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Scientific paper

The upper layer circulation in Kongsfjorden and Krossfjorden—A complex fjord system on the west coast of Spitsbergen

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Abstract: The upper layer circulation in the fjord system of Kongsfjorden and Krossfjorden is investigated based on field observations and a numerical hydrodynamical model. Rotational dynamics have a considerable influence on the circulation pattern in the fjords, but due to the complex topography of the fjord system, horizontal pressure-gradients caused by the sea-surface elevation are established rather fast. This counteracts the rotational dynamics, and the expected circulation pattern with a brackish current confirmed to the right hand side (as seen from the head of the fjord) are not always the case. The upper layer circulation seems to be dominated by the wind field, especially since the effect of the wind is quite persistent after the cessation of the wind.

Strong interaction is shown to take place between the fjord arms, and in the common fjord mouth there might develop an anticyclonic eddy. The exchange between the shelf areas and Kongsfjorden seems to be strong, and processes in the common mouth might propagate far into the fjord as internal Kelvin waves. As a combination of the rotational dynamics and the fjords location and width, the upper layers in Krossfjorden are somewhat more isolated from the shelf compared to Kongsfjorden.

1. Introduction

During the last decade, investigations related to marine biological aspects, sedimentation and hydrology has been performed in the fjords of Svalbard including Kongsfjorden (*e.g.* Weslawski *et al.*, 1994; Dowdeswell and Tranter, 1993; Hagen and Lefauconnier, 1993). However, with the exception of the hydrographic mapping of some fjords at West-Spitsbergen carried out by Weslawski *et al.* (1991, 1994), little is known about the physical oceanography in the fjords of Spitsbergen. Investigations considering the formation and transport of deep water has been carried out in Storfjorden (*e.g.* Quadfasel *et al.*, 1988; Schauer and Fahrbach, 1999). Considering other Arctic fjords, a few investigations has been performed in Greenland fjords (*e.g.* Lewis and Perkin, 1982). Since biological processes to a great extent are governed by physical processes, a thorough knowledge of the physics is decisive in order to understand the variations of the biological conditions. A better knowledge of the circulation in the Kongsfjorden-Krossfjorden system will be beneficial for the interpretation of the biological and chemical data sampled in the fjords. Polar areas are ecologically very vulnerable. The fjords in Svalbard are supplied with freshwater with a high sediment content, and an alteration of the freshwater supply related to *e.g.* climatic changes, may therefore affect the biological production. The productivity is low and an increased runoff due to an increased air temperature may therefore affect the ecology of the fjords considerably through the alteration of the salinity, stratification and transparency of the upper layer (Eilertsen *et al.*, 1989; Weslawski *et al.*, 1994; Hasle and Heimdal, 1998). It is therefore crucial to have knowledge about the upper layer circulation in the fjord system.

Rotational dynamics (Coriolis force) have been shown to have an significant impact on fjord dynamics in wide, stratified fjords (Proehl and Rattray, 1984; Cushman-Roisin *et al.*, 1994; Asplin *et al.*, 1999). Kongsfjorden-Krossfjorden is a complex and wide fjord system being stratified due to runoff from the glaciers. The fjord dynamics are therefore expected to be strongly affected by the Coriolis force, both within each fjord arm and also in relation to exchange processes between the fjord arms.

The present paper aims to give a description of the upper layer circulation in the complex fjord system of Kongsfjorden and Krossfjorden. No attempt is made here to investigate the deeper layers of the fjords. The investigation is based on numerical simulations and data sampled on two cruises in 1994 and 1995. Some of the results has been presented in two thesis (reports) by Ingvaldsen (1996) and Reitan (1996).

2. Material and methods

2.1. Field observations

The field program was carried out on two cruises in September 1994 and August 1995. Repeated hydrographic mapping of the fjord system were performed with a CTD covering a dense station net (Fig. 1). On both cruises, 2 moorings with Aanderaa current meters RCM 4 and RCM 7 (Aanderaa Instrument, 1987) were deployed, one in each fjord (Fig. 1). The moorings were deployed for a period of 5–6 days, and the measuring depths were

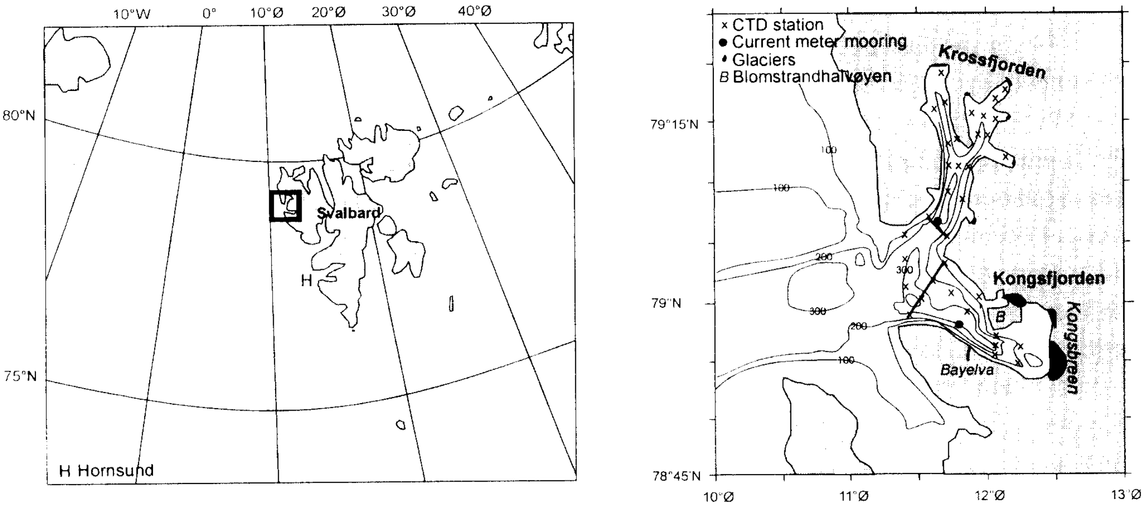


Fig. 1. *Map of the investigated area (left). Sketch of the fjord system (right) showing bottom topography, the position of the CTD-stations, the current meter moorings and the sections (black lines) used in the text.*

2, 10, and 30 m. The principal shortcoming of the RCM 4 is its inability to record currents accurately in regions affected by surface wave motions, therefore the RCM 7 was used as the upper two instruments. The residual current was obtained by removing the tidal component using an order 4 Butterworth filter with a cut-off period of 40 hours (Roberts and Roberts, 1978). To examine the brackish current Lagrangian drifters were used. The drifter is a simple construction consisting of a floating body (15 × 10 × 5 cm), attached by a 40 cm string to a 3-dimensional cross consisting of 2 quadratic, perpendicular plates. The drifters were dropped along a cross section of the fjord and recovered after 10–30 min of drifting period. To ensure minimal influence of the tides, all experiments were performed during nip or spring tide, when the tidal currents are at a minimum. Wind direction and speed was recorded by a permanent automatic meteorological station on board the ship.

