter derived from planktonic organisms (C/N 6–10), probably related to zooplankton that dies by osmotic shock when it is in contact with freshwater from the glacier outflow (Zajakowski and Legezjnska, 2001). They were also characterised by low concentrations of organic matter, due to its dilution into huge amounts of inorganic particles (Görlich *et al.*, 1987). The sill connecting Gerdøya to Lovenøyane seems to act as a trap for fine-grained particles that are aggregating and settling close to the glacier–sea interfaces, leading to preferential accumulation of sediments in the inter-moraine depression.

The sediment cores have been analysed by gamma-spectrometry for determining the vertical profiles of both $^{210}Pb_{ex}$ and ^{137}Cs (Fig. 7). The sediment accumulation rates have been

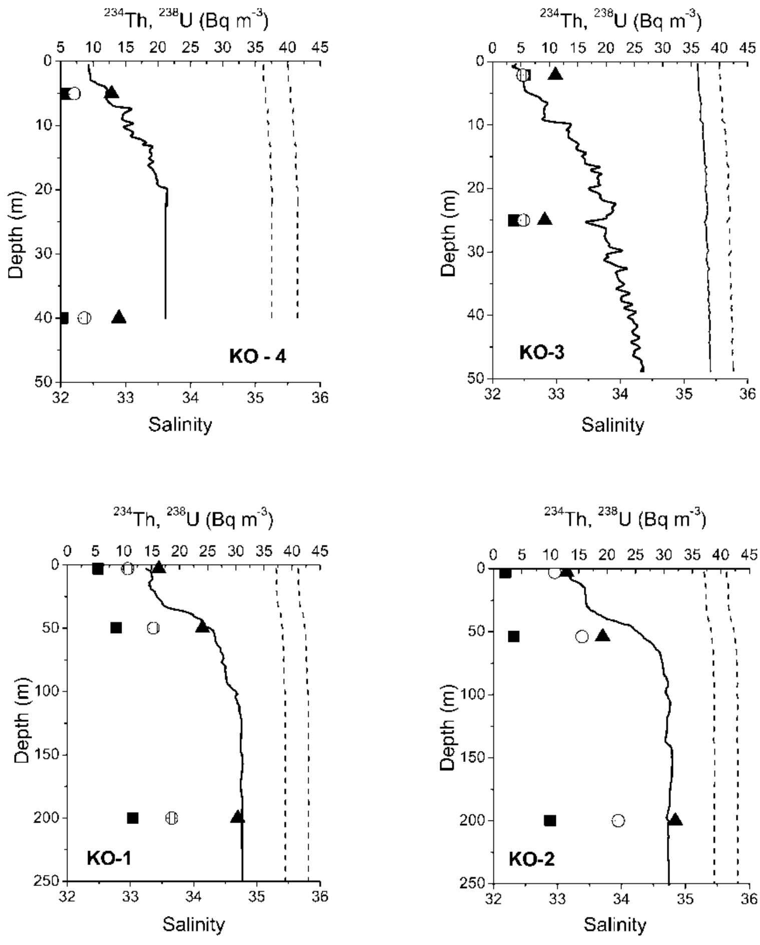

FIGURE 6 Vertical profiles of particulate (■), dissolved (○) and total (▲) ^{234}Th, salinity (—) and ^{238}U (···) represent lower and upper limit of ^{238}U concentration) at two stations in the inner (KO3 and KO4), central (KO1) and outer (KO2) Kongsfiord. At all stations there is a marked disequilibrium between ^{234}Th and ^{238}U, indicating efficient scavenging and particle fluxes decreasing from the inner to the outer fiord.

