# Physical Qualification and Quantification of the Water Masses in the Kongsfjorden-Krossfjorden System Cross Section

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***Abstract*— The Kongsfjorden-Krossfjorden system, situated on the northwest coast of Spitsbergen, is connected to the continental shelf slope by a trough, Kongsfjordrenna, that crosses the 50km wide shelf. Kongsfjorden is the southern arm of this fjord system, and has a maximum depth of 400m. The fjord system has no typical fjord sill, but Kongsfjordrenna seems to function as a sill of around 270 meters. This means that most of the water column in Kongsfjorden is susceptible to exchange with warm and salty Atlantic Water (AW) from the West Spitsbergen Current (WSC) flowing along the shelf slope and with colder and fresher water from the shelf. The water masses found in Kongsfjorden can be viewed on as a mixture between the AW, Winter Cooled Water (WCW) and fresh water either as melt water or river runoff.**

**Winds at the west Spitsbergen coast cause Ekman drift to either pile up or remove surface water from the coast. The result is an altering of the stratification of the water outside the fjord system in the form of downwelling or upwelling. This builds up a horizontal pressure gradient between the coast and the fjord system, forcing water in or out of the fjord area. Conservation of volume demands that exchange takes place in both directions. The exchange with the adjacent shelf is shown to be related to irreversible exchange across the front between the AW along the shelf slope and the ArW on the shelf. Most of the exchanged water crosses the shelf and numerous intrusions to the fjord system take place every year. The marine ecosystem is dependent on such variations, especially on the lower trophic level, such as microbial and zooplankton production. The relative composition of zooplankton depends on water masses and sea ice concentration. Changes in the zooplankton composition will result in altered energy transfer within the pelagic food web with potential consequences for growth and survival of seabirds.**

**This work is based on CTD data from four cruises to Kongsfjorden: last week of April, first week of June, first week of July and third week of September. The volume of AW and freshwater in Kongsfjorden during each of these periods was estimated mainly to investigate the variability in the content of these water types. Estimation of fresh water content due to ice melting and river runoff and the estimation of the amount of fresh water was carried out by subtracting all measured salinities from the maximum salinity measured in the standard shelf slope station The areal network was used to estimate the volume of the mentioned water masses.**

**Variations in the amount of AW and fresh water have been observed between these periods. The comparison of TS profiles at one position in the fjord from all the four cruises, and two profiles from a station in the AW on the shelf slope show some of these characteristics.**

**Evidence that these variations are caused by AW entering the fjord by eddies escaping from the WSC due to instabilities along the front between the WSC and the shelf water has been encounter.**

***Index Terms*— Arctic oceanography, Coastal circulation, Fjord-shelf exchange.**

This work was supported in part by the Norwegian Research Council through the project MariClim, and the European Master program Joint Erasmusm Mundus Master in Water and Coastal Management.

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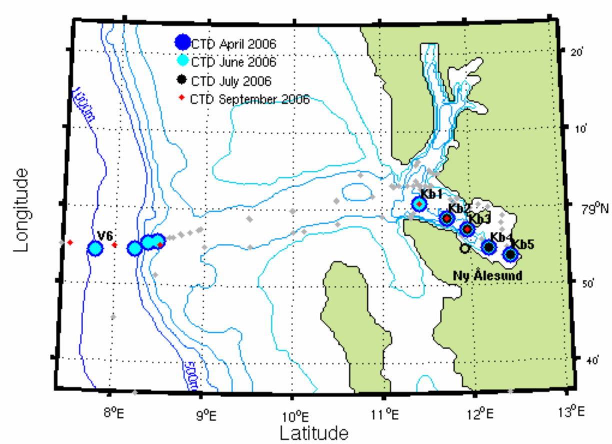



Fig. 1: Kongsfjorden-Krossfjorden system. The position of the CTD from the surveys in April, June, July and September 2006 are indicated through the coulored solid points. The bathymetry of the shelf and the shelf slope can also be appreciated.