2.2. *The numerical model*

The numerical model used for the simulations was the Ecom3D. Ecom3D is a three-dimensional, primitive equation, time-dependent, σ-coordinate, free surface estuarine and coastal ocean circulation model (Blumberg and Mellor, 1987; Mellor, 1996). This model, being the twin of the Princeton Ocean model, has been applied in a number of studies, including fjord and coastal dynamics relevant for fjord and coastal areas of Northern Norway (Cushman-Roisin *et al.*, 1994; Asplin, 1995; Leth, 1995; Svendsen, 1995).

2.2.1. Model design

The modelled area comprises the fjord system and the adjacent coastal area west to 25 km off the fjord mouth. The model domain terminates with sponge-like boundaries towards the north, west and south that operate under the condition called FRS (Flow Relaxation Scheme, see Martinsen and Engedal, 1987). A rectangular uniform grid with resolution 500 m in both the x-(north) and y-axis (east) were used. The vertical resolution (expressed in z-coordinates) varies from 0.2 m near the surface to 30 m near the bottom with 15 of a total of 21 σ-levels in the upper 15 m. The simulations were carried out with a flat bottom of 100 m depth, *i.e.* far deeper than the upper layer which is the subject of investigation. The initial conditions were of no water velocities, no sea-surface elevations and a constant temperature field of 2.5°C including the supplied freshwater. The salinity field was horizontally homogeneous, but with a stratification in the vertical, increasing from a salinity of 32 at the surface to 34.5 at 100 m depth. The forcing of the model included local wind stress and freshwater supply. The wind was channelled along the fjord arms (*i.e.* into or out off), and the wind speed was kept constant over the entire area. The wind speed was increased linearly from 0 to 6.5 cms^{-1} in 6 hours, then held constant for 2 days, before it was reduced linearly to 0 during 6 hours. A thorough comparison between model and data are performed in Ingvaldsen (1996) and Reitan (1996), and their results showed that the model gives qualitatively good results, although there is some quantitative discrepancies between the model results and the data.

2.2.2. Freshwater sources

The most important freshwater sources to arctic fjords are calving and ablation from glaciers, but also melting of fast ice, direct precipitation on the fjord surface, and land/riverine outflow contribute to the freshwater supply (Weslawski *et al.*, 1994). According to Lefauconnier *et al.* (1994) the freshwater supply due to calving from Kongsbreen (Fig. 1) are 0.25 $\mathrm{km}^3\mathrm{year}^{-1}$. The discharge from Bayelva, the largest river in the fjord system, is estimated to only 0.095 km^3year^{-1} (Hagen and Lefauconnier, 1993). Weslawski *et al.* (1991) estimated the total freshwater content in Kongsfjorden to be about 0.3 km^3. Compared to this the calving from Kongsbreen as estimated by Lefauconnier *et al.* (1994) contribute to more than 80% of the total freshwater supply. A total freshwater content of 0.3 km^3 gives for a melting season of three months (June–August) an average freshwater volume flux of 40 m^3s^{-1}. No estimates of the freshwater runoff in Krossfjorden are available, but calving from the glacier boarding in the left fjord arm are relatively large (Den Norske Los, 1992). It is probably the largest source in Krossfjorden, although freshwater is also supplied from all the other glaciers in the fjord. As the glaciers in Kongsfjorden are by far the largest, and are also calving most frequently on Svalbard (Lefauconnier *et al.*, 1994), it is assumed that the freshwater supply to Kongsfjorden is larger than to Krossfjorden. Anyhow, numerical simulations with different freshwater supplies have shown that the circulation in the fjord system is not sensitive for the amount of freshwater supplied, as well as the fraction supplied in the two fjords (Ingvaldsen, 1996). Melt water from the glaciers are supplied as sub-surface discharge (Liestøl, 1988). In the numerical model the freshwater is supplied at the surface, but as discussed in Ingvaldsen (1996) there are indications that the sub-surface discharges are not important for the upper layer circulation in central and outer parts of the fjords. This might be due to most of the freshwater being supplied at the surface by calving from the glaciers.

2.2.3. The cases

Three cases were simulated. Characteristics for the cases are shown below.

The freshwater driven case: Runoff from three sources: 55 m^3s^{-1} from the head of Kongsfjorden and 15 m^3s^{-1} from the head of each of the two main fjord arms in Krossfjorden. No wind.

