Proc. NIPR Symp. Polar Meteorol. Glaciol., **11**, 211-232, 1997

CHARACTERISTICS OF WATER IN KONGSFJORDEN, SVALBARD

Hajime Ito and Sakae Kudoh

National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173

Abstract: The characteristics of the water in Kongsfjorden, Svalbard are summarized. Data collected by NIPR since 1991 are used for discussion. The structure of the water is rather complicated, indicating active movement within the fjord. The seasonal change in the summer half year is followed and the creation mechanisms of the structure are explained. The glaciers occupy most of the drainage basin. Glacier hydrology governs the fresh water supply. A particular wind pattern is found in the fjord, whose origin is also closely related to the glacier cover. The access to Greenland Sea water at depth is another factor, which dictates the characteristics of the water. The fjord water is a heat store and fresh water dump, and contributes to the maritime local climate. The characteristics of the water are revealed to the extent that,other disciplines with their research field in the vicinity can describe their physical environment in terms of fjord water.

1. Introduction

Kongsfjorden is one of the large fjords found on the western coast of Spitsbergen, Svalbard (Fig. 1). The characteristics of a fjord are strongly influenced by its surroundings (topography, adjacent ocean, climate, *etc.*). The latter in turn are affected by the former. The local climate and marine ecology of the surrounding area are directly dictated by the water condition. Glaciers, hydrology and land ecology are some of many factors influenced indirectly by the state of fjord water.

The authors and the research group of the National Institute of Polar Research, Tokyo (NIPR) investigated Kongsfjorden primarily to clarify the characteristics of the water masses and the mechanisms governing their creation and modification. The complete results will be presented elsewhere, but this article aims at something different: the accumulated information so far seems worth presenting in such a form that all disciplines related to the water can use it to describe their environment. This is the purpose of the present article; the water of Kongsfjorden is one of the physical components which make up the environment of the vicinity.

2. Observations

2.1. Oceanographic observation by NIPR

NIPR took field observations in September 1991, June 1992, May-June 1993, June 1994 and June 1995. A dinghy was used as an observation platform. Water temperature and salinity profiles were obtained using a salinity-temperature-depth recorder (STD), model AST-1000 M made by ALEC Electronics Co. The accuracies of psu, temperature

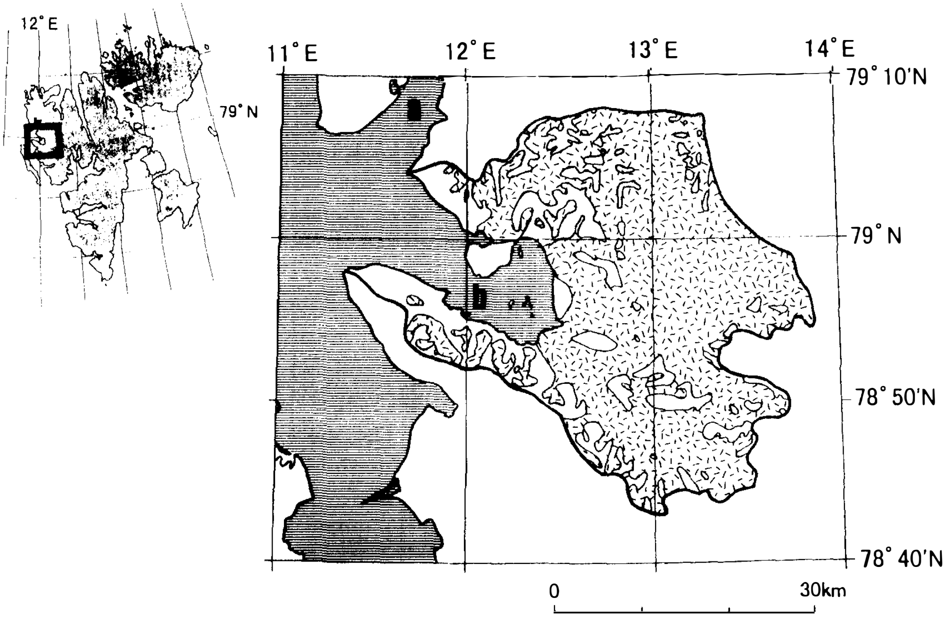


Fig. 1. Kongsf jorden with its drainage basin.
The sea [sea symbol] and glaciers [glacier symbol] are shaded. a: Krossfjorden, b: Kongsfjorden.

and pressure are claimed by the manufacturer to be 0.05, 0.05°C and 0.5 db respectively. The data are recorded at 0.5 db intervals. Stations are located by a Global Positioning System (GPS) receiver, model GP-70 made by Furuno Electronics Co., and are indicated in Fig. 2 with different symbols for each year.

In July and August 1993, additional observations were made using the commercial vessels MS "ORIGO" and MS "POLARSTAR" (ITO and YOSHIOKA, 1994). In addition to STD measurements, the temperature profile was obtained while the ship was in motion using expendable bathythermographs (XBT), model MK-30 made by Tsurumi Seiki Co. The accuracy is claimed to be 0.1°C and 2% of depth respectively. The data were recorded at 1m depth intervals. The ship's position was measured by an on-board GPS receiver and was used as the location of each station. The cruise covered a large area extending over the north-western half of Spitsbergen coastal waters, and many stations were occupied en route. However, only a small number of stations in Kongsfjorden and used for the current study.

2.2. *Cooperative oceanographic observations*

In August and September 1992 and August 1993, an international research cruise in the Greenland Sea was organized by the Norwegian Polar Institute using FV "LANCE" in which NIPR participated (USHIO *et al*., 1994; ITO *et al*., 1994). NIPR was primarily responsible for the XBT measurements on board, which supplement the CTD measurements executed by the Norwegian Polar Institute. Both XBT and CTD data are available for the analyses, but only a very small fraction of the large data set was obtained in Kongsfjorden.

In September 1994, August 1995 and August 1996, the University of Bergen carried out a research cruise in Svalbard fjords, *i.e.* Kongsfjorden, Krossfjorden, Van Mijen Fjorden

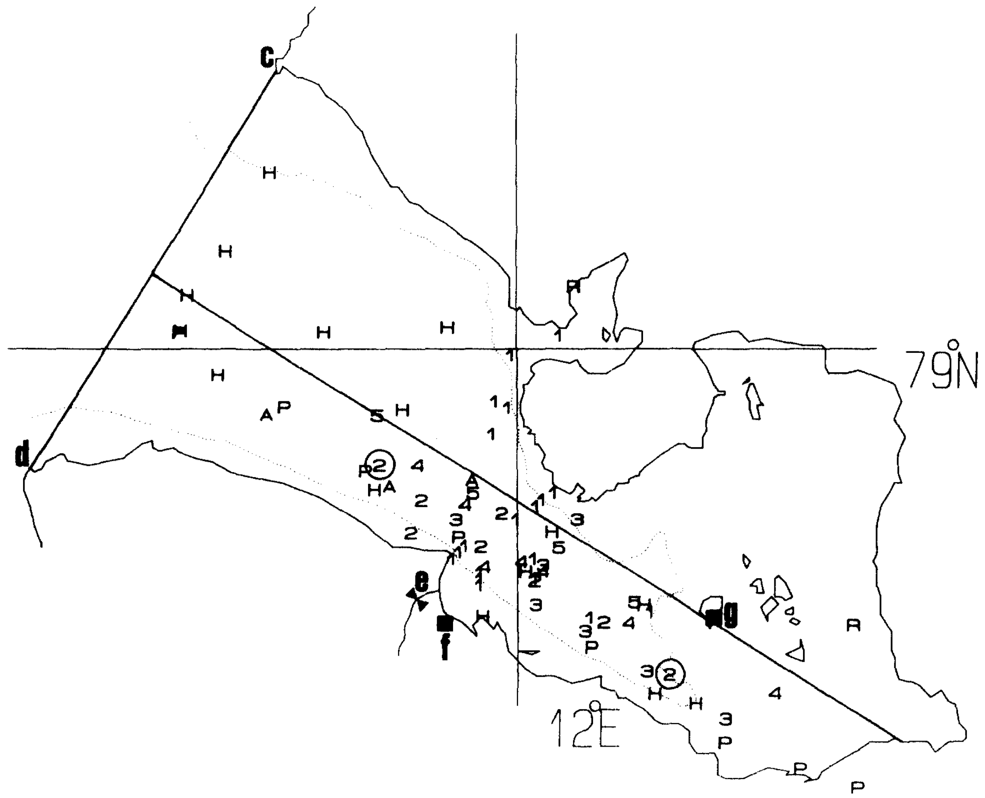


Fig. 2. Kongsfjorden with stations.
Numbers and letters are oceanographic stations made in different years and/or by different cruises: 1, 2, 3, 4, 5 = 1991, 1992, 1993, 1994, 1995 by NIPR's boat. A = 1992 by "LANCE". P, R = 1993 by "POLARSTAR" and "ORIGO". H = 1994 and 1995 by the "HÅKON MOSBY".
At most of the stations, two or more observations were made repeatedly.
c: Kapp Guissez, d: Kvadehuken, e: discharge station Bayelba, f: weather station NIPR Ny-Ålesund, g: weather station Storholmen.

and Isfjorden, using the RV "HÅKON MOSBY" (SVENDSEN, 1996; NORDLUND, 1995). NIPR joined this research cruise. CTD profiles were obtained using Model SBE 9/11 made by Sea-Bird Electronics. The accuracy is claimed to be 0.0004°C, 0.00007 S/m (conductivity) and 0.25% of full pressure scale respectively.

The stations taken by the cruises in the area are also shown in Fig. 2 with different symbols.

