



# Impact of a warm anomaly on export fluxes of biogenic matter in the eastern Fram Strait

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## ABSTRACT

As part of the HAUSGARTEN long-term observatory, sediment trap deployments were carried out before, during, and after the anomalously warm Atlantic Water inflow observed from 2005 to 2007 in the eastern Fram Strait. Downward export of particulate organic carbon (POC), zooplankton fecal pellet carbon (FPC), and biogenic particulate silica (bPSi) were measured from August 2002 to June 2003 and from July 2004 to July 2008 to indirectly assess the impact of the warm anomaly on phytoplankton and zooplankton communities in the region. Lower and less frequent bPSi fluxes were observed during most of the warm anomaly period, reflecting a shift in phytoplankton community composition towards dominance of small-sized phytoplankton under warmer conditions. Lower FPC fluxes observed concurrently with the lower bPSi fluxes may indicate a decrease in fecal pellet production due to changing feeding conditions. In addition, the export of smaller fecal pellets in fall 2005 and spring 2006 suggests a dominance of smaller zooplankton during the warm anomaly. Nonetheless, bPSi and FPC export always increased in the presence of ice cover in the area above the sediment trap, even during the warm anomaly period, suggesting that sea ice is a key factor influencing the frequency of export events in the eastern Fram Strait. The scarcity of ice over the sampling area in 2005 and 2006 may partly be due to the warm anomaly, although solar radiation and ice drift due to wind stress also govern ice cover extent in the region. Overall, the warm anomaly resulted in a shift in the composition of the export fluxes when associated with an absence of ice cover in the eastern Fram Strait.

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## 1. Introduction

The HAUSGARTEN observatory, located in the eastern Fram Strait approximately 120 km west of Spitsbergen, has been maintained by the Alfred Wegener Institute for Polar and Marine Research for more than a decade, providing a unique long-term dataset for this region of the Arctic Ocean (Soltwedel et al., 2005). During this period, a warming of the Atlantic Water entering the Arctic Ocean with the West Spitsbergen Current was recorded in Fram Strait (Beszczynska-Möller et al., 2012). The warmer period began in late 2004, reached a peak in September 2006, and persisted until a significant decrease in temperature was recorded in 2008 (Beszczynska-Möller et al., 2012). This period of increased water temperature was defined as the warm anomaly of 2005–2007, when temperature anomalies exceeding 1 °C were observed in the eastern Fram Strait (Beszczynska-Möller et al., 2012). During this period, the highest mean temperature of the West Spitsbergen Current reached 4.4 °C, whereas the median temperature of the Atlantic Water entering the Arctic Ocean in Fram Strait usually ranges from 3 to 3.5 °C (Beszczynska-Möller et al., 2012). The coin-

cident deployment of a long-term sediment trap at the central station of the HAUSGARTEN observatory before, during, and after that warm anomaly period provided the opportunity to evaluate the impact of an increase of water temperature on export fluxes in the entrance to the Arctic Ocean.

Several studies have investigated the biological impact of warmer ocean conditions on marine ecosystems. In northern Chile, the high surface temperature anomaly observed during the El Niño episode of 1997–1998 led to lower phytoplankton biomass and primary production (Iriarte and González, 2004), a dominance of small-sized phytoplankton (Escribano et al., 2004; Iriarte and González, 2004), lower diatom export fluxes (Romero et al., 2001), an increase in small-sized zooplankton (González et al., 2000a; Escribano et al., 2004), and reduced export of particulate organic carbon (POC) (González et al., 2000b). The 1997–1998 El Niño event also resulted in a substantial decrease in phytoplankton biomass and in a dominance of small-sized phytoplankton off Oregon (Corwith and Wheeler, 2002) and British Columbia (Harris et al., 2009), as well as reduced phytoplankton biomass (Chavez et al., 2002), lower zooplankton abundance, and a shift in zooplankton community composition off central California (Marinovic et al., 2002). Similarly, anomalously warm ocean conditions off Washington in 2005 resulted in lower phytoplankton biomass, lower phytoplankton productivity, and dominance of small-sized