## 1. Introduction

The Kongsfjorden-Krossfjorden system, situated on the northwest coast of Spitsbergen, is connected to the continental shelf slope by a trough, Kongsfjordrenna, that crosses the 50km wide shelf. At its inner end, the fjord has five tidewater glaciers. Kongsfjorden is the southern arm of this fjord system, and has a maximum depth of 400m. The fjord system has no typical fjord sill, but Kongsfjordrenna seems to function as a sill of around 270 meters (Fig. 1).

Outside the fjord, the water mass contained in the West Spitsbergen Current (WSC) is the Atlantic Water (AW), which is the northernmost extension of the Norwegian Atlantic Current.

Due to the fact that the WSC is constrained by geostrophy and topographic steering to flow along the shelf slope, the flux of AW water toward the fjord mouth must be a consequence of ageostrophic processes. This current flows northward following the shelf slope and is separated by a frontal region to the local Arctic-type water (ArW) on the shelf. The ageostrophic processes take place along this front as instabilities forming filaments of AW that escape the WSC on varying temporal and spatial scales [1]. AW is characteristically the warmest and most saline (T >3ºC and S >34.9) while the ArW is cooler and fresher (-1.5ºC <T <1.0 ºC and 34.30 <S <34.80 ). As a result of the instability processes on the front, part of the AW enters Kongsfjorden and mixes with ArW as it crosses the shelf. The water mass denominated Transformed Atlantic Water (TAW) is the result of this mixing.

Among the internal fjord water masses we will find the Surface Water (SW) formed from glacial melting (and in a minor quantity form snowmelt, precipitation, run-off and groundwater discharge) which is dominant during late spring and summer (28.0 <S <34.0). SW salinity range is not restricted due to the fact that it is determined by the distance to the glacier. The mechanisms for forming Intermediate Water (IW) is through entrainment and mixing at the boundary of the SW with the underlying AW and TAW (T <1.0 ºC and 34.0 <S >34.65).

During the winter and autumn Local Water (LW) and Winter Cooled Water (WCW) are formed. Both are formed in the fjord through surface cooling and convection. LW is generally of low temperature (-0.5ºC <T<1.0 ºC) (warmer than WCW) and with salinity range dependent on the water present in the fjord at the end of the summer. On the other hand, WCW is produced by sea ice formation and it is associated with convection during intense cooling, and therefore it has a higher density (T< -0.5ºC and 34.30 < S < 34.80). WCW has been reported found throughout Kongsfjorden at the end of the winter and is also detected throughout the year at the bottom of deep basins and depressions [2].

IW can also be formed, apart from the previously mention SW entrainment process into TAW, through two distinct processes; gradual warming and freshening of LW and WCW, depending on the time of the year.

This temperature and salinity domains will be represented in a T-S diagram in Fig. 2.

Kongsfjorden is strongly influenced by both Atlantic and Arctic physical factors at the same time, therefore biodiversity and animal populations are being strongly structured. Most likely Climate Change will influence the fjord water masses. With an increased intrusion of AW, the process would alter the species composition toward boreal species, whereas the glacial input and distance from the coast would tend to make the inner part of the fjord more Arctic [3]

The relative composition of zooplankton depends on water masses and sea ice concentration. Changes in the zooplankton composition will result in altered energy transfer within the pelagic food web with potential consequences for growth and survival of seabirds[1]

## 2. Exchange Processes

### 2.1 Local forcing

#### *2.1.1. Local wind response*

In previous studies (see e.g., [4]) the mean flows were considered to be driven by density differences in the water masses. There was little consideration of the wind driven circulation of a stratified estuary. By experimentally observing the isopleth assumed to represent the lower limit of the upper fresh water layer, Svendsen and Thomson [5] identified the relation between the wind and the freshwater thickness. When the flow direction is upfjord, the brackish layer thickens due to the stacking up of the freshwater. When the flow is downfjord, the brackish layer thickness along the fjord is small.