2.3. *Related observations*

The NIPR research station in Ny-Ålesund on the south coast of Kongsfjorden (Fig. 2) is equipped with a weather station, which has been in operation since August 1992.

A weather station was set up on a small island, Storholmen, in the fjord in June 1995 by NIPR and has been in operation since then.

The Norwegian Water Resources and Energy Administration (NVE) has recorded the discharge of Bayelva, a river running into Kongsfjorden, since June 1989. The authors obtained the data from NVE. A group from NIPR also carried out hydrological field work in the area in 1992, 1993, 1994 and 1995 (KODAMA *et al.*, 1995), and supplied the authors with additional hydrological data.

2.4. *Results*

All available oceanographic data are used for the analysis without distinction as to their source. The results are voluminous and are not presented here in complete form. The discussion in the following chapters will present specific results only where necessary or convenient.

3. Environment of Kongsfjorden

3.1. *Geography*

Kongsfjorden is located in the Arctic at 79°N, 12°E (Fig. 1). It is 26 km long and 8 km wide with several small islands in it and runs from ESE to WNW. It joins with Krossfjorden at the mouth and then with the Greenland Sea. The fjord is defined to be the area inside of the line connecting the tips of two peninsulas, Kapp Guissez and Kvadehuken, in this article, as indicated in Fig. 2.

Kongsfjorden is representre of the fjords in the region with its shape: a narrow, long and deep water body. The land on both sides is steep.

The geometry of the fjord is measured on Chart 522 (Norwegian Polar Institute, 1974) and given in Table 1. The coast line refers to the state of the tidal glacier extent in 1970, when the survey was made for the chart. The area was measured with a planimeter at each depth given in the table, *i.e.* the area within a depth contour. The volume was

Table 1. Geometry of Kongsfjorden.
Annually varying features such as glacier termini are shown in the state observed in 1970.

Fjord					
area	total	208.8 km ^{2}	width	entrance	12.9 km
	islands	1.3		mean	8.0
	10 m depth	184.5	length	maximum	26.1 km
	20 m depth	167.9	section	entrance	2.5 km ^{2}
	50 m depth	139.0		mean	1.1
	100 m depth	101.6	depth	maximum	428.0 m
	200 m depth	71.0		threshold	280.0
	300 m depth	27.6		mean	141.0
	400 m depth	1.3	coast line	total	89.6 km
volume	total	29.4 km ^{3}		glacier	15.9
Drainage basin					
area	total	1260.5 km ^{2}		tidal glacier	928.0 km ^{2}
	of fjord	603.7%		of glacier	94.2%
	with fjord	1469.3 km ^{2}	altitude	maximum	1314.0 m
	glacier	985.6 km ^{2}			
	of total	78.2%			

then computed. Svalbard Topographic Maps 1 : 100000 are used for the measurement of the drainage basin: A6 (Krossfjorden), A7 (Kongsfjorden), B6 (Eidsvollfjellet) and B7 (Tre Kroner) (NORWEGIAN POLAR INSTITUTE, 1966 to 1990). Where the chart and map claim different positions for glaciers, the chart was chosen. The Table describes the shape of the fjord and basin. It is noted that the majority of the drainage basin is covered by glaciers, and most of the glaciers reach the sea.

Unsystematic observations were made of the tidal conditions in situ. The tide is diurnal with a range of *ca.* 2 m, and the tidal current is weak. Ice conditions were also observed unsystematically. Little sea ice grows in the fjord, but many small pieces of glacier ice are found at the surface of the fjord during most of the year.

3.2. Atmosphere

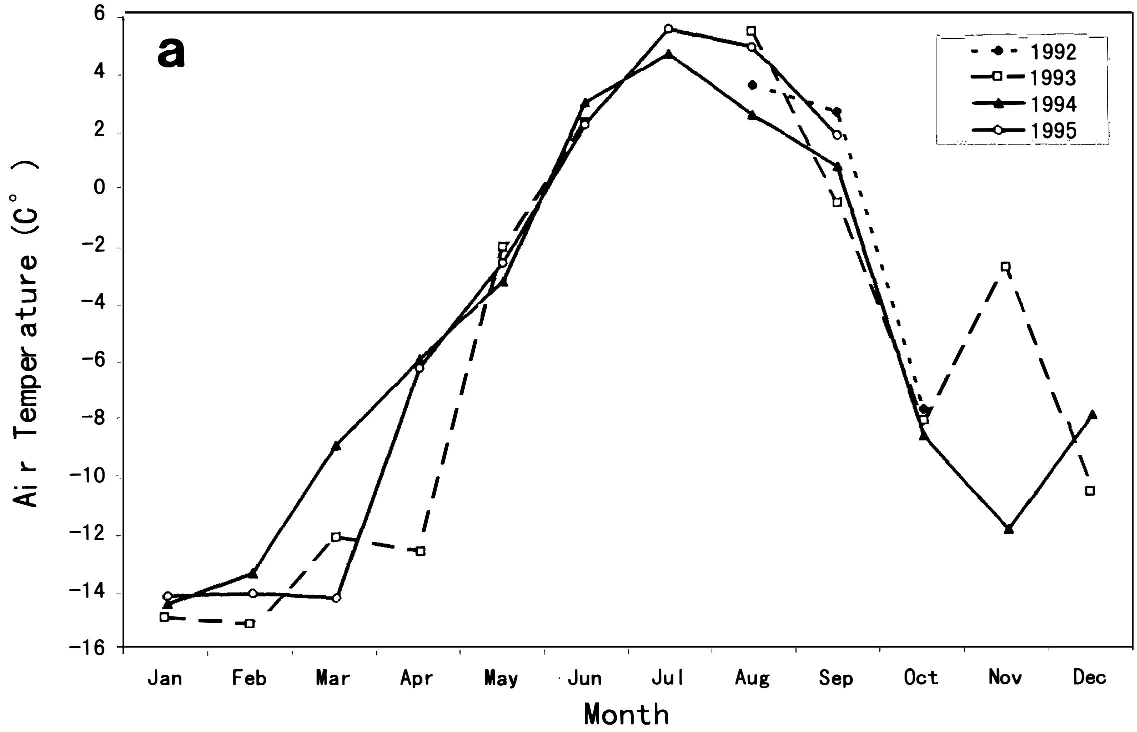
Fjord water is in contact with the over-lying atmosphere through its surface all year. Even a fjord, which is described as a 'deep' water body, is relatively spread out. (A cube containing the water of Kongsfjorden would have a height of more than 3 km, more than 20 times the actual depth of 140 m.) The influence of the atmosphere must therefore be significant in modifying the fjord water.

The air temperature observed at the NIPR station in Ny-Ålesund is plotted in Fig. 3a. The air temperature is rather high for the latitude, yet cold enough, with an annual mean temperature of around −5°C. The warm air heats up the fjord water in summer and cools it down in winter through heat exchange. Balance is, however, not achieved annually. The annual mean water temperature is estimated to be slightly above 0°C. The atmosphere has received positive heat when one year's cycle is completed.

Solar radiation is another heat source and is plotted in Fig. 3b. It is noted that the periods during which the water gains heat from a warm atmosphere and from the sun are displaced by a couple of months from each other.

Wind not only plays an important role in heat exchange between the water and atmosphere, but it is also one of the very few driving agents of the water, which is by itself rather immobile. It is already known that the wind speed and direction above the fjord water are different from those measured on land at the NIPR Station. The surface wind above water is different from that at altitude (the NIPR Station has an altitude of 35 m above sea level), and/or it extends horizontally only within the area immediately above water. The wind record on an island in the fjord is expected to represent the wind above the sea better, and is used for the study, although the record length is only 13 months.

Brief inspection of the record shows that the wind is limited to two opposite directions along the fjord axis. This is characteristic of a canal flow with both sides walled by land. Figure 4 shows the monthly mean wind speed and monthly maximum gust speed. (gust= wind recorded in a minute) It is windy in winter and less windy in summer. The temperature difference is greater in winter between the ice-free sea and glaciers at altitude. Katabatic wind flow from the glaciers is suspected to be the origin of the seasonal difference, hence of the wind. Figure 5 shows monthly vector means of wind velocity, which represents a transport potential. The surface water is driven outward from the fjord. The data recorded in such a short period may be biased and should be carefully interpreted, although the wind tendency in this particular period is believed to indicate general wind conditions to some extent.