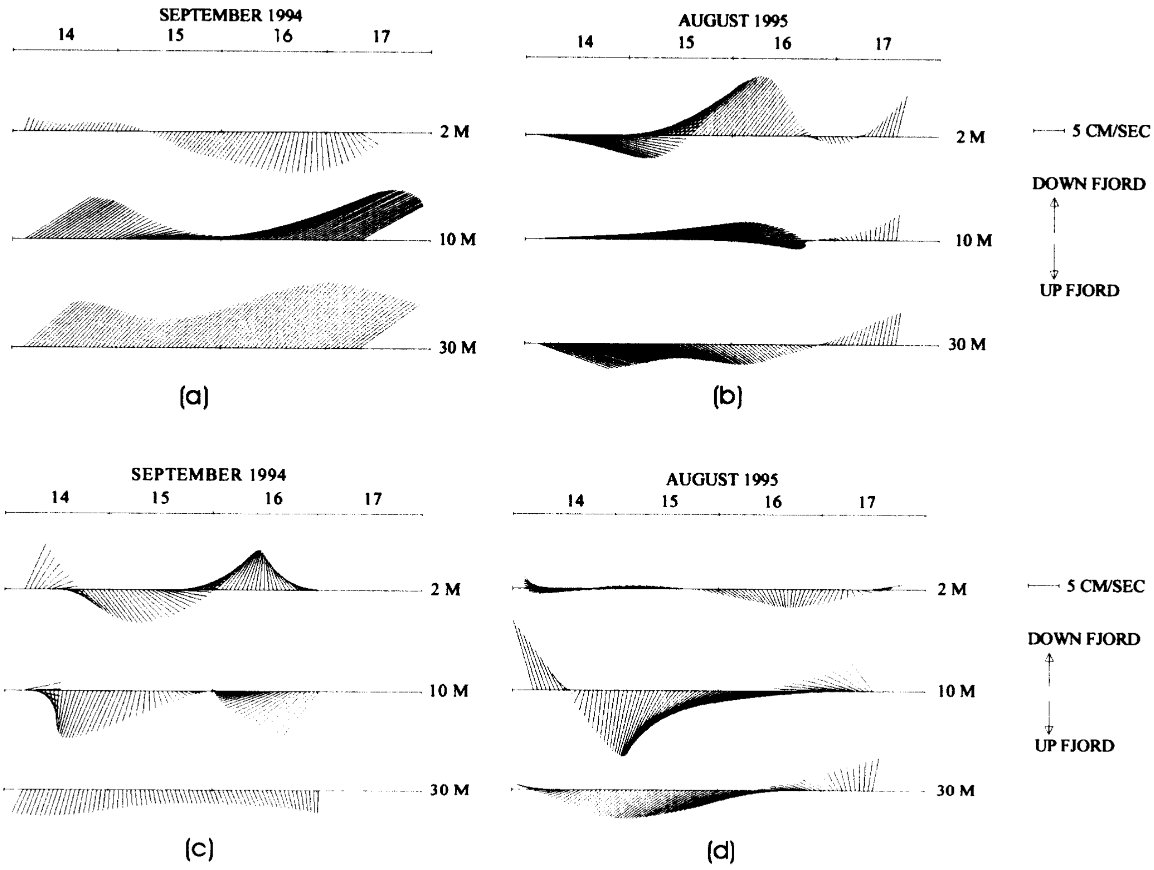
The freshwater and down-fjord wind driven case: Runoff as the first simulation. After the freshwater driven circulation is established, a down-fjord wind field of 6.5 ms^{-1} is superposed. The wind forcing is present for 2 days before tuned of.

The freshwater and up-fjord wind driven case: Same as above, but with up-fjord wind.

3. Results and discussion

In the following discussion, periods dominated by either freshwater driven circulation or combined wind-freshwater driven circulation are identified in the field observations. However, when analysing the field observations, one must keep in mind the "memory" of the fjord system, i.e. the inertia of the system. Based on an analysis of observed surface layer response to a varying wind field, Svendsen (1981) found that more than 10% of the current in 2 m depth was related to the wind action with a lag of 6 hours. Furthermore, remote forcing of the coastal waters outside the fjord system might in periods dominate the local fjord dynamics as shown by *e.g.* Svendsen (1977) and Asplin *et al.* (1999).

Rotational effects are important if the width of a fjord is larger than the internal radius of deformation (*i.e.* the ratio of the internal wave speed to the Coriolis parameter, *e.g.* Gill, 1982). A rough two-layer approach based on the observed vertical density distribution gives a Rossby radius of 3.1 km ($H_{surf}=15$ m, $H_{low}=245$ m, $\rho_{surf}=1026.3$ kgm^{-3}, $\rho_{low}=1027.8$ kgm^{-3}, $f=1.43.10^{-4}s^{-1}$). Kongsfjorden are about 8 km wide in central parts and Krossfjorden about 6 km. Thus the rotation of the earth is important for the flow. This is confirmed



(a) (b)

(c) (d)

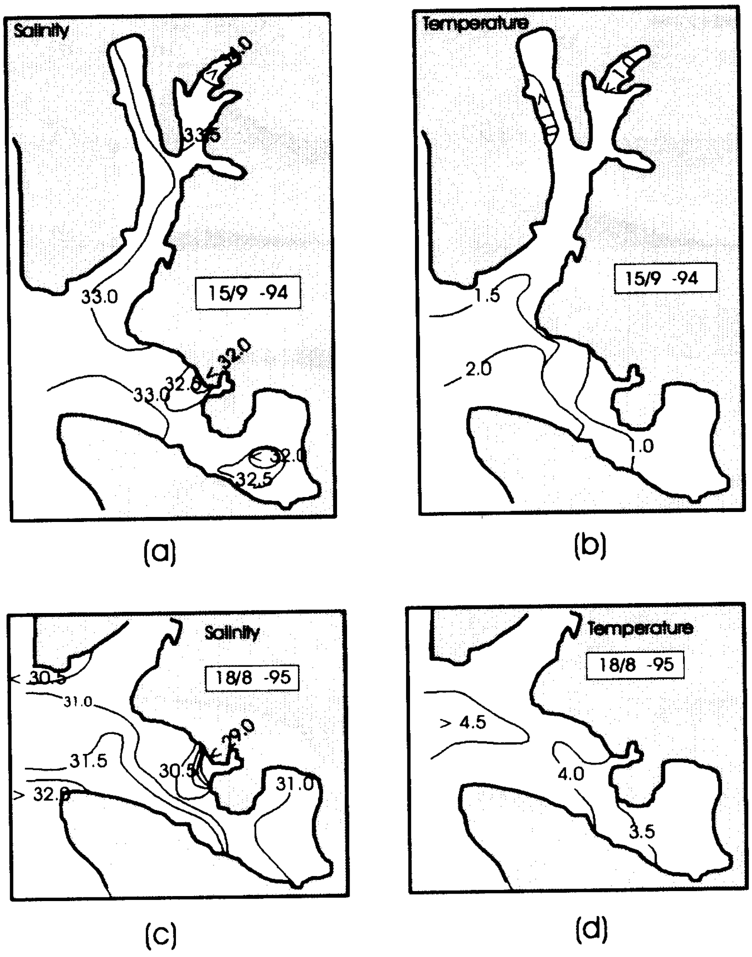
Fig. 2. Current velocities from the moorings in Kongsfjorden in (a) September 1994, (b) August 1995, and in Krossfjorden in (c) September 1994 and (d) August 1995.

by the time series from the current meter moorings which show the current to be deflected towards the right hand side (Fig. 2).