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phytoplankton (Kudela et al., 2006). Each of these observations was made in an eastern boundary upwelling ecosystem where the anomalously warm surface conditions inhibited the upwelling of nutrient-rich waters, suggesting that the phytoplankton community, and indirectly the zooplankton community, were primarily influenced by nutrient limitation during the warm episodes (Kudela et al., 2006). However, recent observations suggest that water temperature also has a direct impact on phytoplankton size and community structure. Morán et al. (2010) observed an increasing contribution of small cells to total phytoplankton biomass with higher water temperature in the North Atlantic Ocean, whereas Hilligsøe et al. (2011) reported an increase in the importance of small cells in the phytoplankton community and a decrease in zooplankton production with increasing temperature from a dataset acquired in all major ocean basins. Because the fate of particulate organic carbon in the euphotic zone depends on phytoplankton and zooplankton communities (González et al., 2000a, b), changes in phytoplankton and zooplankton composition during a warm anomaly are reflected in the magnitude and composition of the export fluxes.

In contrast to warm anomalies inhibiting the main input of nutrients in eastern boundary upwelling ecosystems, it is unlikely that the warm anomaly episode of 2005–2007 affected nutrient concentrations in the eastern Fram Strait, although no measurements are available to support this assumption. The long-term measurements of export fluxes at the HAUSGARTEN observatory should therefore reflect the direct impact of an increase in temperature on phytoplankton and zooplankton composition in the eastern Fram Strait. In the present study, fluxes of POC, zooplankton fecal pellets and biogenic particulate silica (bPSi), a proxy for diatoms, were measured prior to, during, and after the anomalously warm conditions of 2005–2007 to indirectly evaluate the impact of the warm anomaly on the pelagic system.

## 2. Materials and methods

### 2.1. Remote sensing

Daily averaged sea ice concentration for the area above the sediment trap (78°30′–79°30′ N; 2°30′–6°30′ E) was obtained by analysis of Advanced Microwave Scanning Radiometer-EOS (AMSR-E) data provided by the National Snow and Ice Data Centre. The 89 GHz AMSR-E sensor and the ARTIST sea ice (ASI) algorithm were used, yielding a spatial resolution of  $6.25 \times 6.25$  km (Spren et al., 2008).

Daily sea surface temperature for the area above the sediment trap was obtained at a spatial grid resolution of  $0.25^\circ$  from the NOAA Optimum Interpolation Sea Surface Temperature Version 2 (NOAA OISST v2) dataset (Reynolds et al., 2007). The daily  $0.25^\circ$  sea surface temperature data were spatially re-interpolated onto mooring positions and averaged monthly to be consistent with the water column temperature time series obtained from the oceanographic moorings.

### 2.2. Oceanographic moorings

Since 1997 an array of oceanographic moorings has measured temperature, salinity, and ocean currents between the Greenland and Spitsbergen shelves along 78°50′ N (Beszczynska-Möller et al., 2012). In this study, water temperature data obtained at the nominal depths of  $\sim 50$  m and  $\sim 250$  m in the partial section from 3 to 5° E (between moorings F6 and F8 deployed south of the sediment trap) were used (Fig. 1). Temperature data were collected at 1 or 2-h intervals, despiked and low-pass filtered with a cut-off period of 40 h to remove the tidal signal. To construct Hovmöller diagrams, temperature data with the time step of 1 month

(averaged monthly) and the spatial step of 1 km (interpolated) were used. Detailed description of data accuracy and treatment can be found in Fahrback et al. (2001) and Schauer et al. (2004).

