



A contribution to the knowledge of Arctic zooplankton diurnal variability (Kongsfjorden, Svalbard)

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Abstract: Zooplankton was investigated at fixed site in 24 hours in Kongsfjorden, a glacial fjord situated on the west coast of Spitsbergen (Svalbard) (79°N, 12°E), in order to unveil the level of diurnal variability in community composition and abundance. Parallel to zooplankton study water temperature and salinity were measured while information on local tides and winds was obtained from external sources. Observed changes did not exceed the range of variability regarded intrinsic, resulting from the nature of plankton. Because of this low variability we are of the opinion that the data presented can be regarded a valid measure of the natural heterogeneity of zooplankton communities in hydrologically dynamic Arctic coastal waters in summer. The observed changes in zooplankton were primarily induced by the complex dynamics of the fjord's water masses. In spite of importance of tidal forcing, the variability in zooplankton did not demonstrate similar temporal fluctuations due to modification of the water movement by other irregular forces (local wind). Also, we have not found any indication of diel vertical migration in coastal water in the Arctic under the condition of midnight sun.

Key words: Arctic, Kongsfjorden, zooplankton, fjords, diurnal variability.

Introduction

Former studies of zooplankton communities in Svalbard waters were primarily concentrated on spatial or long-term changes (Koszteyn and Kwaśniewski 1989; Kwaśniewski 1990; Hop *et al.* 2002; Basedow *et al.* 2004). Results of these studies indicated relatively high variability in the zooplankton composition and abundance on various spatial and temporal scales. It was suggested that such changes were caused mainly by variable advection of Atlantic and/or Arctic (shelf) waters into the fjords, and by variable glacial and river runoff (Willis *et al.* 2006). Generally, no clear signs of vertical migration were observed in the previous studies

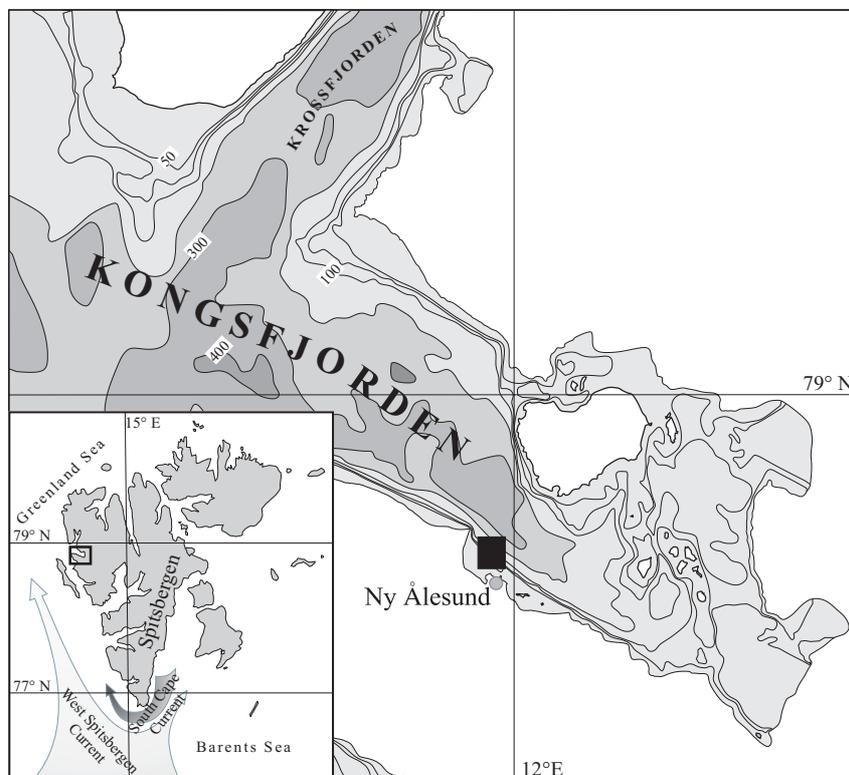


Fig. 1. The map of Kongsfjorden and location of the sampling site (black square). Location of Kongsfjorden in Svalbard Archipelago and the scheme of the main sea currents in the insert.

from the Svalbard area (Digby, 1961) and it is generally accepted that such migrations are very limited or do not occur under midnight-sun conditions due to the lack of day-night light cycle (Raymont 1983; Lalli and Parsons 1997; Błachowiak-Samołyk *et al.* 2006).