A fjord broader than the internal radius of deformation may, under the influence of a wind field, experience a wind-driven cross-fjord volume transport (Ekman transport). The piling up against the side will lead to cross-fjord horizontal density gradients. The transient behaviour due to the distortion of the interface will travel as an internal Kelvin wave with the shore on the right side (looking in the direction of propagation) having a width comparable to the internal radius of deformation. In a similar way a distortion of the density field at the coast, *e.g.* by coastal downwelling/upwelling broken by a fjord mouth, may generate internal Kelvin waves which can propagate into and inside a fjord.

3.1. The freshwater driven circulation

The mapped surface salinity and temperature distribution shown in Fig. 3 are sampled during calm conditions and are expected to mainly reflect the freshwater driven flow. The general feature of the hydrography is the appearance of fresher and colder water on the northern side of Kongsfjorden and the western side of Krossfjorden, indicating the importance of the rotational dynamics in deflecting the brackish water current to the right. The deflection is reproduced by the numerical model (Fig. 4a), which shows the effect to be

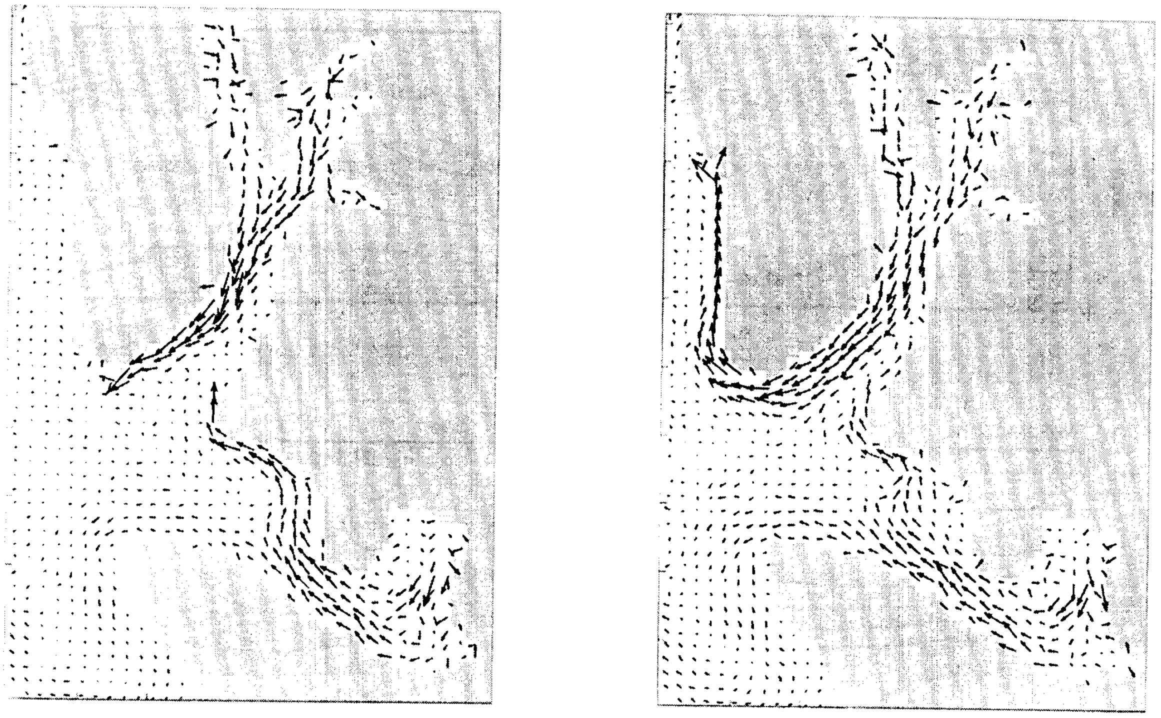


(a) (b)

(c) (d)

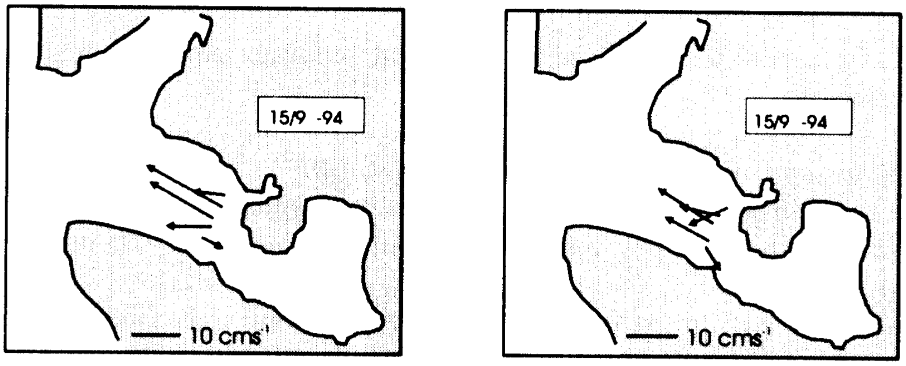
Fig. 3. Horizontal distribution of salinity and temperature in the surface layer during calm conditions.

particularly conspicuous when the flow passes around Blomstrandhalvøyen and the junction between the fjords. The flow describes a semi-circle movement, where the Coriolis acceleration acts in the direction of a centripetal acceleration. It is also a possibility that the lateral friction in the boundary layer along the fjord side may have an amplifying effect. Frictional torques act to reduce the relative vorticity within the frictional boundary layer on the landward side of a boundary flow, and a negative relative vorticity will cause a deflection towards the side of the fjord. After a while the stacking up of water in the bight boarding Blomstrandhalvøyen builds up a cross-fjord pressure gradient which displaces the flow towards the left hand side of the fjord in that area (Fig. 4b). The gradient is enhanced by discharge from the glacier in the lagoon as seen by the low saline water in the area (Fig. 3a and c). The displacement of the flow in Kongsfjorden is confirmed by the drifter experiments performed in this area during calm winds (Fig. 5), showing the highest velocities in the middle of the fjord, and low velocities with a cross-fjord component in the bay of Blomstrandhalvøyen. The inflow along the southern side of the fjord is not expected to be connected to the freshwater driven flow, and will be discussed later. The brackish water current seems to be limited to the upper 5–6 m in central and outer parts of both



(a) (b)

Fig. 4. Current velocities at surface after (a) 5 days, and (b) 8 days simulation time of the freshwater driven case.