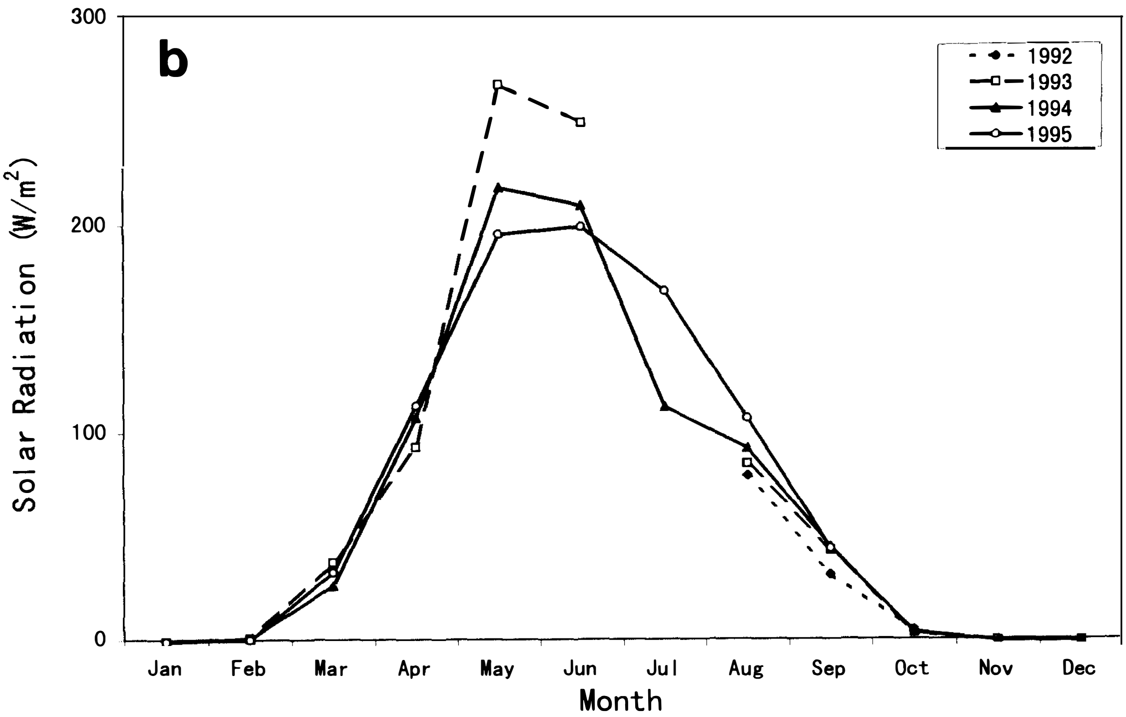


Fig. 3. Air temperature and solar radiation at Ny-Ålesund. The measurement was made at the NIPR station (see Fig. 2).

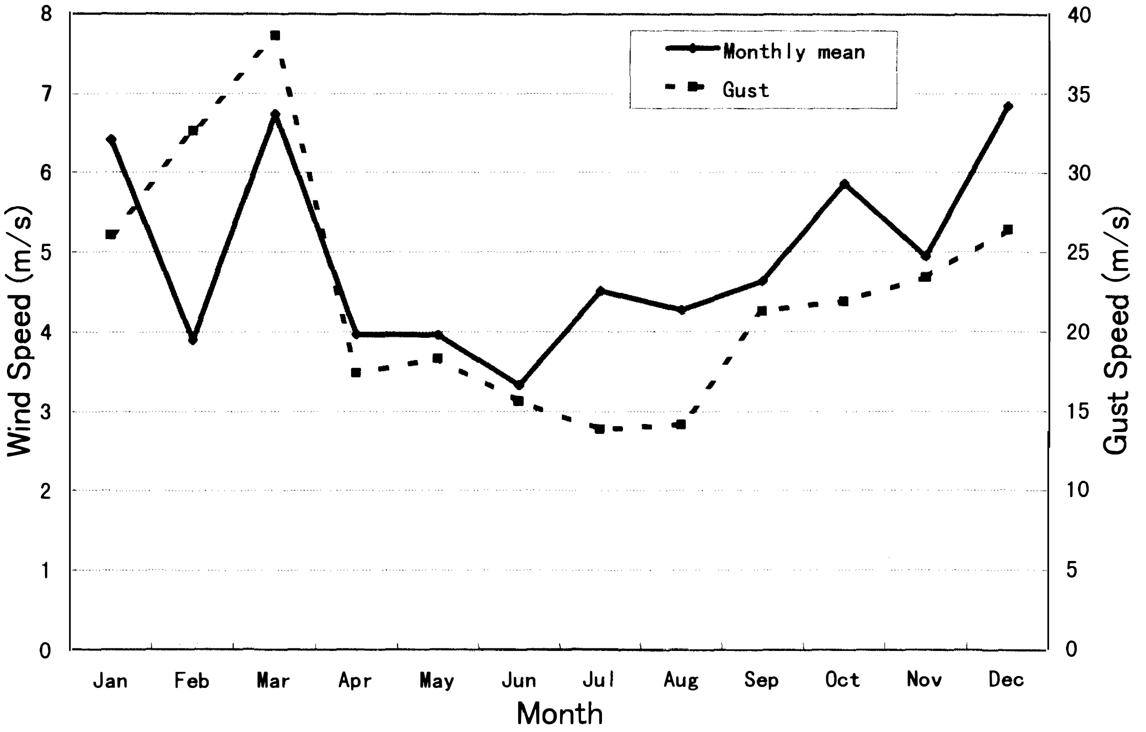


Fig. 4. Wind speed at Storholmen.
The position of the station is shown in Fig. 2.

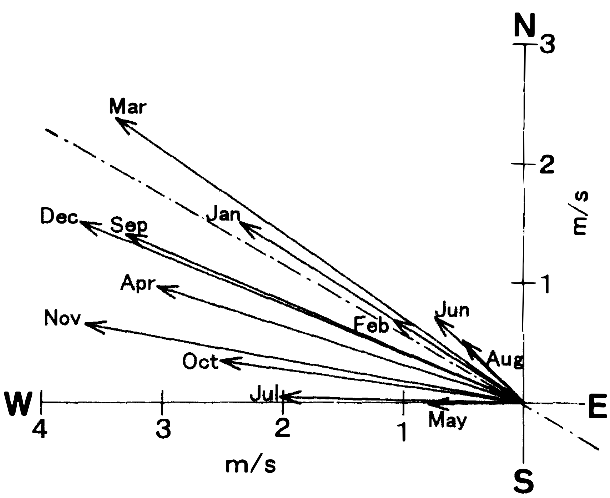


Fig. 5. Monthly vector mean wind at Storholmen.
The station position is shown in Fig. 2.

3.3. Hydrology

The bayelva is the largest river in the basin. The area of its own drainage basin is 31.6 km^2, of which 54% is covered by glaciers. The length is 10 km from the divide to the river mouth and 3km from the lower end of the glacier.

Discharge data obtained and supplied by NVE are shown in Fig. 6. The value fluctuates from one day to another as well as from one year to another, but generally starts

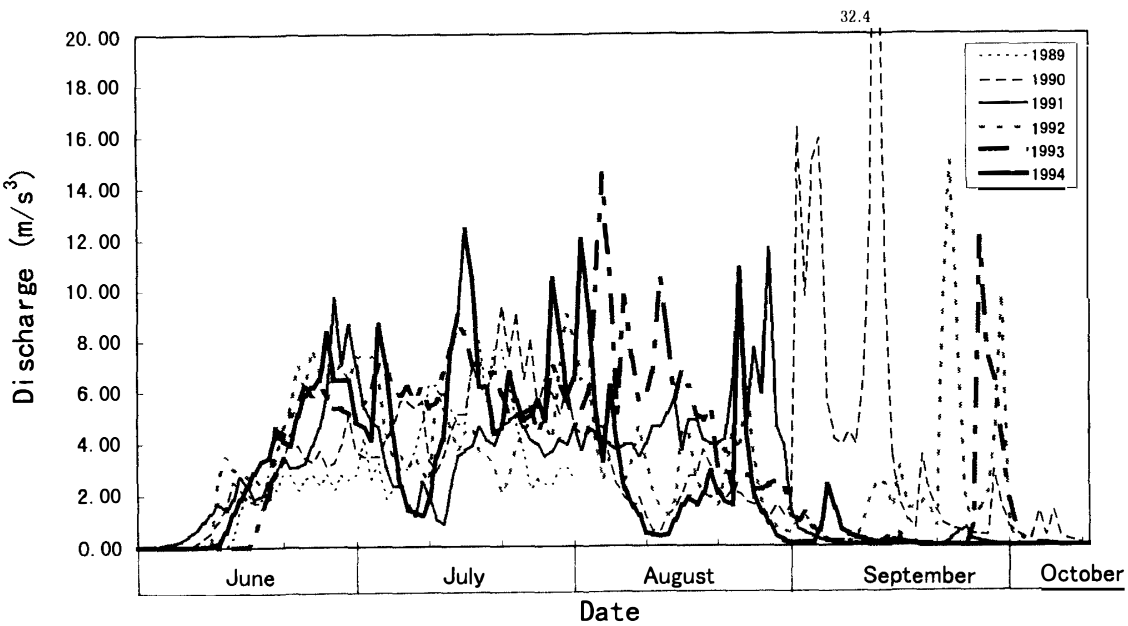


Fig. 6. Discharge of Bayelva.
The station position is shown in Fig. 2.