Kongsfjorden is one of the largest fjords of the Svalbard Archipelago. It is a part of the Kongsfjorden-Krossfjorden two-fjord system located on the northwest coast of Spitsbergen Island (Svendsen *et al.* 2002; Fig. 1). Kongsfjorden has two recognisable parts: outer basin, opened directly to the sea and inner basin, separated by an underwater sill, where glaciers calve and the main fresh water runoff takes place. Advection of the Atlantic water from the West Spitsbergen Current (WSC), flowing along the slope west off the fjord, or Arctic (shelf) water from the coastal current, flowing parallel over the shelf, as well as winds, tides, and fresh-water discharge, are driving forces governing the water stratification and movement in the fjord (Svendsen *et al.* 2002). The role of advection is probably crucial for the abiotic structure of the fjord because of the lack of a sill at the fjords' entrance. This process seems to be of importance also for zooplankton populations

(Hop *et al.* 2002; Willis *et al.* 2006), and, as a consequence, for the entire ecosystem, especially for plankton feeders like fish and birds.

The aim of this study was to fill the gap in our knowledge of short-term variability in the zooplankton community in a fjord that is strongly influenced by shelf-fjord water mass exchange.

Material and methods

This study is based on a set of zooplankton samples collected in Kongsfjorden during the period from 16:00 CET (Central European Time) July 23 to 16:00 CET July 24, 1997 in four hour intervals. The sampling was carried out from RV *Oceania* anchored close to the south coast of the fjord at 78°56'00'' N, 11°56'50'' E (Fig. 1). The depth at the sampling site was a compromise between the plan to sample at fixed point and the capability of the ship to lay at anchor. Tides and winds caused the ship movement when at anchor, therefore, bottom depth varied during sampling from 95 to 115 m. Samples were collected vertically by mean of MPS (Multi Plankton Sampler 92A, Hydro-Bios, Kiel; opening area 0.25 m², net mesh size 0.180 mm), from three discrete layers corresponding to the hydrological structure of the water column (Fig. 2). The structure of the water column was established based on temperature and salinity measurements done with a Sea Bird CTD probe every four hours, prior to zooplankton sampling. The water layers distinguished were named after the predominating water masses, following the classification by Svendsen *et al.* (2002) and Cottier *et al.* (2005). The deep layer included waters of the highest salinity and the lowest temperature, resembling characteristics of the Local Water (LWL). The middle layer, comprising the main temperature and salinity transition, was preoccupied by the Intermediate Water (IWL). The surface layer (SWL) had the lowest salinity, typical of the Surface Water. Wind speed and direction were obtained from the Norwegian Polar Institute observatory in Ny Ålesund and information on tides is from the Tide Tables (1997).

Zooplankton samples were fixed with a 4% formaldehyde solution in seawater buffered with borax. Samples were counted and sorted in the laboratory of the Institute of Oceanology, Polish Academy of Sciences following standard procedures (Omori and Ikeda 1984; Harris *et al.* 2000). Zooplankters >1cm were identified and counted in the entire sample. Zooplankters <1cm were identified and counted in 2ml subsamples. *Calanus* species were distinguished on the basis of prosome length (Kwaśniewski *et al.* 2003).

To estimate the variability in zooplankton the coefficient of variation (CV%) (Sokal and Rohlf 1980) was used. In order to determine if there was a relationship between zooplankton and hydrological parameters, the stepwise multiple regression analysis (*Statistica* v. 6) for the density of particular zooplankton components and the average temperature and salinity in the water layer was employed. The null