(a) (b)

Fig. 5. Drifter experiments performed during calm conditions.

fjords (Fig. 6a and c). The velocities in the core are 5-20 cms^{-1}. The saline water in the inner parts of the fjord, as observed in the surface layer maps (Fig. 3), may have two reasons; entrainment of saline water to ascent freshwater from below the glacier, and the fjords "memory" of wind-driven upwelling happened the previous day. Generally, the temperature are higher and the salinity lower in August 1995 compared to September 1994,

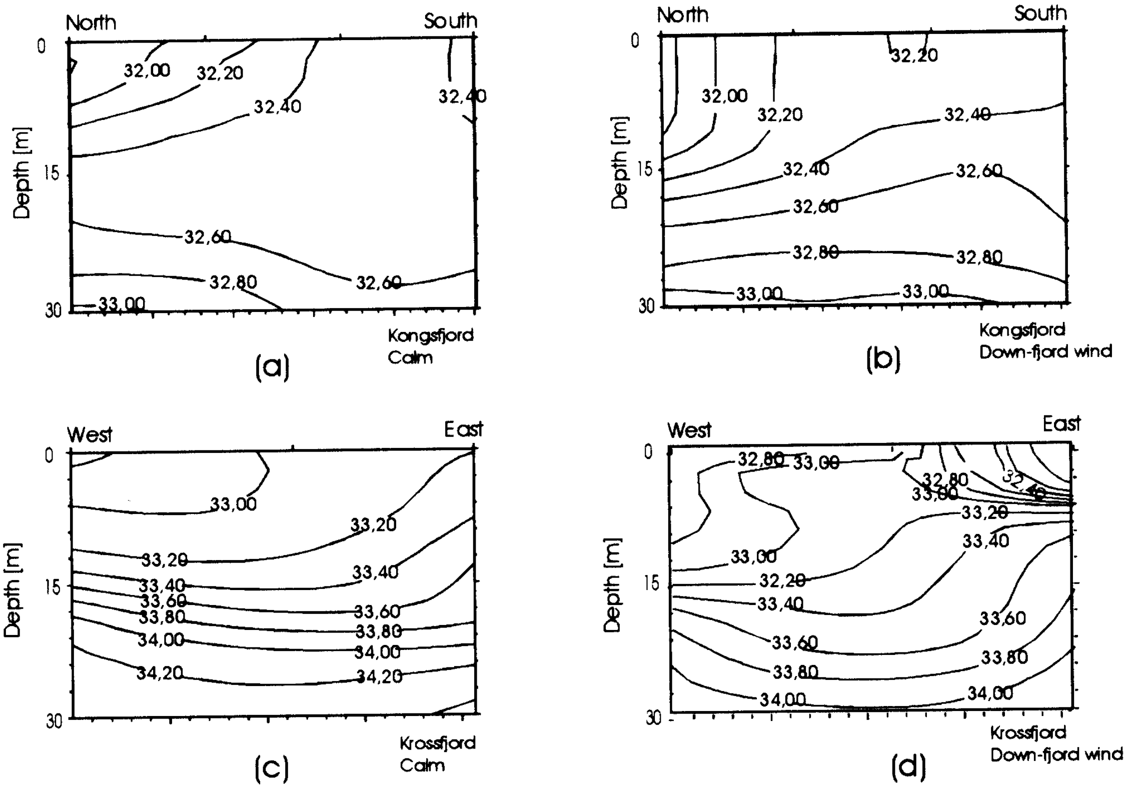


Fig. 6. *Observed distribution of salinity in cross sections (looking up-fjord) in Kongsfjorden during (a) calm conditions and (b) down-fjord wind, and in Krossfjorden during (c) calm conditions and (d) down-fjord wind.*

which is due to the fact that the air temperature and freshwater supply are higher in August than in September.

3.2. Freshwater and down-fjord wind driven circulation

These conditions were present in both fjords during the samplings shown in Fig. 7. The surface layer hydrography reflects a down-fjord flow along the northern side of Kongsfjorden. Compared to the situation with no wind, the brackish flow seems to be narrower and more confirmed to the right hand side. This is in accordance with the findings by Cushman-Roisin *et al.* (1994) who studied the effect of rotational dynamics on fjord circulation. The Ekman transport towards the side of the fjord will confirm the extent of brackish water and give an increase of the water level. Downwelling, with a resulting deeper brackish layer on the right hand side, and upwelling (and possibly an out-cropping of the interface at the surface), are expected on the left hand side (Cushman-Roisin *et al.*, 1994). This shows up nicely in the vertical section from Kongsfjorden (Fig. 6b), where the depth of the brackish layer is about 15 m, although out-cropping of the interface is not present. The numerical simulations show that the wind has a pronounced intensificating effect on the flow in both fjords (Fig. 8a). In the narrowest part of Kongsfjorden the current has a strong component towards the left hand side, while in the outer parts it is towards the right hand side. This is in very good accordance with the drifter experiments performed during