### 2.3. Sediment trap

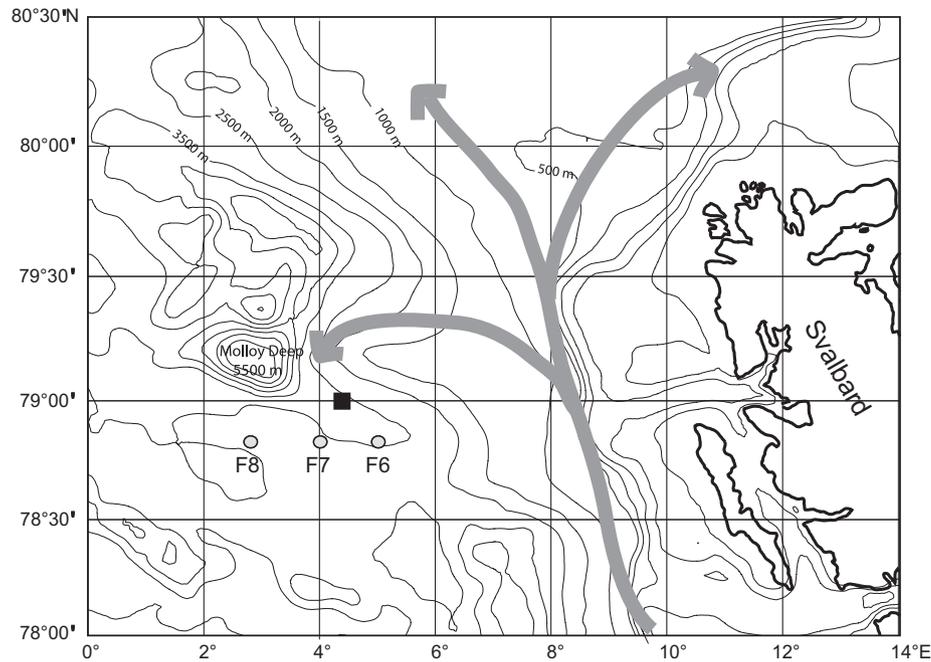
A modified automatic Kiel sediment trap with a sampling area of  $0.5 \text{ m}^2$  and 20 collection cups (Kremling et al., 1996) was deployed and recovered every year from August 2002 to July 2008 at the central station of the HAUSGARTEN observatory (Fig. 1; Table 1). The sediment trap was located in the confluence zone of the warm Atlantic Water with cold water masses of Arctic origin (Fig. 1). A malfunction of the sediment trap prevented the collection of sinking material for the deployment year of 2003–2004. The depth of the sediment trap varied between 179 and 280 m depending on the deployment year (Table 1) and sampling cups rotated at intervals ranging from 7 to 59 days depending on the season. Sampling cups were filled with filtered seawater adjusted to a salinity of 40 with NaCl and poisoned with  $\text{HgCl}_2$  (0.14% final solution) to preserve samples during deployment and after recovery.

In the laboratory, swimmers were removed with forceps and rinsed under a dissecting microscope and samples were split for different measurements. Triplicate subsamples for POC measurements were filtered on pre-weighed GF/F filters (pore size:  $0.7 \mu\text{m}$ ) pre-combusted at  $500^\circ\text{C}$  for 4 h. POC filters were soaked in 0.1 N HCl for removal of inorganic carbon and then dried at  $60^\circ\text{C}$ . POC measurements conducted on a CHN elemental analyzer were not corrected for dissolution of organic material in the sampling cups and should be considered as minimum values. Subsamples for bPSi were filtered on polycarbonate filters (pore size:  $0.8 \mu\text{m}$ ) and bPSi measurements were obtained by wet-alkaline digestion of the samples (von Bodungen et al., 1991). Zooplankton fecal pellets were enumerated (5–700 pellets depending on the subsample) and measured using a dissecting scope. The length and width of each fecal pellet (broken or intact) were measured and pellet volumes were calculated according to the shape of the pellets. Cylindrical pellets were attributed to calanoid copepods and ellipsoidal pellets to appendicularians (González et al., 2000a). Fecal pellet volumes were converted to fecal pellet carbon (FPC) using a volumetric carbon conversion factor of  $0.057 \text{ mg C mm}^{-3}$  for copepod pellets and  $0.042 \text{ mg C mm}^{-3}$  for appendicularian pellets (González et al., 1994; González and Smetacek, 1994). POC fluxes were averaged for each collection period (coefficient of variation <15%), while POC, bPSi, and FPC fluxes were converted to daily fluxes for each collection period. Pearson's correlation coefficient was used to measure correlation between POC, bPSi, and FPC fluxes. A one-way analysis of variance was used to test for the effect of deployment periods on fecal pellet size.