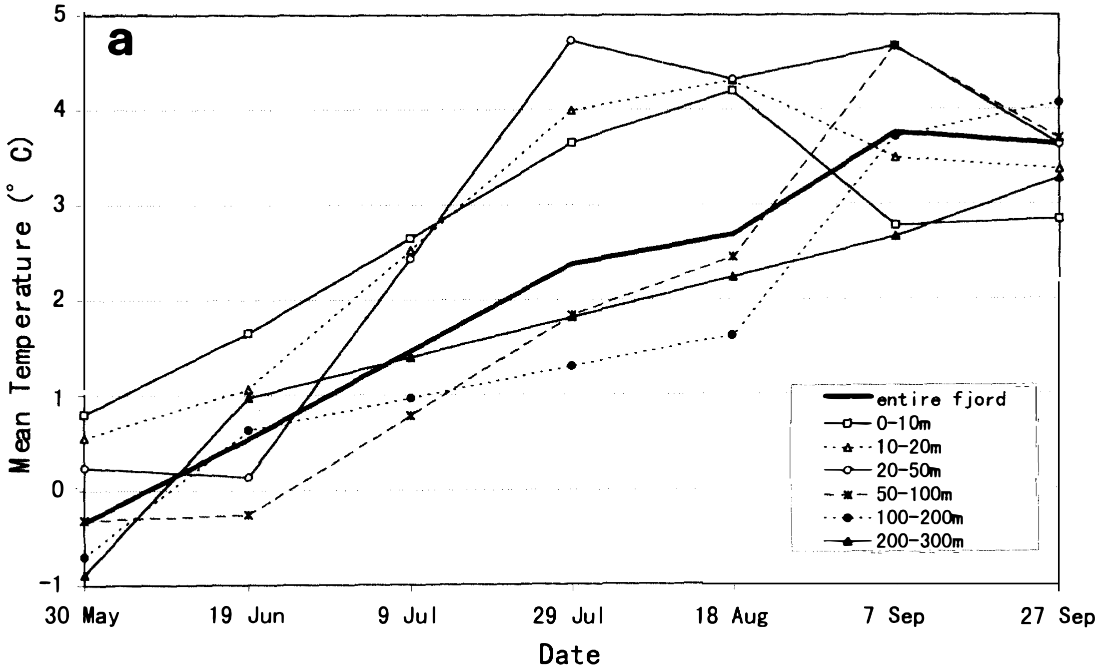
at the beginning of June and stops at the beginning of October. Mean discharge is calculated to be 0.03 km^3/year, with a discharge height of 1000 mm. Assuming that the mean discharge height of Bayelva basin is applicable to the entire Kongsfjorden basin, 1000 mm multiplied by 1469.3 km^2 yields a total annual discharge of 1.5 km^3. Uncertainty in the estimation of the hydrology in the entire basin is found in the extrapolation rather than in the observations. The hydrology in a small sub basin partially covered by a mountain glacier need not represent that of the entire basin with large tidal glaciers; both quantity and time of discharge may be completely different. However, no hydrological work has been done on a tidal glacier in the area, and the estimation is the best available at present.

4. Water of the Fjord

4.1. General

The fjord water is treated in bulk first to investigate its general characteristics. The observation period is divided into seven sub-periods, each 20 days long: 20 May to 18 June through 17 September to 6 October. The sub-period is represented by the middle day: *e.g.* 30 May and 27 September for the first and last sub-periods respectively. The fjord water mass is divided into six horizontal layers. For each sub-period and layer, mean temperature and salinity, shown by different symbols in Fig. 7, are calculated. Using the fjord geometry, mean temperature and salinity of the entire water are calculated for each period, and connected with thick lines in Fig. 7. It is indeed warmer and less salty than the open sea at the same latitude, at least during the summer half year.

The fjord water gains heat in spring and crosses 0°C upward at the end of May. It is continuously warmed until the end of August when a maximum of 3.8°C is reached. The temperature stays around this value for a month until winter cooling starts in October.



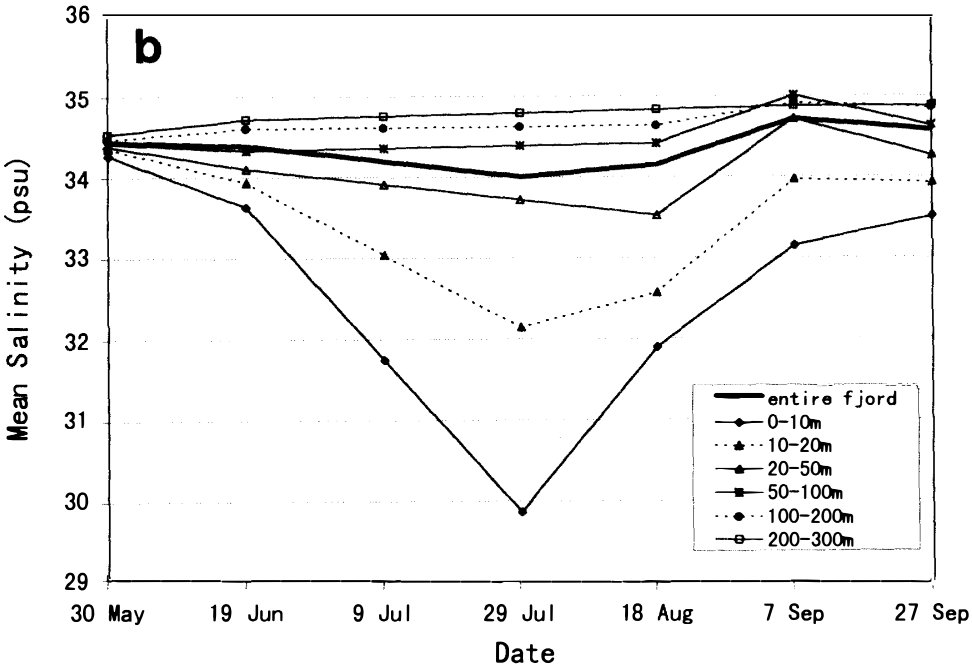


Fig. 7. Mean temperature and salinity of water in Kongsfjorden.
Thick line indicates temperature and salinity of entire water. The thin lines with symbols indicate horizontal layers. The upper and lower boundary depths of each layer are shown in the figure, where the distance shows the depth from the water surface.

The starting time of the warm-up is not seen in the Figure but is estimated to be some time in April from unsystematic observations in situ. The tendency in water temperature seems to represent that of a water body placed in a similar location. The heat gained during the three summer months, *i.e.* only the period shown in the Figure excluding the uncertain pre-warming period mentioned above, is calculated. The difference in mean temperature between the maximum on 7 September and the initial value on 30 May is multiplied by the water mass and the specific heat to yield a heat gain of 4.87×10^{17} joule altogether or 300 W/m^2 on average. The same amount of heat or more must be transferred back to the atmosphere in winter, providing that there is no great change in the heat condition at a given time of year between succeeding years. The fjord is indeed a large heat reservoir, and contributes to the maritime climate of the vicinity.

The salinity decreases as the season progresses as well (Fig. 7b). However, the minimum is reached one month in advance of the temperature maximum and a couple of months in advance of river discharge termination. Furthermore, the salinity at the beginning, at the end of May, does not seem to be a maximum, indicating that fresh water inflow starts in an earlier month. The fjord is supposed to be filled with Atlantic Deep Water at 34.95 psu at the end of winter, and fresh water is added in summer to reduce the mean salinity to a minimum of 34.00 psu by the end of July. The fresh water required is calculated to be 0.797 km^3 or a drainage height of 542 mm in the entire basin. Noting that the calculation assumes no fresh water loss, *i.e.* all fresh water is completely mixed with the existing fjord water before it leaves the fjord, and this is not always realistic, the actual discharge must be larger. The calculated figure is thus within the range that the hydrological investigation suggested, 1000 mm.

4.2. Layers

Obviously the fjord is not filled with water all at the mean temperature and salinity (see Fig. 7), but the water possesses rather complicated structure. While each of the interesting layers will be discussed later, they are summarized and named in this section for convenient reference. The name layer presumes that the water is homogeneous horizontally. To what extent this is true will be discussed later, and the fjord water is considered here along a vertical column. Figure 8 is a schematic TS profile. There are several layers noted. (A single TS profile does not necessarily have all the layers.) The layers are explained from the top downward. The names serve only for reference within this article.

Surface Layer (A–B): The water surface reflects its immediate local environment, such as river discharge, floating ice pieces *etc.*, strongly, and sometimes shows quite different characteristics from the subsurface water. This is often extremely local and varies quite rapidly horizontally, and the layer thickness is small, when it exists: from some tens of centimeters to a couple of meters. The observations often missed this layer.

Top Layer (B–C): The uppermost water next to the surface layer (the latter is quite often absent) is directly influenced by the atmosphere, radiation and fresh water inflow. The influence is first experienced by the uppermost water but is then transmitted downward, thus the layer thickness increases with time. Despite the name 'top' it can, perhaps in late winter, reach the bottom in its extreme limit. The water is often highly mobile at depth and irregularities in the temperature curve are frequently observed, indicating active horizontal intrusion.

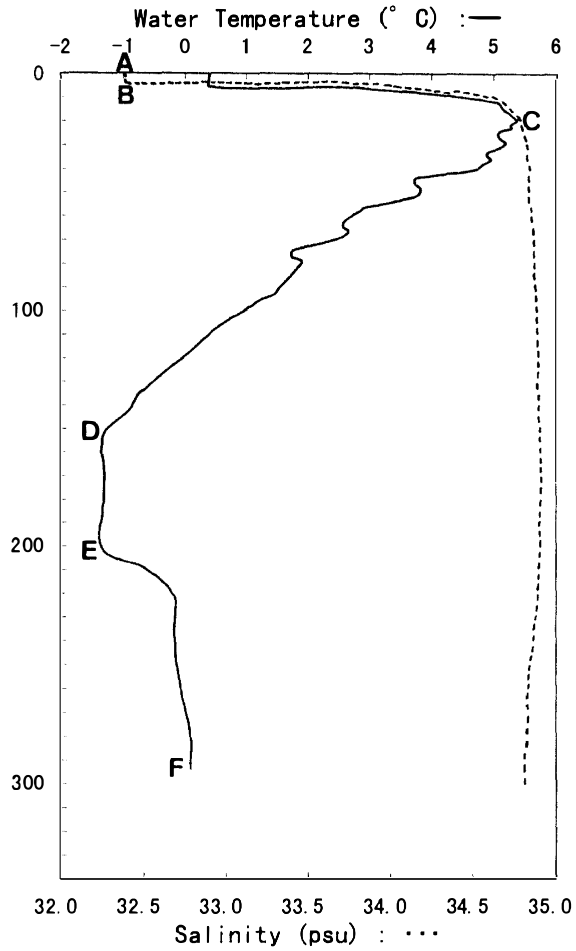


Fig. 8. Schematic profiles of water temperature and salinity.
The scales on the axes are arbitrary. Symbols, A through F, are referred to in the text.