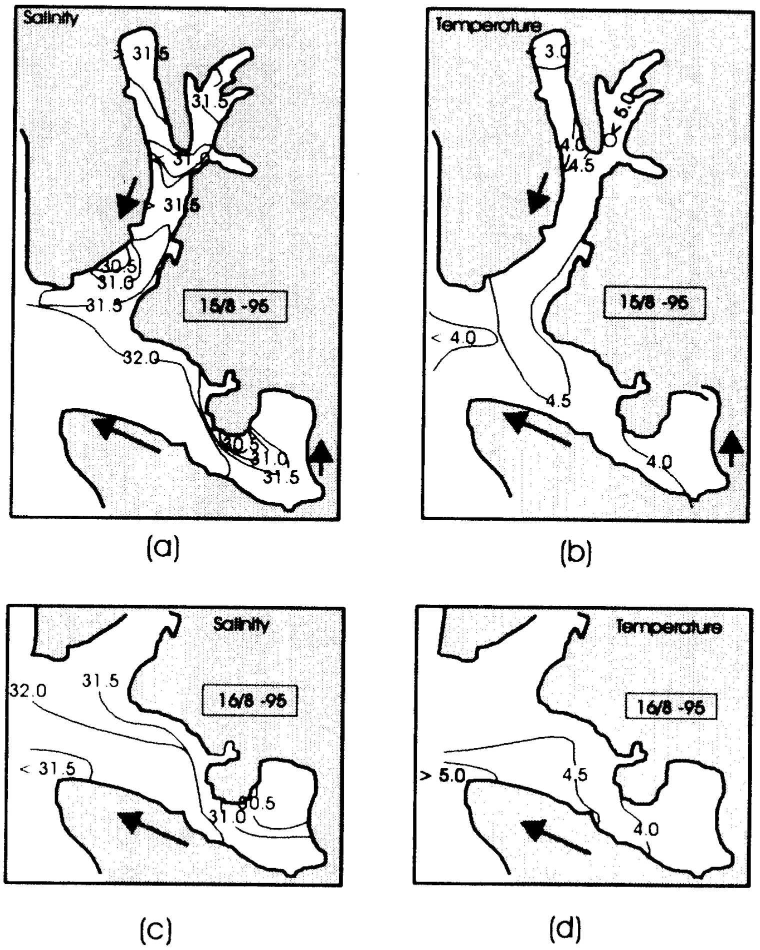
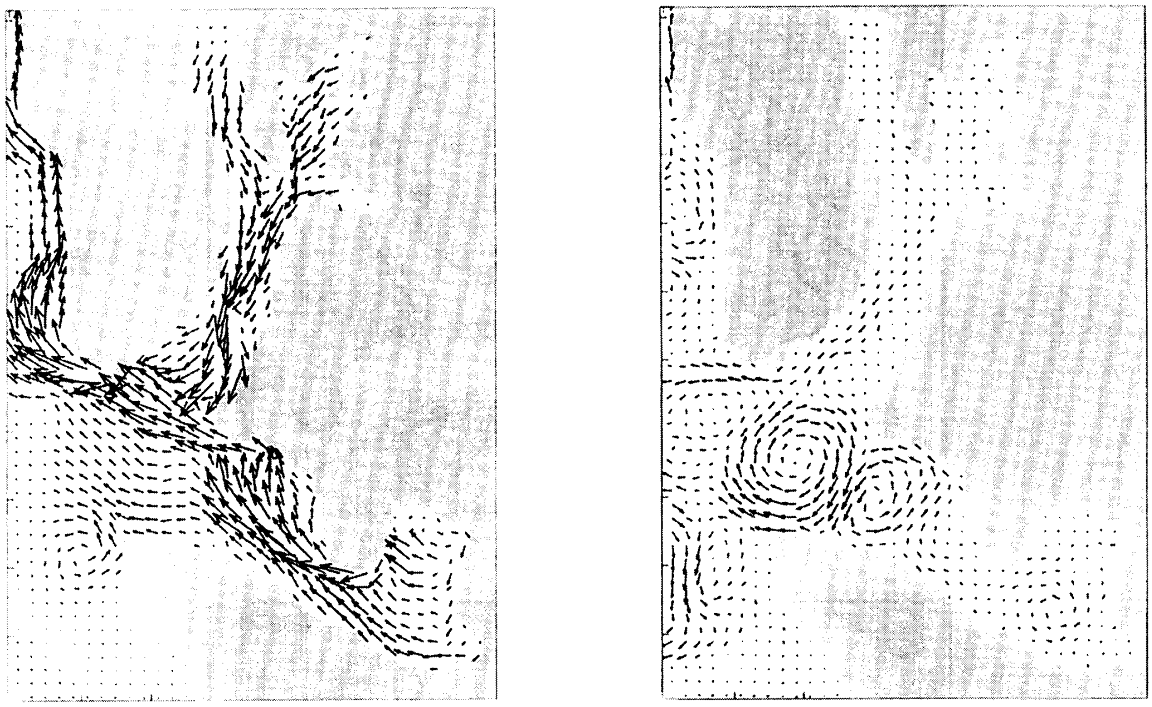


Fig. 7. Horizontal distributions of salinity and temperature in the surface layer during down-fjord wind. The heavy arrow represents the wind conditions during the mapping (1 cm = 5 ms^{-1}).

down-fjord wind (Fig. 9a–c). Due to its lesser width and more complicated topography, there is a more complicated structure in Krossfjorden (Fig. 8a), a result also evident from the surface layer maps (Fig. 7a). Because of the accumulation of surface waters from Kongsfjorden and the common fjord mouth, the waters of Krossfjorden must cross the fjord towards the left hand side in outer parts to escape the fjord (Fig. 8a). This is consistent with the drifter experiments (Fig. 9d–e).

An interesting feature of the fjord system arises after the cessation of the wind (Fig. 8b). In Krossfjorden the freshwater driven circulation is re-established after a few days (due to higher velocities when the fjord is under the influence of wind, a different scaling are used in this figure compared to Fig. 4). In Kongsfjorden the effect of the wind is more persistent, and even 5 days after the wind cessation, the freshwater driven circulation is not re-established (Fig. 8b). As the wind seldom is calm for that long, this means that the pure freshwater driven flow is a rare event in Kongsfjorden. Another interesting phenomena is the anticyclonic circulation developing in the mouth of the fjord system. The longevity of the eddy suggest a geostrophic balance, as the level of energy then are at a minima while all other motion requires more energy to be sustained. Such an anticyclonic eddy might also



(a) (b)

Fig. 8. Current velocities at surface after (a) 1 day with wind forcing and (b) 5 days after the wind has ceased in the freshwater and down-fjord wind driven case.

develop during calm conditions (Ingvaldsen, 1996).

3.3. Freshwater and up-fjord wind driven circulation

These conditions did not appear during any of the surface layer mappings, and seems to be a more seldom occurring event than down-fjord wind (Reitan, 1996). However, on August 17, 1995, the conditions in Kongsfjorden are close, with the exception for the down-fjord wind in the inner part of the fjord (Fig. 10). The effect of the wind is mainly to stack up water at the head, being reflected in the salinity distribution which indicates a cross-fjord front at the Blomstrandhalvøyen. The drifter experiment performed in the Kongsfjorden shows, as expected, an up-fjord current (Fig. 12), being strongest along the left hand side of the fjord, in accordance with the simulations (Fig. 11a). The reduction in the velocity field at the narrowest part of Kongsfjorden is due to an internal Kelvin wave generated by the wind (Reitan, 1996). These waves propagate into and around the fjord with the fjord side on the right looking in the direction of the wave propagation as described by Svendsen (1995). During the period with up-fjord wind the water level at the head of the fjords increase significantly, and when the wind cease this water flush out as a strong brackish water current. Consequently, a circulation similar to the freshwater driven flow, although much stronger, is re-established 2 days after the cessation of the wind (Fig. 11b). As in the simulation with down-fjord wind, an anticyclonic eddy is developed after the cessation of the wind.