## 3. Results

### 3.1. Ice concentration and water temperature

Ice cover was frequently absent in the region above the sediment trap during the sampling period, and when present ice concentrations remained mostly <20%. Higher ice concentrations (>40%) were observed in June 2003 and in April, May, and June 2008 (Fig. 2a). Sea surface temperature and water temperature at  $\sim 50$  and  $\sim 250$  m displayed seasonal variation, with low values measured in winter and spring and high temperatures observed in summer and fall (Fig. 2b–d). The highest water temperatures ( $4$ – $5.5^\circ\text{C}$ ) were observed in September 2006 at all depths investigated, while the lowest temperatures ( $0.8$ – $1.8^\circ\text{C}$ ) were measured in winter-spring 2003 at  $\sim 50$  m and  $\sim 250$  m and in spring 2008 at the sea surface. The study area was strongly influenced by



**Fig. 1.** Location of the sediment trap (square) deployed from August 2002 to June 2003 and from July 2004 to July 2008 at the central station of the HAUSGARTEN observatory in the eastern Fram Strait. Location of 3 oceanographic moorings (circles) near the sediment trap from which water temperatures at ~50 m and ~250 m were interpolated for the deployment period. The gray lines represent branches of the West Spitsbergen Current carrying Atlantic Water in the region.

**Table 1**

Position, depth, sampling period, and deployment days of the sediment trap deployed at the central station of the HAUSGARTEN observatory.

Deployment year	Position	Depth (m)	Sampling period	Deployment (days)
2002–2003	79°01.04 N; 4°19.77 E	280	August 14 2002–June 10 2003	300
2004–2005	79°00.99 N; 4°20.62 E	280	July 15 2004–June 15 2005	328
2005–2006	79°01.00 N; 4°20.62 E	179	August 27 2005–July 20 2006	359
2006–2007	79°00.82 N; 4°20.50 E	230	August 26 2006–June 20 2007	335
2007–2008	79°00.82 N; 4°20.62 E	190	July 23 2007–July 15 2008	298

Atlantic Water, as the Atlantic Water mass is defined as warmer than 2 °C (Schlichtholz and Houssais, 2002; Beszczynska-Möller et al., 2012).

### 3.2. Export fluxes

Increased POC fluxes were observed during fall and spring seasons, except in spring 2005 and in fall 2006 when POC fluxes remained low (Fig. 2e). POC fluxes were <30 mg C m<sup>-2</sup> d<sup>-1</sup> except for 2 periods in August 2004 and in April–May 2007 during which POC fluxes increased to almost 50 mg C m<sup>-2</sup> d<sup>-1</sup>. The timing of the peak in POC export varied amongst deployment period, with the highest POC fluxes measured in May in 2002–2003 and 2006–2007, in August in 2004–2005, in July in 2005–2006, and in April in 2007–2008. Microscopic observation of the sediment trap material revealed that the majority of the material contributing to the POC flux was unidentifiable.