Seasonal Layer (C-D): When surface conditions change within a single summer half year, different top layers are created. An older top layer has intruded deeper than a new one, as more time was available. At a given time, the water at a certain depth conserves the influence of old surface conditions of that year, while the new influence has not arrived at that depth yet. This part of the water column is called the seasonal layer. The point at which the top layer catches the seasonal layer shows often a temperature peak (C). As this depth can be so small that the horizontal movement is still considerable, the peak occasionally has a flat or twin headed shape through horizontal intrusion. No name is given to the flat part or between peaks, *i.e.* they are not considered to be an independent layer.

Winter layer (D-E): This water, which the surface conditions of the present year have not reached yet, preserves the winter state, and is called the winter layer. The layer itself is only found early in spring. After the layer disappears as the upper and/or lower layers invade, a temperature trough is often noticed where it was. Water is mobile even in the depths, and a flat bottomed trough or twin trough is common.

Bottom Layer (E-F): The warm water detected at great depth is called bottom water.

The Atlantic Deep Water is a possible origin of this water. It comes into the fjord somehow over the sill without suffering much change in its characteristics. The 'bottom' layer lies indeed on the bottom in many cases, but is occasionally found afloat at intermediate depths. Some condition seems to favor an intrusion at this depth. Below a floating bottom layer, a top layer, seasonal layer, winter layer or another bottom layer is found.

Figure 9 shows a series of T-S diagrams obtained during the summer half year. Some of the layers explained above are noted in each figure. Figure 9a is the initial condition for the summer modification of the water column; only this diagram was a reconstruction.

Figures 9b through 9e are a series of diagrams which describe the summer modification. The pair of diagrams Fig. 9e and 9f indicates the start of winter cooling through deep mixing. The density curves were also investigated but are not shown, as the water was always stable and the curves are uninteresting. The change of structure is explained in chronological order below.

4.3. Winter condition

One of the most remarkable characteristics of Kongsfjorden is found in the ice conditions in winter. The fjord is known to be unfrozen despite its location at high latitude. The middle of the fjord, approximately from the 100 m depth contour outward, does not develop a stable ice cover in most years. Thin pack ice is blown out of the fjord by the wind, and the fjord surface maintains open water characteristics throughout the

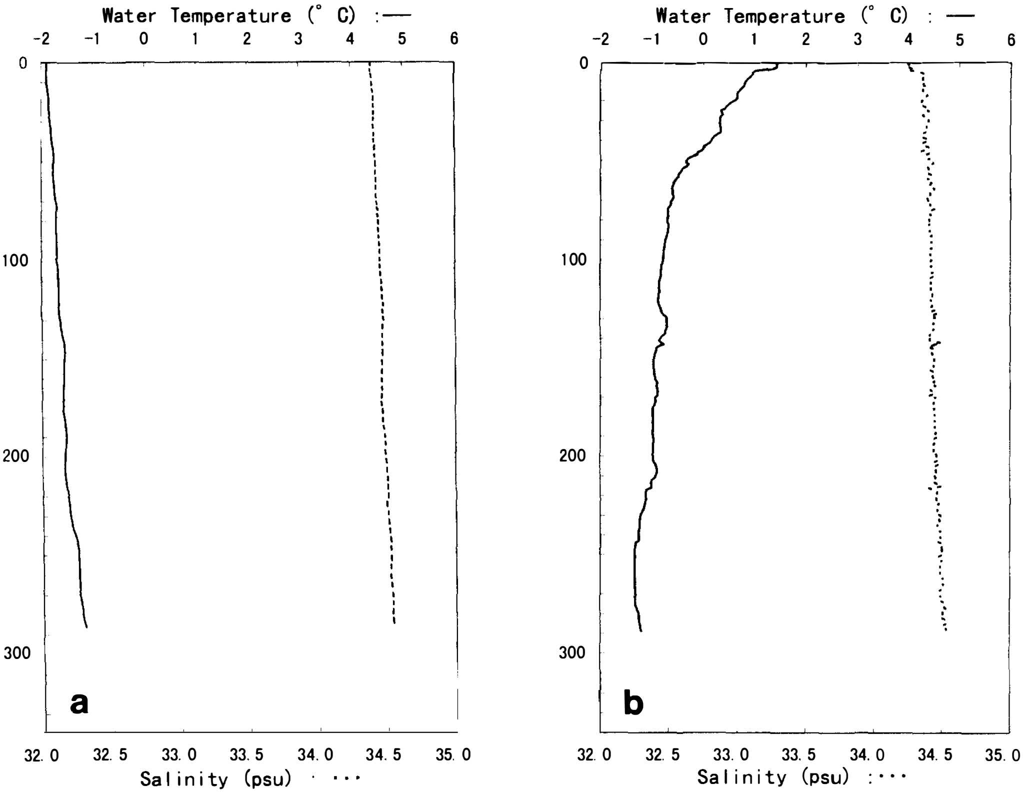


Fig. 9. Temperature and salinity profile of Kongsfjorden.
a: March (reconstructed), b: 29 May, c: 16 June, d: 8 August, e: 13 September, f: 22 September.

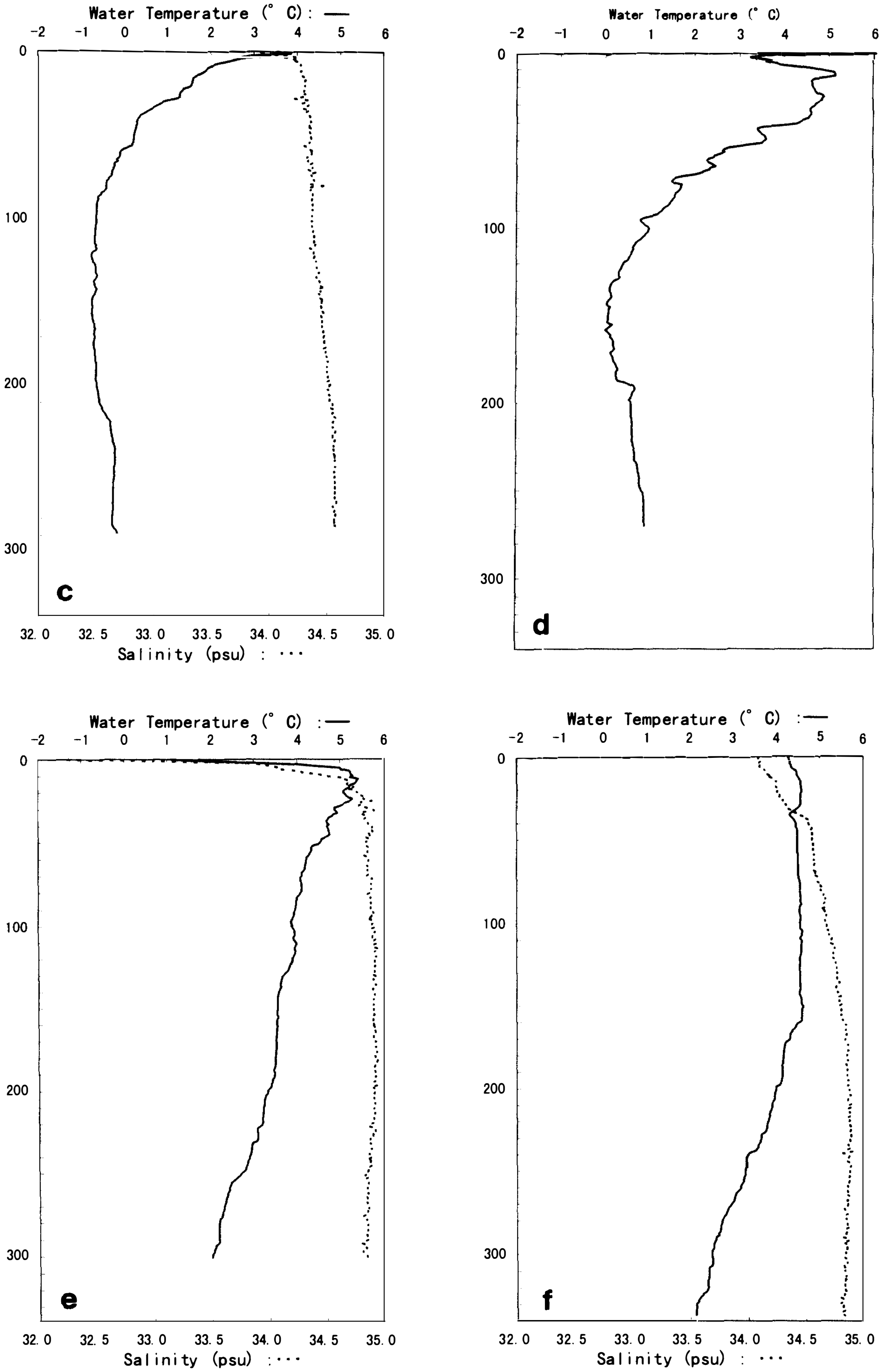


Fig. 9 (Continued).

winter. A great amount of heat is pumped out of the water into the overlying atmosphere through the ice-free surface. The fjord thus contributes to the mild local winter climate of the vicinity. The mild climate would be, however, severe enough to freeze the surface of the fjord in mid- or late winter, if it were an isolated sea water tank with limited depth. This indicates that the heat stored in the water locally during summer is insufficient to supply the atmosphere with heat throughout the winter.

There are no oceanographic observations available for the period from October to April. Nevertheless, it is desirable to have an idea of the winter state. It is reconstructed using related observations.

The surface water is cooled by the cold atmosphere. The "coldness" (=negative heat) is distributed through a layer of finite thickness, so that the decrease of the surface temperature is modified. The strong wind prevailing in winter induces mixing of the water, which accelerates the distribution of the coldness into the depth. The coldness eventually reaches the bottom and a very gentle temperature gradient occurs through the entire water depth. Great water depth and strong mixing thus keep the cooling of the surface to a minimum.