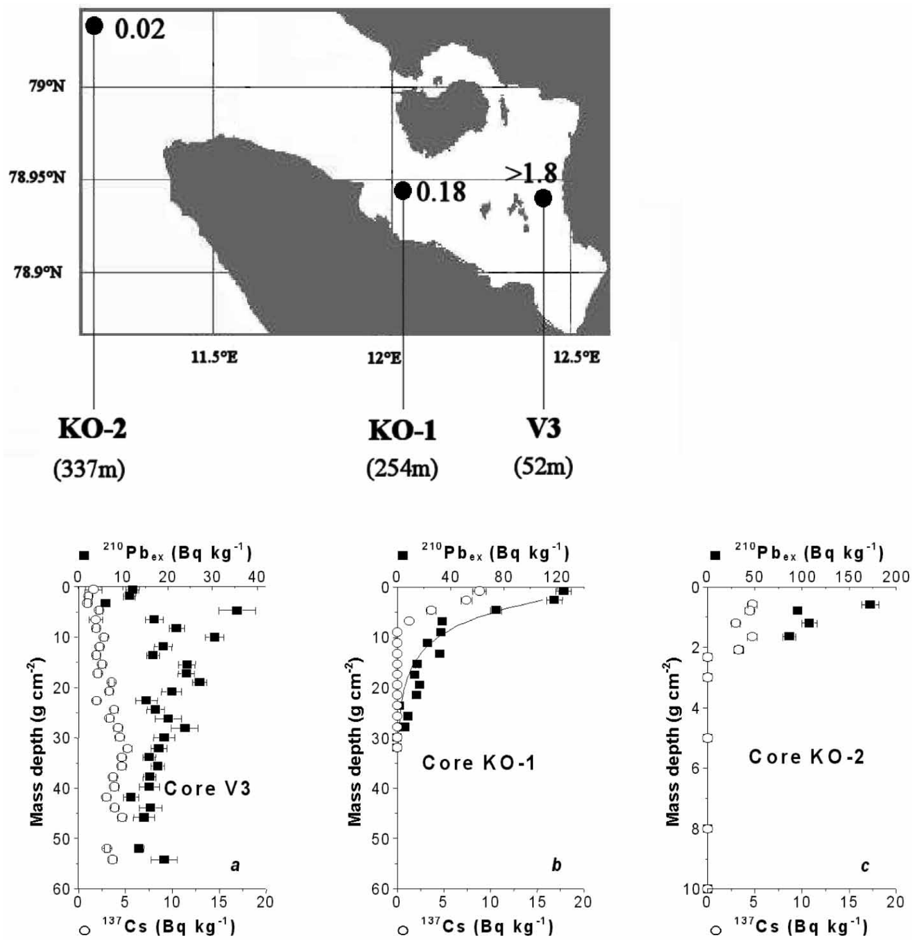

FIGURE 7 Sedimentation rates ($g\,cm^{-2}\,yr^{-1}$) from the inner to the outer fiord. The activity–depth profiles of $^{210}Pb_{ex}$ and ^{137}Cs in sediments are reported in (a), (b) and (c).

estimated by the vertical profiles of $^{210}Pb_{ex}$. The constant rate of supply model was used (Robbins and Edgington, 1975; Appleby and Oldfield, 1978). The sedimentation rate is highest and close to the Southern part of Kongsvegen (exceeding $1.8\,g\,cm^{-2}\,yr^{-1}$), and it is 1 order of magnitude higher than in the trough between Ny Ålesund and Blømstrand (0.2–$0.4\,g\,cm^{-2}\,yr^{-1}$), and two orders of magnitude higher than that found ($<0.02\,g\,cm^{-2}\,yr^{-1}$) in the outer fiord and on the continental shelf.

4 CONCLUSIONS

The main marine features of the late-summer situation in the inner Kongsfiord, at the glaciers–sea interface, have been delineated.

Warm ocean water entered the fiord across the southern passage at about 20–25 m depth. Before the opening of the Blømstrand passage, mathematical models described outflow of water also from the northern passage of Lovenøyane, but only few pulses related to tidal oscillations were recorded in our short timeseries. Warm ocean water intrusion across the northern passage of Lovenøyane was negligible and the water in the northern part of the inner fiord was cold and fresh. Large veins of cold surface water exit the inner fiord across the recently opened passage between Blømstrandbreen and Blømstrand island. This brackish cold water strongly affect the surface temperature in the northern part of the outer fiord. Before the opening of Blømstrand passage, Svendsen *et al.* (2002) described this veins as 'small amount of brackish water' and has not been considered in the description of the oceanography of the fiord.

The lenses of cold dense water at the bottom indicate that dense water formation has taken place in the area during winter or that entering warm ocean water was replaced by very cold dense water sometime during the year. Further studies on these dense bottom waters are required. However, vertical movements of the water and turbulence are reported to occur at the glacier–sea interface (Hakkinen, 1987; Greisman, 1979; Hop *et al.*, 2002) where the abrupt changes of temperature and salinity due to ice melting can also affect productivity and sedimentation.

The hydrological pattern described is possibly the result of the 'recent' (eighties) opening of the passage between Blømstrand and Blømstrandbreen, which activated a novel circulation regime, and likely influenced also sedimentation and biological processes in the inner part of Kongsfiord.

The fiord acts as a trap for fine-grained particles exported by the glaciers. In particular, the areas of highest sedimentation regime are located in the inter-moraine depressions, close to the sea–glacier interfaces.

Further investigations are needed to define the seasonal variability, and to assess the consequences of the Blømstrand passage on the inner Kongsfiord ecosystem.

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