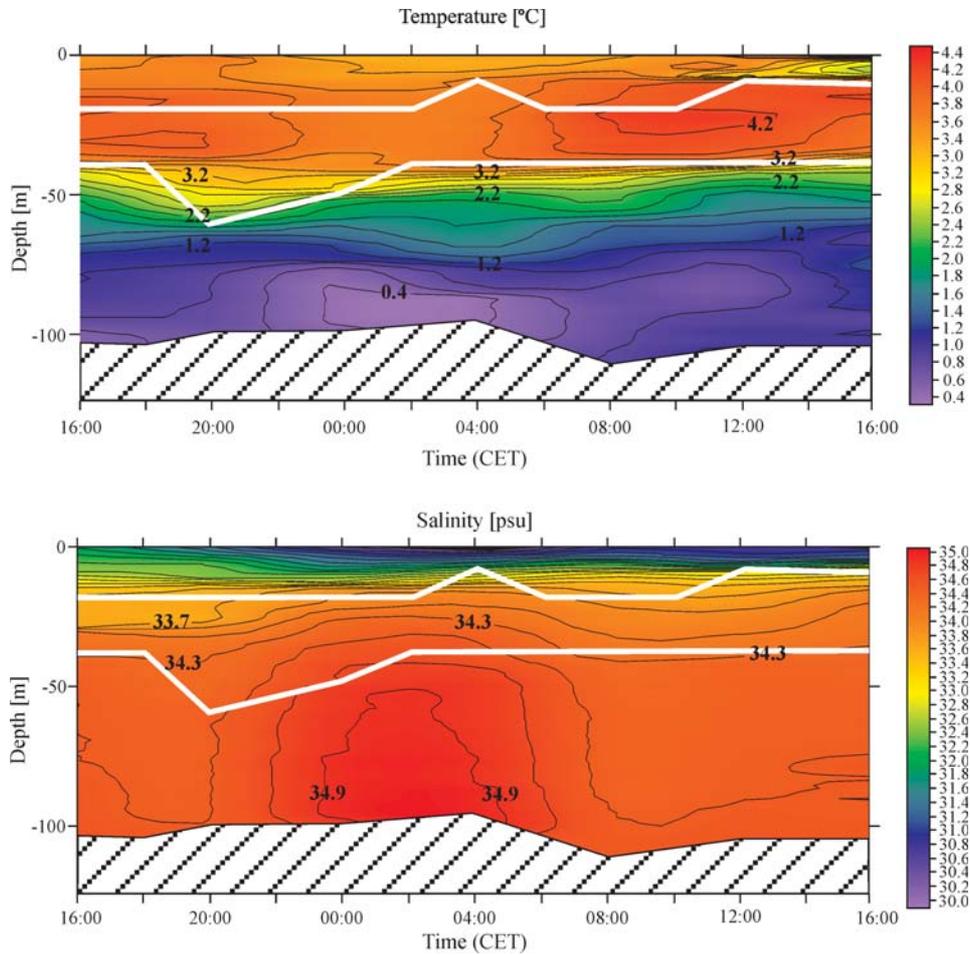


Fig. 2. The 24 hour run of temperature (a) and salinity (b) at the sampling site. White lines indicate span of the water layers distinguished.

hypothesis (h_0), tested irrespective of the water layer, was: zooplankton abundance variability is not dependent on the observed hydrological variability (temperature, salinity).

Results

The water column average density of all zooplankton at the sampling site varied from 1610 to 2410 ind. m^{-3} (Fig. 3). No clear-cut relationship between changes in zooplankton abundance and the tide cycle could be discerned and the variation of the average zooplankton density was low (CV = 14%).

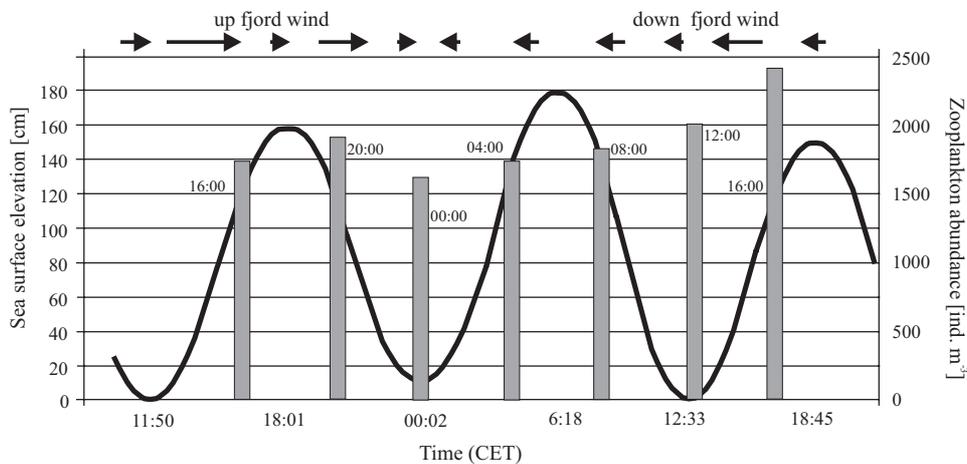


Fig. 3. Sea surface elevation [cm, black line] relative to zero sea level and average zooplankton density [ind. m⁻³, bars] at individual sampling. Arrows indicate a relative wind strength.