The distribution of coldness requires time. The surface may be quickly frozen before the coldness is transported downward. The outgoing wind blows out the created ice from the fjord, before it becomes stable fast ice. Since ice and relatively cold water at the surface are selectively taken out, the water column loses coldness through the process. It is also noted that the ice transported away has low salinity and leaves salt in the fjord.

Cooling by the atmosphere continues, while the fjord water resists freeze-up through the means stated above, and finally the entire water column approaches the freezing point. The water at depth has no more capacity to take coldness without freezing itself. As the surface water is not much colder than that at depth, the selective removal of surface water by the wind does not take coldness away any more.

However, the wind still removes water, and makes the fjord mass balance negative. As a lowering of water level is not observed to occur, the same amount of water must be supplied from the outside ocean, presumably at depth. If the supplied water is warm, the cooling of the water column is modified.

Figure 10 shows temperature profiles along Latitude 79°N to the west of Kongsfjorden. The observation was made in summer, but similar conditions are assumed to also exist in winter at depth. There is warm water, probably originating from Atlantic Deep Water, at depth. Providing that the sill of a fjord is deeper than 150 m, the fjord has access to the warm water. The pumping-in mechanism is hypothesized above.

The supply of deep water must be maintained throughout winter, as the outbound strong wind prevails all year round. The role as a heat supplier is, however, only remarkable when the water column is very cold. Especially when the fjord water is warm as at the beginning of winter, the deep water brings the coldness in.

An exciting race is run in the fjord in winter among the elements/mechanics explained above. The no-freeze-up party wins in most years, showing a temperature profile, like Fig. 9a, at the end of winter. The losing party, the atmosphere, is consoled with a great amount of heat: not only all the heat that the fjord water collected in summer but also the heat the deep water brings in is transferred to the atmosphere in winter.

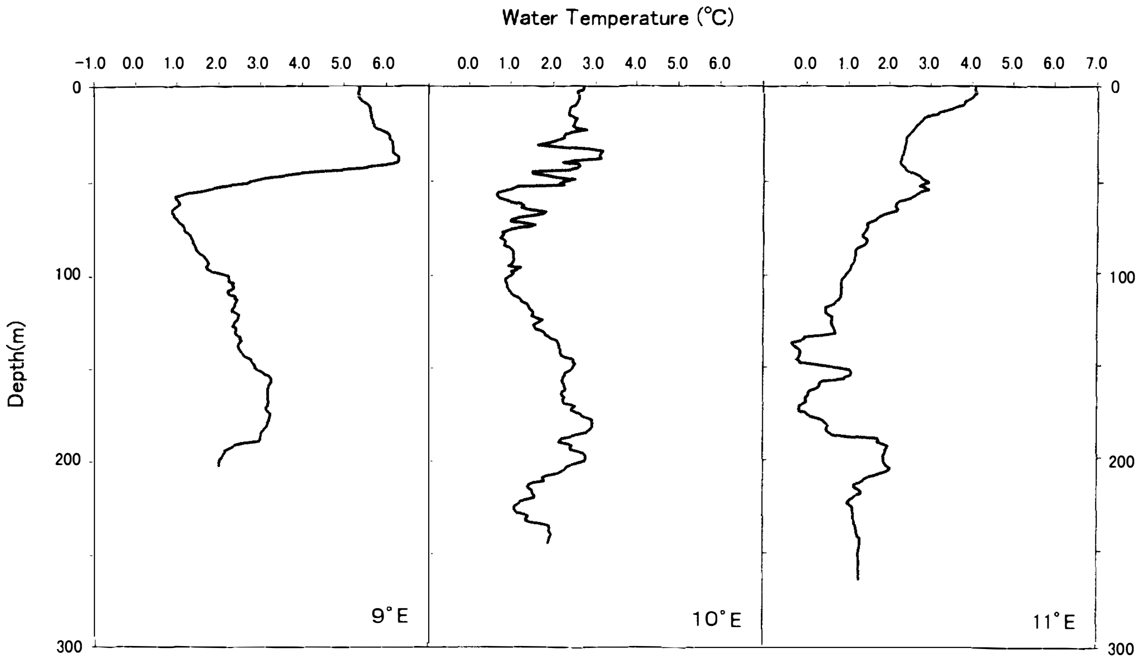


Fig. 10. Temperature profile along 79°N to the west of Kongsfjorden. See position of 79°N in Fig. 1, though stations are out of range.

4.4. Fresh water

Another remarkable characteristic of Kongsfjorden is found in the manner in which fresh water is supplied. A fjord generally obtains a greater amount of fresh water, compared with coastal water off a straight shore, due to the long coastline and larger drainage basin. Kongsfjorden is no exception: a large quantity of fresh water compared to its own water mass is given to it and thins the salt water in the fjord. Kongsfjorden is located at such a latitude that the discharge is limited the summer months. A great amount of fresh water is thus supplied concentrated in these months. The fjord hydrology is highly variable according to the season. The majority of the drainage basin is covered by glaciers, and many glaciers reach the sea. The fresh water is not obliged to come through certain points, *i.e.* river mouths, but enters almost anywhere and at any depth. The start of the fresh water supply is suspected to be in advance of the start of the river discharge. (Otherwise the September salinity cannot be higher than that of May in Fig. 7b.) Melting mechanisms of large tidal glaciers may differ from these of a snow deposit or small inland glacier. The air temperature peak is shifted from that of radiation for a month or two (Chapter 3). The maximum in water temperature is shifted from the salinity minimum for a similar time length, as discussed in subsection 4.1. The fresh water supply in Kongsfjorden is suspected to be dictated by the radiation as much as by air temperature.

When fresh water is supplied, surface water is forced out of the fjord since there is no change in water level. The water immediately below is pulled by viscosity, and the water balance of the fjord becomes negative. The fjord must obtain water from the adjacent sea for compensation. The inflow of the deep water is maintained by the wind throughout the year. It is further activated, as the fresh water income increases. Figure 11 shows the

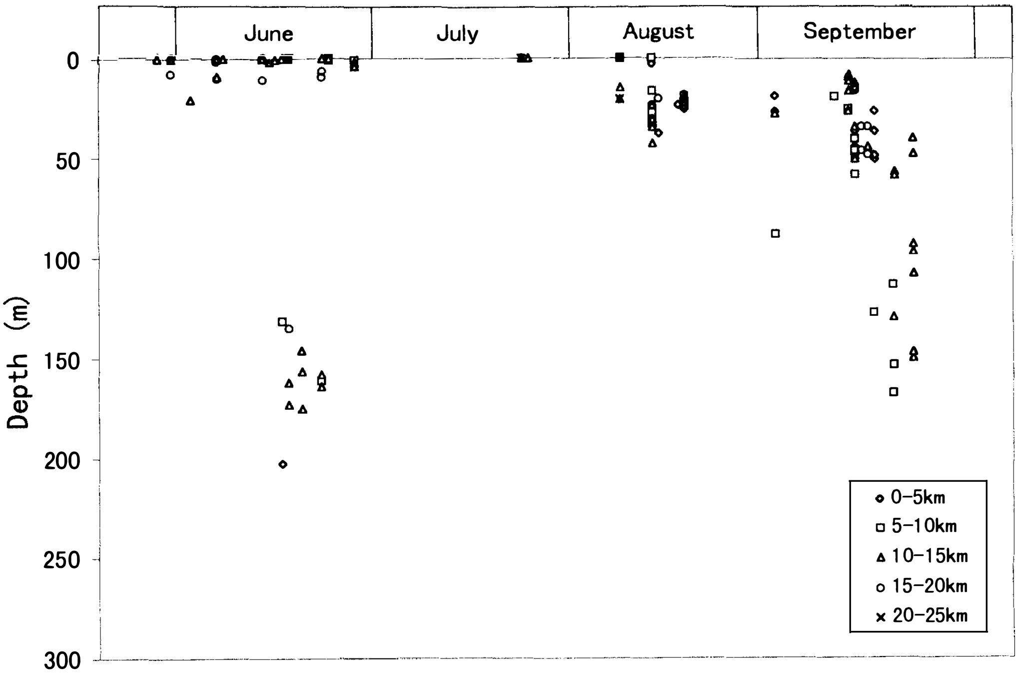


Fig. 11. Depth of the temperature maximum.
Each profile showed the maximum temperature at a certain depth, which is plotted. Different symbols show distance from the fjord entrance (see reference line in Fig. 2): 0 km at the entrance, greater distance further into the fjord.