They concluded that the most important forcing for the circulation is the wind stress. The freshwater runoff does not derive an important circulation itself; however the freshwater by causing the strong stratification is important in trapping the wind-stress response to near-surface layers [5]

#### *2.1.2 Rotational effect*

When a fjord width exceeds the baroclinic Rossby radius of deformation, Coriolis effect inside the fjord is significant. The Rossby radius is the relation between the phase speed of internal Kelvin waves, that depends on the stratification, with the Coriolis parameter. In a summer situation in Kongsfjorden, this radius, in a rough estimation, is about 4 km, which is half the average width of the fjord [6].

Coriolis effect causes the interface between the upper fresh water and the saltwater below, to slope downward toward the right and the sea surface downward toward the left in the northern hemisphere. The tidal response is a Kelvin wave propagating with land to the right around the fjord [1].

#### *2.1.3. Topographic Steering*

A supplementary effect to rotation is the principle of conservation of potential vorticity, which forces the current to follow isobaths; the so called topographic steering. This is likely to be an important factor for guiding AW into Kongsfjorden through the Kongsfjorden trough [7].

### 2.2 Coastal forcing

#### *2.2.1 Up and Downwelling*

Stratification of coastal water near the fjords was thought to be controlled by seasonal runoff variations or by variations in the water properties of the offshore currents. However, later on coastal studies showed that the major changes in coastal stratification are wind induced (e.g., [8]). Offshore winds blowing at the west of Spitsbergen cause Ekman drift that either pile up or remove surface water in the vicinity of the coast. As a result, up-welling or down-welling occur outside the fjord. Down-welling is the downward vertical movement of the water which is being piled up towards the coast by the Ekman-drift, and upwelling is the upward directed vertical movement of deeper water masses replacing the surface water which has been removed from the coast by Ekman-drift. The resulting change in density of the coastal water generates a horizontal pressure gradient between the coast and the fjord system forcing the water in or out the fjord area [9].

Svendsen and Thomson [5] noticed that onshore wind and wind from the south causes downwelling outside the fjord, which induces considerable interaction between circulation patterns in fjords and on the adjacent continental shelves. The response of the fjord was that heavier water in the fjord to run out at intermediate depth, down to sill depth, while the surface water in the fjord is replaced by lighter water from outside the fjord. If the wind field blows in the reverse direction, the process would be upwelling. The water inside is then lighter so the exchange would also reverse.

### *2.2.2. Geostrophic Control*

An alternative mechanism of the classical hydraulic control by sills or constrictions was given by Kinck, O´Brien and Svendsen [10]. The wind forced coastal circulation in form of its geostrophic alongshore current, strongly affect the circulation by controlling the free surface and the pycnocline displacement, a dynamic response in the coastal current to the Ekman-drift forced upwelling and down-welling explained in the previous subsection. In addition to coastal influences, processes within the fjord can produce circulations. Variations in the vertical turbulent mass transport within a fjord cause pressure gradients which induce currents. However, this diffusively-driven circulation is usually quite weak and can be dominated by the coastal stronger circulation due to upwelling and downwelling.
There are differences in the response to alongshore and across-shore wind stress. When the fjord is forced by up and down-fjord winds, i.e. across-shore, there is an induced tilt in the free surface and the pycnocline but the total volume of water in the fjord remains constant. On the other hand, if the wind is strongly alongshore, a net transport into or out the fjord produces flooding or emptying of the fjord as a whole. Observations from the model results suggest that the free-surface is a reflection of the pycnocline slope, i.e. it is baroclinic, not barotropic. The velocity shear is large in some cases which can have a strong effect on vertical diffusion.
As conclusions, Klink, O´Brien and Svendsen [10] stated that the alongshore geostrophic coastal current strongly control the fjord circulation. This current produces the effect of elevating or depressing the free surface and the pycnocline and thereby controlling the displacement of these surfaces at the fjord mouth. The resulting pressure gradients within the fjord, together with the consideration of the topographic conditions at the mouth (non linear considerations) drive the circulation in the fjord.