Copepoda (including nauplii) made up the bulk of the zooplankton at the sampling site (95–97%; Table 1) throughout the study. Dominant taxa were *Oithona similis* (50–60%) and *Calanus finmarchicus* (10–14%) together with Copepoda nauplii (6–13%). Less important were *Pseudocalanus* spp. (7–11%) and *Calanus glacialis* (3–5%). The variation of the relative abundance was the lowest for *O. similis* and the highest for Copepoda nauplii (Table 1). The non-copepod zooplankton comprised only a minor fraction of the zooplankton. Of some importance were only Echinodermata larvae, Mollusca (Bivalvia larvae and larval/juvenile *Limacina helicina*), and Appendicularia.

Temporal changes in zooplankton in individual water layers were more variable. Zooplankton density was on average the highest (1680 to 3010 ind. m⁻³) and moderately variable (CV = 22%) in the LWL (Fig. 4a). It was the lowest (1130 to 1810 ind. m⁻³) and the least changeable (CV = 17%) in the IWL while in the SWL it was at intermediate level (840 to 2110 ind. m⁻³) but showed the highest variability (CV = 25%). During the first twelve hours tendencies in zooplankton density changes were identical and at 04:00 the densities got almost equal in each particular layer. After this singular point the densities changed in a different manner. The density in the LWL was increasing while this in the IWL was decreasing persistently. In the SWL zooplankton density varied in up and down manner around approximately the same mean value with momentary minimum at 08:00.

As for the individual zooplankters, *C. glacialis* was concentrated in the IWL and LWL with densities of 47–140 ind. m⁻³ and 71–100 ind. m⁻³, respectively (Fig. 4b). It was the least numerous in the SWL (14–79 ind. m⁻³) and only at the end of the study did its density equal that in the LWL. Two particular points in the temporal changes of *C. glacialis* abundance are worth mentioning: the maximum in the

Table 1
Changes in the relative abundance [%] of the zooplankton taxa at the sampling site and the coefficient of variation (CV, %) of the relative abundance.

Taxon	Time (CET)							CV[%]
	16:00	20:00	00:00	04:00	08:00	12:00	16:00	
<i>Oithona similis</i>	52.8	60.4	60.7	55.6	56.0	61.0	58.5	5
<i>Calanus finmarchicus</i>	14.1	11.9	10.3	11.1	12.1	10.8	14.1	13
<i>Pseudocalanus</i> spp.	8.8	9.1	8.2	7.0	8.9	9.0	11.1	14
<i>Calanus glacialis</i>	5.5	3.2	4.2	3.6	5.3	3.2	3.1	25
Copepoda nauplii	13.1	8.8	8.8	15.3	7.3	7.9	6.6	33
Copepoda	97.4	97.7	95.8	95.4	95.4	97.1	96.6	
Other taxa	2.6	2.3	4.2	4.6	4.6	2.9	3.4	

IWL at 08:00, followed by rapid decrease towards the last observation, and the minimum in the SWL at 04:00. The coefficient of variation (CV) of *C. glacialis* density in the SWL, IWL, and LWL was 54%, 33%, and 15%, respectively.

C. finmarchicus was the most abundant in the LWL (260–590 ind. m⁻³) while in the SWL and IWL its density reached 79–150 ind. m⁻³ and 65–190 ind. m⁻³, respectively (Fig. 4c). In the LWL and SWL *C. finmarchicus* density had minima at different times (00:00 and 08:00, respectively) but in both layers it increased to maximum value observed at 16:00. The CV was almost equal for the IWL (CV = 25%) and LWL (CV = 26%), and it was only slightly higher in the SWL (CV = 33%).

Pseudocalanus spp. exhibited similar distribution and variability pattern to *C. finmarchicus*; the highest densities (260–540 ind. m⁻³) were observed continuously in the LWL, in particular at the end of study (Fig. 4d). The densities in the IWL and SWL were only 14–80 ind. m⁻³ and 24–100 ind. m⁻³, respectively. The variability in the temporal changes of *Pseudocalanus* density was higher in the SWL and IWL (CV = 42% and CV = 54%, respectively) than in the LWL (CV = 27%).