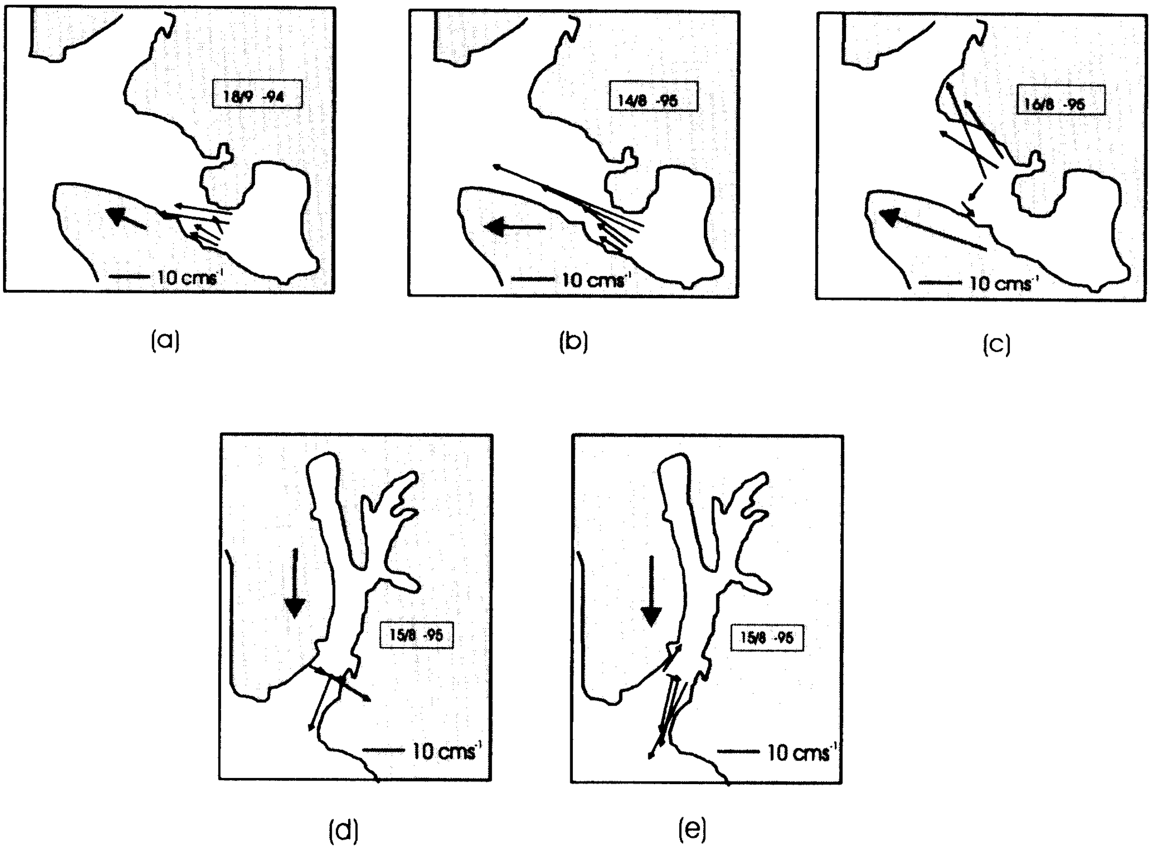


Fig. 9. *Drifter experiments performed during down-fjord wind. The heavy arrow represents the wind conditions during the mapping (1 cm = 5 ms^{-1}).*

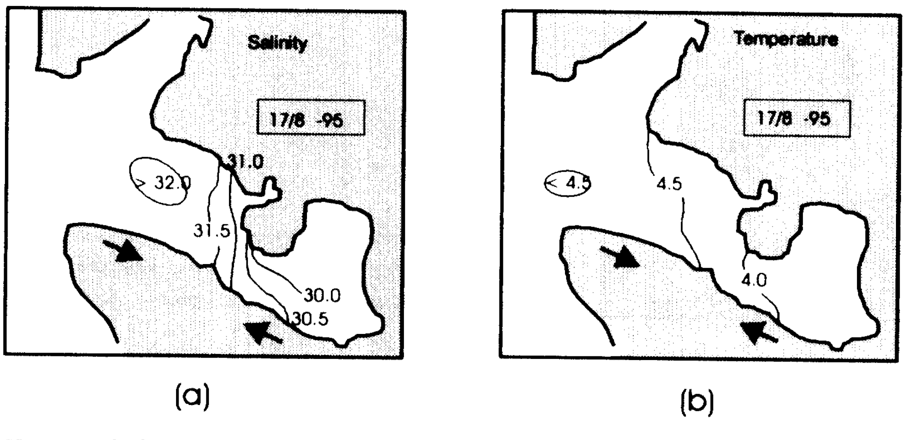


Fig. 10. *Horizontal distributions of salinity and temperature in the surface layer during up-fjord wind. The heavy arrow represents the wind conditions during the mapping (1 cm = 5 ms^{-1}).*

3.4. Exchange of water

The numerical simulations show that with calm conditions the freshwater driven flow from Kongsfjorden continue into Krossfjorden as a wedge on the eastern side (Fig. 4). The