## 3. RESULTS

This work is based on CTD data from five surveys to Kongsfjorden: last week of April, second week of May, first week of June, first week of July and third week of September.
TS profiles from the different cruises were graphed in a TS diagram in order to identify the distribution of the water masses.

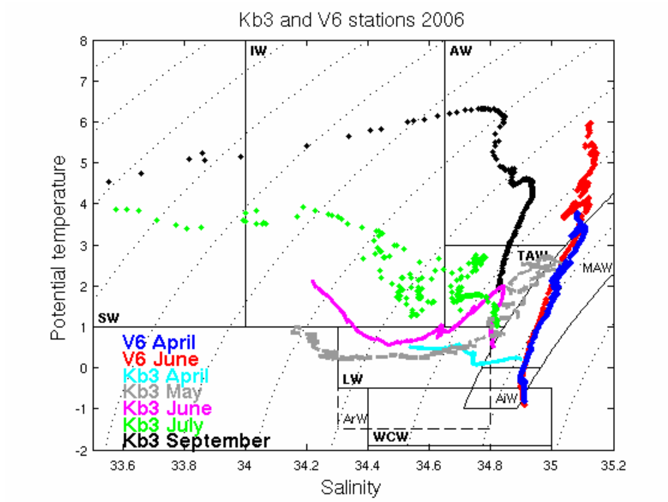


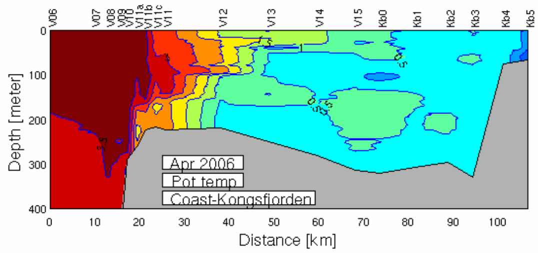

Figure 2: TS diagram with profiles representing data from April to September 2006. V6 is the sampling station in the shelf slope. Kb3 is the sampling station in Kongsfjorden. The positions are shown in Figure 1.

In April, Figure 2, we can clearly identify and separate the TS-profile taken inside Kongsfjorden (Kb3) from the profile taken on the shelf slope (V6). It is also represented in April section plot (Fig. 3). The front on the shelf edge between AW and ArW is very distinct. Moreover, inside the fjord (Kb1-Kb5sampling stations, Fig. 1) the water column is homogeneous.
The May data has not been calibrated yet, so they will not be analysed any further in this work. But they are interesting because the presence of an AW intrusion is evident in this period. It can be seen in the profile shown in Fig. 2, as the mixture of AW and LW, classified as TAW.
In the June sampling profiles (Fig. 2), for the shelf slope we found a displacement of the distribution toward the AW. LW is still very much present in the fjord and TAW is being produced as mixing between inflowing AW and LW. IW is being formed in the Surface. This is also seen in the section plot Fig.4. In July the TS profile (Fig. 2) shows that LW on no longer present in Kongsfjorden. The distribution of IW is wider than before. Fresh surface water SW show up in the diagram, and can be also clearly seen in the section plot (Fig. 5) During July no water samples were taken from the shelf slope.
The water masses in September were exceptionally warm. In Kongsfjorden AW and TAW is very dominant, and SW and IW give evidence of strong stratification. The deepest part of the Kongsfjorden profiles is placed along a mixing line between AW and LW. The section plot, Fig.6, shows the thick layer of SW and IW, and the warm and high salinity AW and TAW below.
Depth ranges for each type of water mass has been identified from depth profiles of temperature and salinity from the stations Kb1-Kb4. This is summarized in Table 1 with some comments to the formation process.