In case of *O. similis* the variability in density was the most irregular and dissimilar between individual layers. The density in LWL varied from 730 to 1490 ind. m⁻³ with the pattern of temporal changes resembling that of *C. finmarchicus* and *Pseudocalanus* spp. (Fig. 4e). The density in the IWL varied from 760 to 1230 ind. m⁻³ with maximum at 08:00. In the SWL *O. similis* had two abundance maxima with values close to 1450 ind. m⁻³ at 20:00 and 12:00, and one minimum of 530 ind. m⁻³ at 08:00. The relative temporal changes in the abundance were higher for the SWL and LWL (CV = 28% and CV = 27%, respectively) than for the IWL (CV = 15%).

Nauplii of Copepoda were concentrated mainly in the SWL (160–500 ind. m⁻³) (Fig. 4f). In the IWL and LWL nauplii density range was 52–210 ind. m⁻³ and

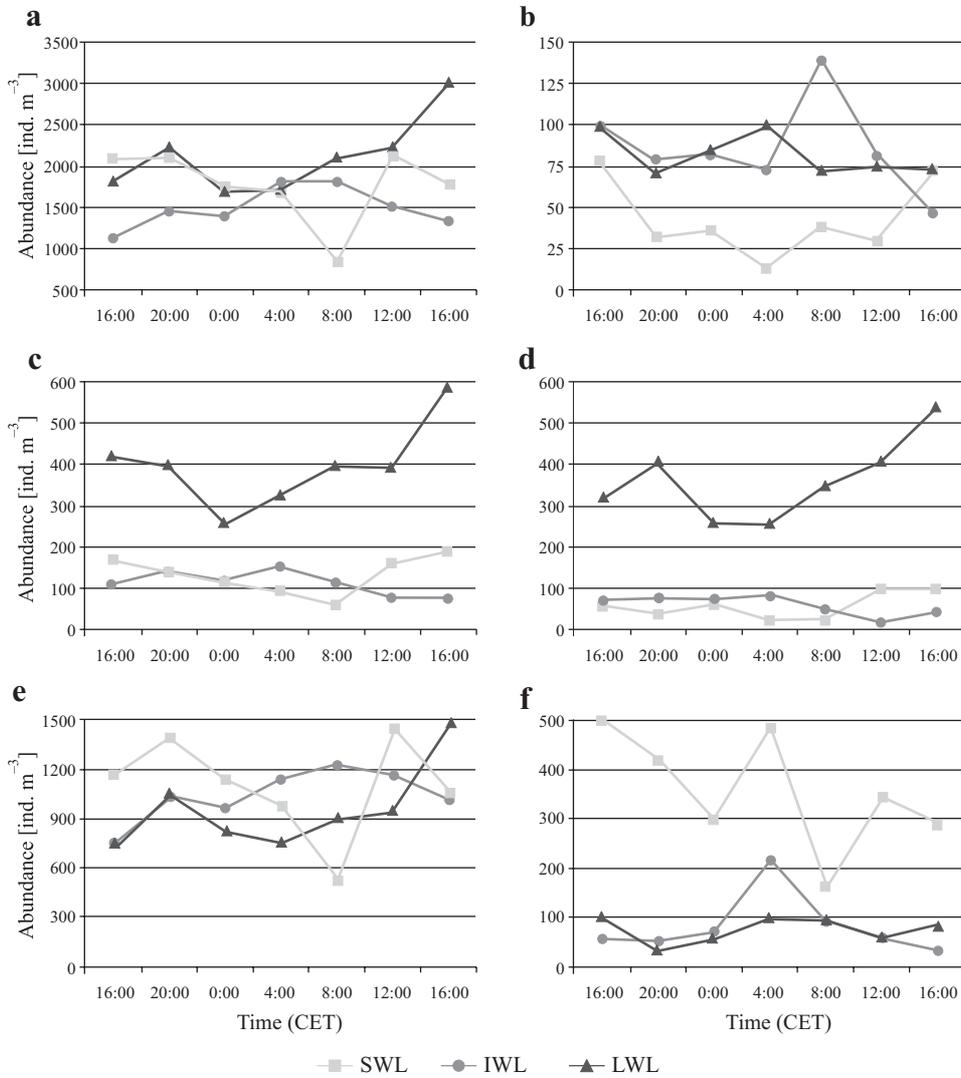


Fig. 4 Changes in abundance of: a) total zooplankton; b) *C. glacialis*; c) *C. finmarchicus*; d) *Pseudocalanus* spp.; e) *O. similis* and f) Copepoda nauplii in layers. SWL, IWL, LWL indicate surface water layer, intermediate water layer and local water layer, respectively. Note different abundance scales.