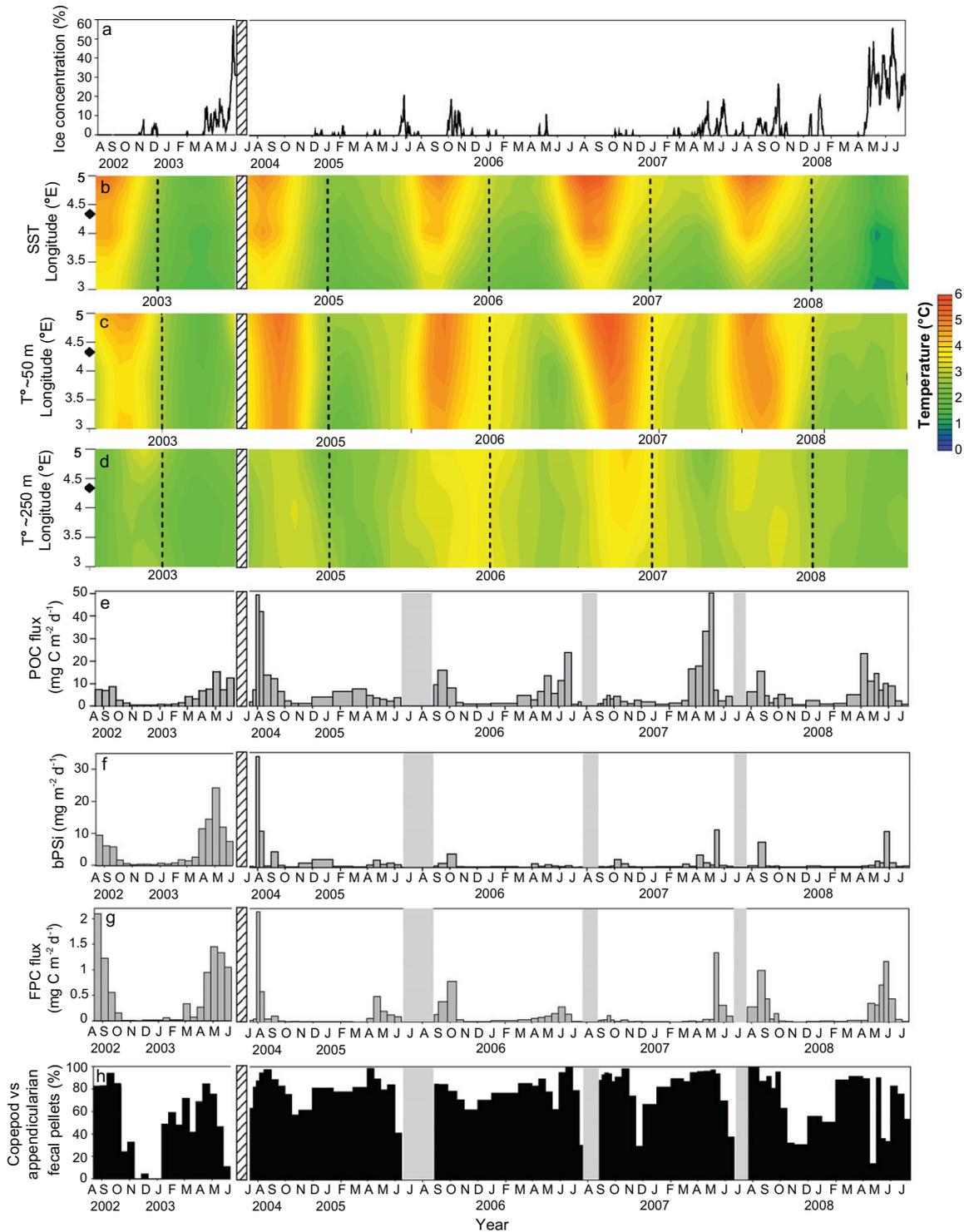
Export fluxes of bPSi remained <5 mg m<sup>-2</sup> d<sup>-1</sup> during most of the sampling period, including the complete deployment period of 2005–2006 (Fig. 2f). In 2002–2003, high bPSi fluxes (5–25 mg m<sup>-2</sup> d<sup>-1</sup>) were observed from August to October and from April to June. In the following deployment years, bPSi fluxes moderately increased (~10 mg m<sup>-2</sup> d<sup>-1</sup>) during short periods in August 2004, May 2007, August 2007, and May 2008, except for the highest bPSi fluxes (>30 mg m<sup>-2</sup> d<sup>-1</sup>) observed at the end of July/beginning of August 2004. Microscopic observation of the sediment trap material confirmed that the large majority of bPSi was associated