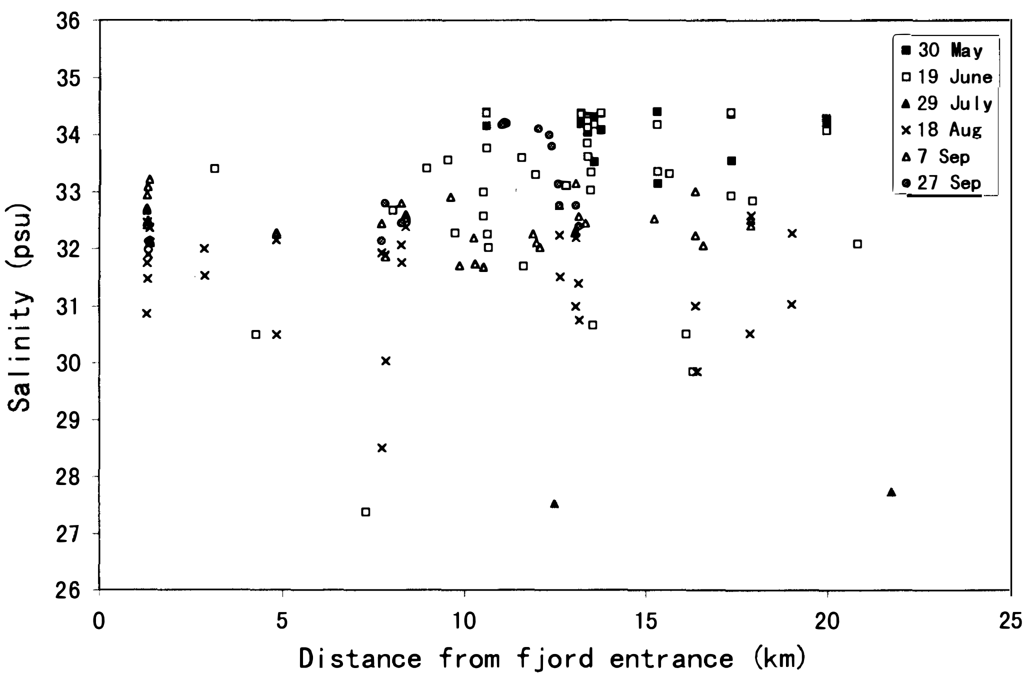


Fig. 12. Surface salinity of Kongsfjorden (see reference line for the distance in Fig. 2). Different symbols are used for different sub-periods.

depth at which the maximum temperature is observed. The first half of the figure is used here. In mid-June, the discharge approaches its maximun and the fjord water is still cool; the intruding deep water around 150 m depth shows the maximum temperature of the entire water column. Before this date, the fresh water supply must be small; only a little deep water comes in and does not form a temperature maximum at depth. After that time, the upper part of the column gains a higher temperature and the maximum at depth is invisible, although deep water continues to come in.

Some maxima are noticed in Figure 11 not at the surface nor at depth but slightly below the surface, at a depth of 5 to 10 m at the beginning of the season. This indicates a thick surface layer of melt water, observed in the inner part of the fjord, *i.e.* close to the glaciers, only. Figure 12 shows the salinity at the surface. During the period that the melting is intense the salinity is generally reduced, but the salinity value is scattered over a wide range. Both diagrams indicate that the fresh water is not easily mixed with existing fjord water.

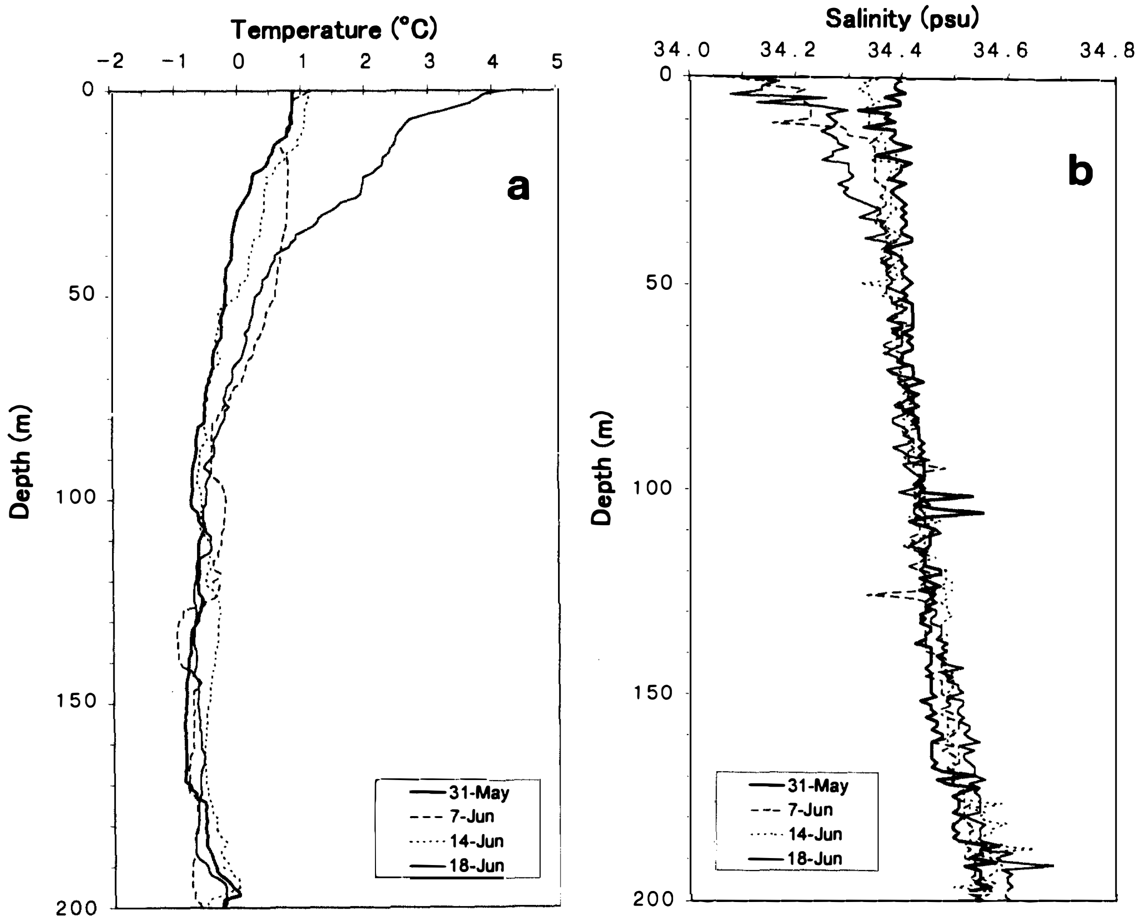


Fig. 13. Temperature and salinity of Kongsfjorden in summer. The measurement was made at a single point in the middle of the fjord.

4.5. Summer stability

One expects, in June and July, that heating by warm air and radiation are intense, and other factors could be neglected. This is certainly not true; the mean temperature of the fjord (Fig. 7) does not rise more rapidly in these months than in other months. The expectation is based in the fact that the upper part of the water column is intensely heated in that period and one usually observes the water near the surface only. A strong positive (=decreasing downward) temperature gradient makes the upper part of water extremely stable. Heat is hardly transported downward as the transport relies on conduction, and the water to this thickness is isolated. Figure 13 is used by the authors to explain how poorly mobile organisms, such as phytoplankton, are trapped in the water of the uppermost 50 m until they use up the nutrients which are trapped there as well (ITO and KUDOH, 1996). The overflowing water is warm, and brings the heat from the fjord away, increasing the loss of the heat received. The deep water with constant temperature is not much warmer than the now warmed-up fjord water and brings no heat into the fjord. All these together heat up the fjord less effectively than one imagines from the surface observation.

4.6. Along the fjord axis

A fjord is a water body with a long shape, and homogeneous characteristics from one end to the other are not expected. It is not symmetric either in the direction of the axis in many aspects: access to open ocean at one end only, more glaciers toward one end, prevailing wind in one direction, *etc*. The water may behave differently in different places within a fjord, consequently. The axis is drawn in Fig. 2 for reference. The difference in the characteristics is sought in the record, grouping the stations with distance from the fjord entrance.

No difference is detected in most of the comparisons. A conclusion has not been drawn yet, that mixing within the fjord appears to be quite thorough so that the water in different parts of the fjord shows similar characteristics. Scattering of data obtained at nearby spots in a similar period of the year can be large, in which case it would mask the along-axis difference, even if the latter exists.

Figure 14 shows one of few cases in which a difference is found in the data. The water temperature at the surface is plotted against distance from the fjord entrance. Different symbols are used for different times of year. The surface temperature on 29 July, ▲, decreases toward the inside of the fjord: $-1.5°C/10$ km. This is the period in which summer stability near the surface is at a maximum, and the fresh water supply from the glaciers at the head of the fjord is still considerable. The sea water has been warmed up, so that the fresh water from glaciers with temperatures close to 0°C is distinctively cold. In other periods one or more of the factors are not fulfilled and the temperature gradient is not visible.

Large scattering is noticed in the figure, *e.g*. on 19 June, □. A gentle gradient may exist within the range of the scattering without being detected. Furthermore the scattering is reduced as the fjord entrance is approached. It is concluded that inside the fjord the water presents widely scattered characteristics, and masks possible systematic change most of the time.