36–100 ind. m⁻³, respectively. In the SWL the density gradually decreased, but showed a down and up fluctuation in the middle of the study. The changes in the density were rather low and had an oscillating character in the IWL and LWL, with a maximum at 04:00, more pronounced in the IWL. The relative temporal changes in Copepoda nauplii density were high and CV equalled to 34%, 74%, and 32 % in the SWL, IL, and LWL, respectively.

Table 2
 Results of stepwise multiple regression testing relationship between changes in temperature and salinity and in zooplankton abundance. β – standard regression coefficient, R^2 – coefficient of determination, p – significance level. $p < 0.05$ in bold. Variables excluded from the final model marked as “ex”.

Taxon	Temperature			Salinity		
	β	R^2	p value	β	R^2	p value
<i>C. glacialis</i>	ex			0.680	-0.462	0.00070
<i>C. finmarchicus</i>	-0.900	0.801	0.00000	ex		
<i>Pseudocalanus</i> spp.	-0.930	0.860	0.00000	ex		
<i>O. similis</i>	ex			ex		
Copepoda nauplii	ex			-0.840	0.702	0.00000

The results of the multiple regression analysis show significant negative relationship between the zooplankton density and temperature for *C. finmarchicus* and *Pseudocalanus* spp., while salinity component of the regression for these taxa was excluded from the model (Table 2). Regarding salinity, significant negative relationship was shown only for Copepoda nauplii and positive for *C. glacialis*. No significant relationship with neither temperature nor salinity was revealed for *O. similis*.

Discussion

The sampling site was situated at the southern coast where the prevailing circulation of water masses is directed up-fjord (Ingvaldsen *et al.* 2001; Svendsen *et al.* 2002; Basedow *et al.* 2004). The circulation in Kongsfjorden is governed by distant forces (large scale currents, tide and coastal winds) as well as local forces (fresh water runoff and local winds). In the summer situation, with developed stratification, the circulation typically comprises two layered system, including upper layer and deep layer, separated by pycnocline (Svendsen *et al.* 2002). The distribution of temperature and salinity at the sampling site (Fig. 2) suggests that this was the case during our study. The SWL may be identified with the upper layer that undergoes upper layer circulation pattern while the LWL and to some extent the IWL may be identified with the deep layer, where the circulation follows the deep layer circulation pattern. For the duration of the study we did not observe any pronounced shift in intensity or direction of both distant and local circulation driving forces except for the change in the local wind (Fig. 3). The day before sampling the wind had blown down-fjord, but it turned up-fjord a few hours before the first sampling and blew with the maximum speed of 8 m s^{-1} . The wind direction changed again at night (at 00:00) and blew down-fjord for the rest of the study with

the maximum speed of 5 m s^{-1} . While the general pattern of water stratification persisted the entire study, there were two significant fluctuations observed in the water mass characteristics. In the SWL there was a decrease of temperature and salinity towards the end of the study that started most likely before midnight, coincident with the shift in wind direction from up-fjord to down-fjord. In the LWL, on the other hand, there was an appearance of an insert of colder and more saline water, located between midnight and 04:00, coincident with the shift in the wind direction and in the tide phase from low to high water. We think that the change in the wind pattern can be accounted for the observed changes in the water mass characteristics and the anticipated fluctuations in the circulation pattern. During the first part of the study the tide was rising and the wind was up-fjord, which resulted, most likely, in an intensified up-fjord circulation in both upper and deep layers. Such a situation could lead to stacking of the surface water at the fjord head and the development of the across-fjord front and down-fjord pressure gradient (Svendsen *et al.* 2002). The pressure gradient, together with the turn of the tide phase and the decline and the subsequent shift of the wind to down-fjord, contributed, together to the turning of the flow in the upper layer (SWL), to down-fjord and/or cross-fjord flow that started possibly around midnight. The down-fjord flow in the SWL probably endured for the duration of the next rising tide and lasted until the end of our study, because of the continuous down fjord wind. The down-fjord flow in the SWL transported water from the head of the fjord, which is generally colder and less saline (Węśławski and Legeżyńska 1998; Svendsen *et al.* 2002). As regards the fluctuations in the LWL, we argue that the turn in direction of the circulation in the SWL have caused a compensating flow in the deeper layer, and that the insert of the colder and more saline water was the evidence of such a compensation, related most likely to an upwelling or the horizontal advection of a pocket of water of different characteristics, from the inner/northern part of the fjord.