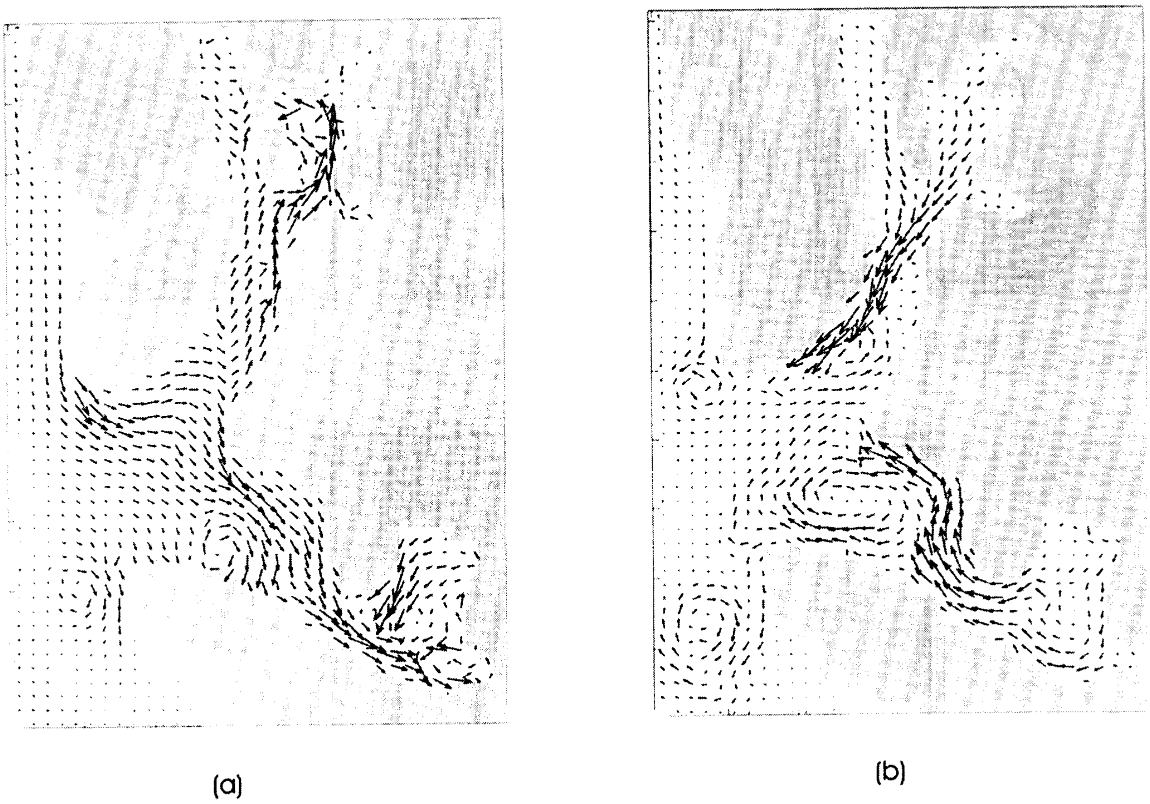


Fig. 11. *Current velocities at surface after (a) 1 day with wind forcing and (b) 2 days after the wind has ceased in the freshwater and up-fjord wind driven case.*

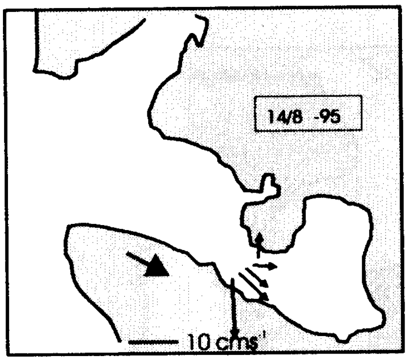


Fig. 12. *Drifter experiments performed during up-fjord wind. The heavy arrow represents the wind conditions during the mapping (1 cm = 5 ms^{-1}).*

internal Kelvin wave generated by up-fjord wind propagating around Kongsfjorden, show the same characteristics; when reaching the junction of the fjords, it continues into Krossfjorden (Reitan, 1996). As calm winds for longer periods are rare events in the fjord system, it is likely that the flow conditions in general are rapidly changing. The inflow from Kongsfjorden to Krossfjorden are therefore not expected to be a persistent feature, it is more likely to originate under certain favourable conditions. The inflow from Kongsfjorden to Krossfjorden suggests that the local conditions in Kongsfjorden will influence the outer parts of Krossfjorden. A more comprehensive field program will be necessary to give definitive support and eventually explanations to these phenomena. Kongsfjorden will also indirectly affect the conditions in Krossfjorden, as the Coriolis effect causes the outflow from Kongsfjorden to leave the fjord system at the right hand side of the common mouth (Fig. 8a), and thereby blocking the exchange of water between Krossfjorden and the shelf. On the other hand, the development of an anticyclonic eddy in the common mouth will probably enhance the exchange between Krossfjorden and the shelf and counteract the exchange between Kongsfjorden and the shelf (Fig. 8b and 11b), as the eddy will lead the surface waters from the shelf into Krossfjorden and block the outflow from Kongsfjorden. As this eddy is developed in the numerical simulations with different driving forces, it is expected to be a frequent, but not persistent feature also in nature.

Numerical simulations has revealed internal Kelvin waves generated by wind to propagate around Kongsfjorden (Reitan, 1996). More generally Svendsen (1995) showed that processes on the shelf might propagate far into wide fjords as internal Kelvin waves. Asplin *et al.* (1999) examined the non-local wind-driven fjord-coast advection in a broad fjord in western Norway. They found that the temporal current field associated with internal Kelvin waves generated at the coast may replace ~50% of the upper water layer in the fjord within 1–2 days. As Kongsfjorden is wide and open, it is likely that the shelf might influence the fjord. Some support to this can be found in the drifter experiments performed during calm conditions (Fig. 5), where both experiments show a weak inflow on the southern side of Kongsfjorden. This is probably an internal Kelvin wave propagating from the shelf into and, if not damped, around Kongsfjorden.

In a narrow fjord with strong stratification rotation can be relatively unimportant because the width of the fjord is substantially less than the internal Rossby radius. The classical assumption that the circulation in the fjord is hydraulically controlled in the mouth of the fjord may then be justified. Hydraulic-controlled circulation may also exist in parts of a fjord where there are narrow passages and/or sills, and it has been shown that the exchange in narrow, stratified fjords take place as a pressure driven, mainly two-layer circulation (Svendsen, 1977, 1981; Klinck *et al.*, 1981; Stigebrandt, 1990). If rotational dynamics were not important in this fjord system, the brackish current would not be confirmed to the right-hand side of the fjords, and it would not describe the semi-circle movement around Blomstrandhalvøyen and the junction between the fjords. However, as the width of the fjords are larger than the baroclinic Rossby radius, rotation become important. The investigation indeed showed that the rotational effect play a significant role controlling the upper layer circulation in this complex fjord system. This is consistent with results found in broad sub-arctic fjords (Svendsen, 1991; Cushman-Roisin *et al.*, 1994; Asplin, 1995; Svendsen, 1995; Leth, 1995; Asplin *et al.*, 1999). No attempt is made to describe the circulation and investigate the exchange in the deeper layers. This is an important aspect which should be done. Further investigations will procure, in addition to 3-D simulations, a comprehensive field program based on time series of current and hydrography in selected sections across the fjords and across the adjacent shelf area.

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