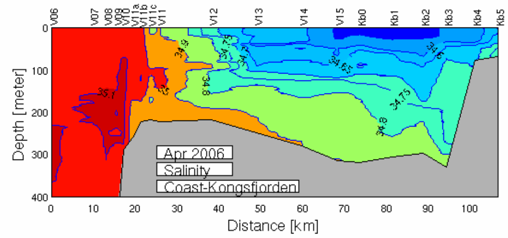
TABLE I
WATER MASSES LOCATION

| | April | June | July | September |
|---|---|---|---|---|
| **Internal** | | | | |
| Winter-cooled water **WCW** (T<-0.5; 34.40< S<35.00) | | | | |
| Local water **LW** (-0.5<T<1.0; 34.30<S <34.85) | 0-350 m Well mixed water column. | 30-110 m and >270 m Remnants from spring | | |
| Surface water **SW** (T >1.0; S<34.00) | | | 0-20 m From Calving and Melting Glaciers. | 0-25 m. Very low Salinity. |
| **Mixed** | | | | |
| Transformed Atlantic water **TAW** (1.0 <T< 3.0; S>34.65) | | Strong mixing from LW and AW 110-270 m | >110 m Because intrusion of AW is still happening at high depths | > 200 m. Remaining from previous month |
| Intermediate water **IW** (T>1.0; 34.00< S <34.65) | | 0-30 m (Surface heating has warmed LW above 1ºC) | Throughout the whole water column 20-110 m | 25-50 m |
| **External** | | | | |
| Atlantic Water **AW** (T > 3ºC; S >34.65) | | | | 50-220 m The Temperature is very high. |

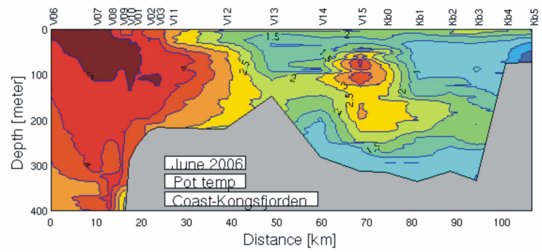
Table 1: Configured through the identification of the different water masses in the salinity and potential temperature vertical profiles in the different mouths of 2006. The samples were taken from the stations Kb1,Kb2, Kb3 and Kb4 inside Kongsfjorden.



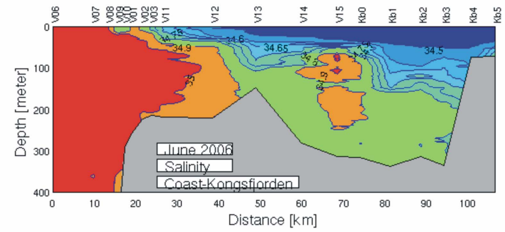

3 a)



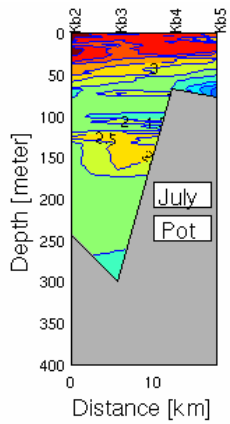

3 b)



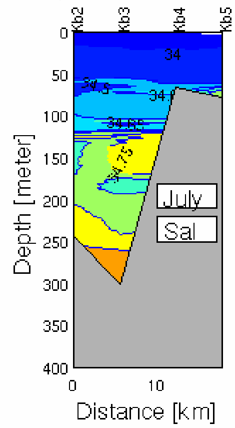

4 a)



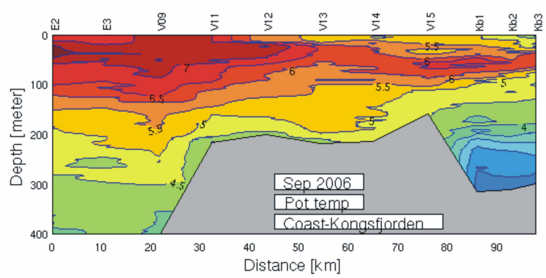

4 b)