Zooplankton collected during present study included taxa known from earlier investigations and zooplankton densities recorded were within the range observed previously in Kongsfjorden (Węśławski *et al.* 1991; Hop *et al.* 2002). The water column zooplankton densities, however, were the highest of the values recorded in the vicinity of the sampling site in other studies. Whether these differences were the result of year to year zooplankton variability, which can be very pronounced (Hop *et al.* 2002) or an artefact because our sampling site was the shallowest of the compared sites, cannot be answered at present.

Zooplankton temporal series presented in this study is the first diurnal series available for Spitsbergen waters, and there are not many such data series from other waters to compare with. Maybe that is why the use of CV as the measure of variability is uncommon in zooplankton ecological studies. Cassie (1968) used CV in the discussion of the error in estimation of zooplankton composition and abundance on the basis of a single plankton sample. Summarizing the available information he concluded that the CV is most often in the range of 22–44%. Cassie also

suggested that, considering the nature of plankton distribution, under good experimental conditions it seems likely that nearly all the variation in the catch can be attributed to the variability in plankton itself. In a study off the north coast of Spain, Fernandez de Puellas *et al.* (1996) found that daily variability in zooplankton abundance at three sampling sites, which were marked by a drogue buoy and sampled up to six times a day, was between 32 and 41%. The results of a recent study on the short-term variability of zooplankton in the dynamic area of the Barents Sea marginal ice zone (Błachowiak-Samołyk *et al.* 2006; Błachowiak-Samołyk unpublished data) indicate that the variability of zooplankton abundance per station varied within 14–29%. Taking into account that in our study the CV for both zooplankton abundance (14%) and the proportion of individual taxa (5–37%) were in this common range, indicated by Cassie as natural, we conclude that the observed short-term zooplankton variability in Kongsfjorden in summer was relatively low. This also justifies saying that typically, in Kongsfjorden coastal waters in summer, zooplankton is dominated by *O. similis* with considerable proportion of *C. finmarchicus*. Low and more variable proportion of Copepoda nauplii, *Pseudocalanus*, and *C. glacialis* is observed at that time.

The vertical distribution of individual zooplankton components during our study concurred with that revealed in other studies in Kongsfjorden or another Spitsbergen waters (Karnovsky *et al.* 2003; Kwaśniewski *et al.* 2003; Walkusz *et al.* 2004). It is assumed that individual taxa or developmental stages occupy preferable habitats and assemble into associations in response to the dynamic equilibrium between the factors shaping the pelagic environment.

In our study, similarly to earlier study in Kongsfjorden (Kwaśniewski *et al.* 2003), *C. finmarchicus* and *C. glacialis*, for example, inhabited deep waters. On the other hand, typically, Copepoda nauplii preferred surface waters while the erratic distribution of *O. similis* was the manifestation of the species' ability to take advantage of unstable conditions often found at different depths in the upper part of the water column (Galliene and Robins 2001; Karnovsky *et al.* 2003; Walkusz *et al.* 2004).

Comparison of the variability in zooplankton distribution and in the water stratification, and temperature and salinity distribution during our study indicates that the changes recorded were parallel or simultaneous. This allows to assume that the primary factor responsible for the observed changes in zooplankton was the water mass dynamics. We think that the dynamics of water masses described earlier, based on our measurements and literature sources (Ingvaldsen *et al.* 2001; Svendsen *et al.* 2002; Basedow *et al.* 2004), reasonably explains the observed variability. We also think that the fact that individual taxa showed different patterns results from their different distribution because of individual environmental preferences. On the other hand, we are of the opinion that the data gathered do not suggest that the studied taxa performed diel vertical migration (DVM) in the course of the study. This is in agreement with the results of majority of the studies on DVM