In the salinity record or in the temperature record at depth, no systematic change along the fjord axis is found (no figures presented). It is concluded that the water in different

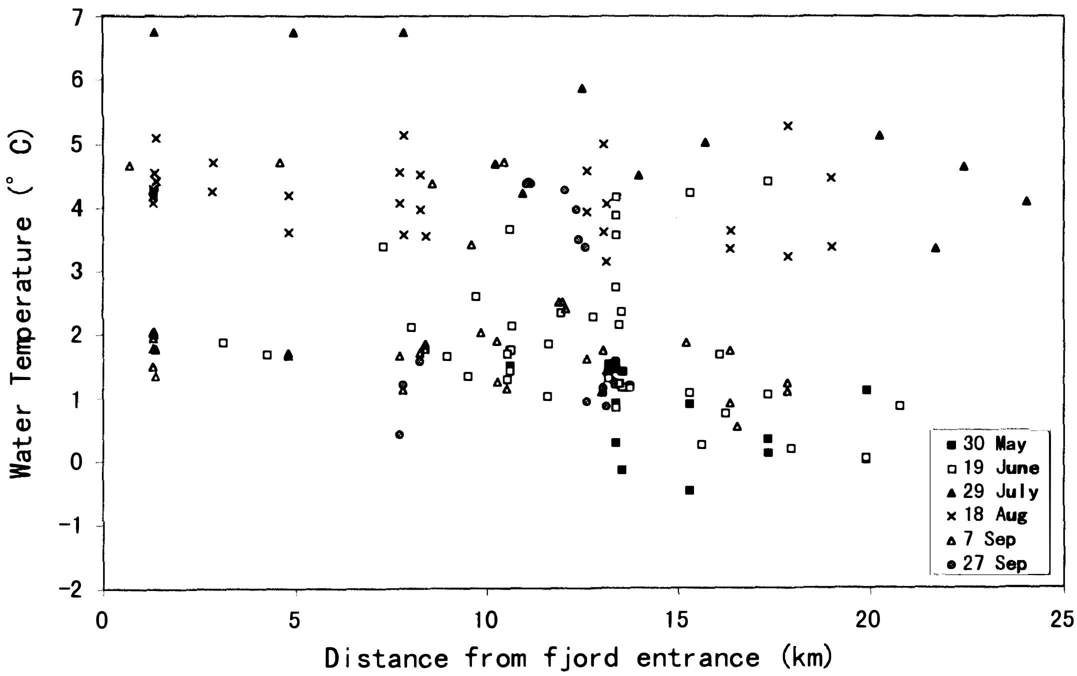


Fig. 14. Surface temperature of Kongsfjorden (see reference line for the distance in Fig. 2). Different symbols are used for different sub-periods.

parts of the fjord may have different characteristics, but the difference is small compared with its own temporal fluctuations.

4.7. Surface cooling

The water temperature at the surface reaches its maximum in mid August, one month in advance of the maximum of the entire water column, and then the water starts to be cooled. The temperature maximum, found at the surface so far, starts to move into the depths. The second half of Fig. 11, which shows the depth at which the temperature maximum is recorded, should be noted. There are no temperature peaks at depth before a certain date, and the depth increases as the season advances beyond this date.

As soon as the temperature maximum submerges, the temperature gradient near the surface turns to positive (= temperature increases with depth). The upper part of the water column loses extreme stability with its cold top. The stability is, however, still maintained by salt. The water column becomes less stable but is not unstable yet. The stability is increasingly reduced, as the cold top grows and fresh water supply is reduced. Once the mixing is triggered, it can reach great depth in this season. During the two days shown in Figs. 9e and 9f, there was a period of strong wind. The mixing in this case reached 100 m depth or more. The water column before the mixing was 'stable'.

4.8. Water movement in the fjord

Fjord water does not present a structure of layers with constant thickness neatly piled up one above another. As one of the temperature profiles of the fjord shows as an example (Fig. 15), layers grow or deteriorate horizontally and contain many hot patches and cold patches. Salt patches are not uncommon but less in number. These irregularities are evidence of water movement.

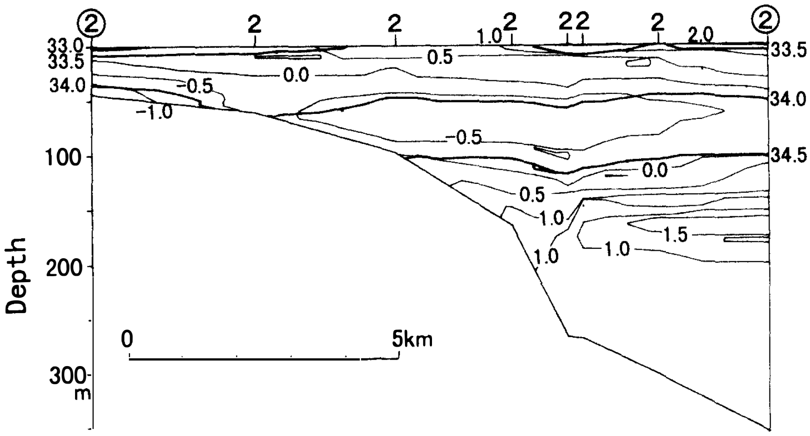


Fig. 15. Longitudinal section of temperature and salinity in Kongsfjorden. The measurement was made on 24 June 1992. "2" shows the station. "Circled 2"s are shown in Fig. 2; the left one in this figure is located deeper in the fjord and the right one toward the fjord entrance.

Three different movements are mentioned above: wind induced surface flow, fresh water overflow and deep water intrusion.

The wind has been regarded as a transport agent above, but is also a powerful mixing agent. It works in both wind directions contrary to its transport role, which is effective only when the wind goes out of the fjord. The mean wind speed is correlated with the mixing and gust wind speed with mixing depth (Fig. 4). Hence, mixing by wind is more active in winter than in summer. The mixing is constrained to the upper part of the water down to 100 m or more.

The fresh water discharge is rather gentle as a mixing agent, but contributes to the irregular structure in a somewhat different manner. The fresh water forms a wedge in order to create a gradient to flow out. The fresh water supply is basically a local phenomenon, and occasionally with the aid of a head wind, the wedge can be rather thick, *i.e.* the boundary between the surface and top layers can be considerably inclined. Succeeding horizontal shear will make an irregular structure through horizontal intrusion. The structure near the surface is complicated when and where the fresh water is supplied.

The deep water does not always come into the fjord along the bottom, but can intrude at a certain depth above the bottom. Nor does it occupy the full width of the fjord or moves straight, necessarily. The deep water comes into the fjord, generally, in a waving "bundle" at mid-depth. A profile cuts through such a "bundle" and detects a hot/cold patch. The bundle can be cut into pieces by its own movement or by other shears to become actual patches in depth. Selective intrusion of deep water is thus suspected to be the origin of some patches.

Tidal movement has not been mentioned so far. Surface current measurements made by the FS "HÅKON MOSBY" indicated no relation to the tidal conditions. The tidal current must be indeed so small in magnitude as to be masked by the water movement driven by wind. However, the magnitude in a relative sense may be different at depth, where no powerful driving force is available. The tidal current, which oscillates and makes obviously little contribution to water transport, may be an effective mixing agent at depth.

All the movements discussed above are in a horizontal plane. There must be vertical movement as well. Observation detected, however, no upwelling or downwelling.

4.9. Inter-annual change

The state of water need not remain the same from year to year. However, no systematic changes were found. This may simply mean that five years' record is insufficient to detect variability.

5. Conclusion

Kongsfjorden is a heat reservoir and is responsible for the maritime/mild climate of the vicinity to some extent. The large water depth, particular wind pattern, adjacent sea with warm water at depth and a deep sill are the elements to build up the large heat capacity of the fjord.

Kongsfjorden receives a considerable amount of fresh water. Lowering of salinity is, however, a seasonal (only in summer) and local (surface) phenomenon. The fjord water as a whole presents the characteristics of sea water in this sense rather than of brackish water.

The influence received at the water surface, such as heat, is delivered to and distributed at depth. The manner and speed of distribution is different according to the season. At a particular time of year, the distribution is slow and part of the water column is virtually isolated.

The water in the fjord has a complicated structure, indicating active movement of water. There may be significant differences in the water characteristics along the fjord axis or between different years. They are masked by the complicated structure, *i.e.* fluctuation around a single point is larger than possible systematic change.

Acknowledgments

Many scientists joined in the field investigation. Many others joined in the analysis. No individuals are named here, but the research would not have been successfully carried out without their cooperation.

Financial support was also manifold; only the major aid is mentioned here but the authors are grateful for all the support: Grant of International Scientific Research Program of the Ministry of Education, Science and Culture, Japan (No. 03041089).

References

ITO, H. and KUDOH, S. (1996): Marine ecological research of NIPR in Kongsfjorden. Proc. Scientific Seminar, Ecosystem Studies in the Ny Ålesund Area. Cambridge, UK, 28 Feb.-1 Mar. 1996.

ITO, H. and YOSHIOKA, M. (1994): Oceanographic observations around Spitsbergen using commercial boat. J. Jpn. Soc. Mar. Surv. Tech., **6**(2), 57-59.

ITO, H., OSTERHUS, S. and USHIO, S. (1994): Temperature profiles of the Greenland Sea in the summer of 1993: Report of oceanographic observation on the R/V Lance cruise. Nankyoku Shiryô

(Antarct. Rec.), **38**, 68-71.
KODAMA, Y., NAKABAYASHI, H., TAKEUCHI, Y., ITO, H. and WATANABE, O. (1995): Runoff characteristics of Bayelva Basin in Spitsbergen. International Symposium Environmental Research in the Arctic, 19-21 July 1995, Program and Abstracts. Tokyo, Natl Inst. Polar Res., 53.
NORDLUND, N. (1995): R/V Håkon Mosby Cruise Report, Svalbard 1995, a physical oceanographic cruise to the Kongsfjorden-Krossfjorden area, Van Mijen Fjorden and the adjacent shelves. Longyearbyen, Norwegian Polar Institute, 23 p.
NORWEGIAN POLAR INSTITUTE (1966 to 1990): Svalbard Topographic Maps 1 : 100000, A6, A7, B6, B7. Oslo.
NORWEGIAN POLAR INSTITUTE (1974): Chart of Svalbard No. 522, from Forlandsrevet to Femtebreen. Oslo.
SVENDSEN, H. (1996): R/V Håkon Mosby Cruise Report, Svalbard 1994, a physical oceanographic cruise to the Kongsfjorden-Krossfjorden area. Bergen, University of Bergen, 23 p.
USHIO, S., HONDA, M. and ITO, H. (1994): Temperature profiles of the Greenland Sea in the summer of 1992: Report of oceanographic observation on the R/V Lance cruise. Nankyoku Shiryô (Antarct. Rec.), **38**, 63-67.

(Received January 10, 1997; Revised manuscript accepted April 23, 1997)