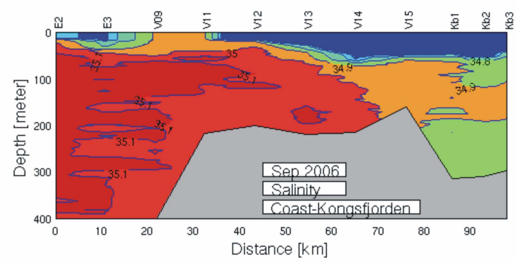

5.a)




5 b)




6 a)




6 b)

Figures 3,4,5 and 6: Longitudinal section plots of Kongsfjorden (from Kb5 up to Kb1) up to the shelf slope. 3) April 4) June, 5) July and 6)September Each month is represented by its salinity section plot (a)) and by it Potential Temperature (b)), in order to better identify the water masses.

## 4. Discussion

In winter, as can be seen in April (Fig. 3), the water column in Kongsfjorden is very homogeneous.

In the specific TS profiles for April (Fig. 2), the shelf slope profile is concentrated mainly in the deep shelf water area classification, i.e mainly MAW, AiW and some very close to in the AW. This is really an example of how the water mass classification is made for the summer situation, and does not quite fit a winter situation. During winter the surface AW is 4-5°C cooler than in summer. On the contrary, the Kongsfjorden water masses are mostly located in the area of LW, and the densest water has characteristics close to the deep Atlantic water (MAW). Only the innermost station has WCW produced from ice freezing, which can be seen in the section plot Fig.3. Cottier et.al. [7] explains how LW this spring was produced by cooling of AW both on the shelf and in the fjord, a process producing exceptionally dense LW. In February the fjord was filled with AW because of an exceptionally long lasting upwelling event on the coast. The warm AW also prevented ice freezing and then also the production of WCW.

LW is the water mass locally formed in the fjord, andidentified in the whole water column in April. However, in posterior months AW from the shelf is again introduced into the fjord through wind originated processes on the coast, mainly filaments of AW escaping the WSC as a result of upwelling events, as explained in section 2.

The AW entering the fjord mixes with LW forming TAW. Inside the fjord it is also guided by topographic steering and the Coriolis rotational effect. But this is not possible to see in our section across the shelf. One would need a section across the fjord to be able to show this. The June water column is characterized by the TAW in the central part of the column and the upper 30m is contained of IW produced by gradual warming of LW, previously the dominant water mass in April.

In July the effect of the calving and melting of glaciers is being obvious in the upper 20 m of fresh water. The deepest LW produced during spring has all been mixed with AW, and formed TAW, which is located in the deepest part (>110 m) Intermediate water (IW) is located in the middle. The whole water column is clearly stratified.

September sampling period coincided after strong period of upwelling that introduced AW into the fjord (50-220m). In the deepest part of the column TAW was found. Above this AW, IW was being located, separating the SW to the upper 25 m.

Summarized our data indicates that the characteristics of the water masses inside Kongsfjorden are very much dependent on processes on the coast, in the frontal zone between AW in the WSC and the shelf water (ArW). These processes are producing filaments of AW entering Kongsfjorden, and this seem to happen at any time of the year. The lack of formation of WCW this winter is then not only an effect of warm air temperatures, but also on intrusion of AW. Moreover, the water mass definitions do not quite fit our data. This may indicate that we are indeed seeing a change in the environmental conditions in the region. And there is a need for a better understanding of the processes leading to intrusion of AW onto the shelf and into the fjords in Spitsbergen.

## ACKNOWLEDGMENT

Thanks to Edmond Hansen, Norwegian Polar Institute, for providing the September CTD data, which was part from a MariClim project campaigns. Thanks also to the participants in the April and June cruises, and to Ragnhild Lundmark Daae for helping in the collect the July-data.

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