in the Arctic (Bogorov 1946; Buchanan and Haney 1980; Longhurst *et al.* 1984; Błachowiak-Samołyk *et al.* 2006), although, there are some studies that suggest the opposite (Digby 1961; Groendahl and Hernroth 1986). As a summary we can thus propose a simplified plot of the observed temporal changes in Kongsfjorden coastal waters zooplankton in summer. At the beginning of our investigation zooplankton showed typical summer vertical distribution. *C. glacialis* avoided SWL and stayed within ILW and LWL. *C. finmarchicus* and *Pseudocalanus* clearly concentrated in the LWL, avoiding not only the least saline and possibly turbid SWL but also the relatively unstable IWL, where steep density gradient most likely occurs, whereas *O. similis* and Copepoda nauplii clearly preferred the SWL. This situation coincided with the rising tide and up-fjord wind. The intensified up-fjord flow in the upper and deep layers transported waters from the outer fjord, which generally have higher abundance of *C. finmarchicus*, *Pseudocalanus* and Copepoda nauplii at this time of the year (Hop *et al.* 2002; Kwasniewski unpublished). For the period between midnight and 04:00 there was a noticeable decrease in densities of *C. finmarchicus* and *Pseudocalanus* in the LWL while that of *C. glacialis* was somewhat increasing. This variation overlapped with the inflow of colder and more saline water from deeper waters or inner fjord. We associate this event with the compensating flow in deep layers, in relation to the reversal of the circulation in the upper layer and down-fjord and/or across-fjord flushing of the surface water, as the consequence of the tide turning to low water and the wind turning to down-fjord as well as breaking of the pressure gradient that had been arising. The down-fjord flow in the SWL transported surface water from the inner fjord which is less populated by marine zooplankton because it is colder, less saline and has more suspended matter due to intense fresh water runoff at the fjord's head. Towards the end of our investigation we observed apparent increasing trends in densities of *C. finmarchicus*, *Pseudocalanus* as well as *O. similis* in the deep LWL. At the same time in the SWL the density of Copepoda nauplii was still decreasing while the density of *C. glacialis* returned to the high value observed at the beginning of the study. We suppose that this situation was the consequence of another arrangement of the circulation driving forces, the rising tide and the down-fjord strong wind, which resulted in intensified up-fjord flow in the LWL and continuation of the down-fjord flow in the SWL. The flow in deep waters occurred most likely along the coast thus assuring advection of the outer fjord water that have higher densities of zooplankters mentioned above, whereas the continuing down-fjord flow was bringing to the sampling site more water from the inner fjord, where the abundance of Copepoda nauplii is supposedly lower. The evident increase in density of *C. glacialis* in the SWL at the very last observation coincides with the appearance of an inflow of colder water. This suggests that even in such a dynamic environment there are mechanisms (*e.g.* meandering of hydrological fronts) creating pockets of waters of different characteristics that can be transported for some time as individual entities in contrasting environment, preserving not only their

physical properties but also their original biological markers. It is possible that the absence of clear variability pattern in the IWL may result from the fact that within this layer there is usually the main density gradient. Consequently, this is most likely the share layer between the main upper and deep circulation layers. Because of the movements of waters above and below, the conditions in this layer can be difficult to comprehend and understand.

The results of the stepwise multiple regression analysis further support earlier findings and our observations of specific relationships between individual taxa and water temperature and salinity such as the negative correlation of Copepoda nauplii density with salinity, indicative of their typical surface dwelling behaviour, although some of the correlation coefficients may look seemingly contradictory to the general knowledge. One has to take into account, however, that the calculated correlations describe the relationships only for the selected circumstances met during the study. In such a milieu *C. finmarchicus* indeed preferred waters of lower temperature, because it was constantly dwelling in the deep layers, avoiding upper layers, which, although of higher temperature, were at the same time most likely of lower salinity.

Conclusions

This paper provides the first insight into the scale of short-term temporal changes in the zooplankton abundance and distribution in the hydrologically dynamic coastal waters in an Arctic fjord Kongsfjorden. The observed changes did not exceed the range of variability regarded as intrinsic, resulting from the nature of plankton, therefore we conclude they were low and typical. Because of this low variability we are of the opinion that the data presented, that come from the spatially fixed time series, can be regarded a valid measure of the natural heterogeneity of zooplankton communities in hydrologically dynamic Arctic coastal waters in summer. Examining the variability in zooplankton in relation to the variability in water mass distribution and circulation indicates that the observed changes in zooplankton were primarily induced by the complex dynamics of the fjord's water masses. In spite of importance of tidal forcing, the variability in zooplankton did not demonstrate similar temporal fluctuations due to modification of the water movement by other irregular forces (first of all local winds). Also, our study did not found any indication of diel vertical migration in coastal water in the Arctic under the condition of midnight sun.

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