with diatoms rather than other Si-producing organisms. Diatoms were observed both as intact cells and incorporated into fecal pellets.

FPC fluxes remained <2.5 mg C m<sup>-2</sup> d<sup>-1</sup> during the complete deployment period (Fig. 2g), generally contributing to less than 15% of the POC flux and to 29% of the POC flux at its highest contribution in August 2002. Increases in FPC fluxes were observed at the end of summer/beginning of fall and in spring but these increases were smaller in spring 2005 and spring 2006 and nearly absent in fall 2006. The highest FPC fluxes were measured in August 2002 and August 2004. The majority of fecal pellets exported every year were copepod pellets, although a higher proportion of appendicularian fecal pellets were exported during 2002–2003 and 2007–2008 (Fig. 2h). The average volume and width of copepod and appendicularian fecal pellets collected in fall and spring/summer were similar every deployment year except in 2005–2006 when the volume and width of exported fecal pellets were significantly lower than in all other years sampled ( $p < 0.05$ ; Fig. 3).

### 4. Discussion

The long-term sediment trap fluxes obtained in the eastern Fram Strait from August 2002 to June 2003 and from July 2004 to July 2008 revealed a change in the export of biogenic matter during the warm anomaly period of 2005–2007. These variations in the magnitude and composition of the export flux before, during, and after the warm anomaly reflect the impact of the rapid



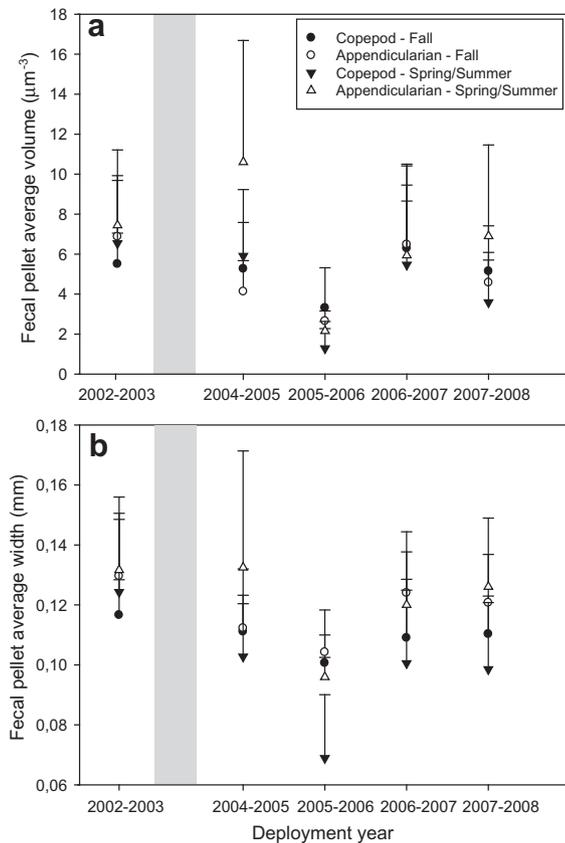
**Fig. 2.** (a) Satellite-derived daily sea ice concentration averaged over the sampling region (78°30–79°30 N; 2°30–6°30 E), (b) Hovmöller diagram of satellite-derived daily sea surface temperature, (c) Hovmöller diagram of monthly averaged water temperature measured at ~50 m, and (d) at ~250 m, (e) POC fluxes, (f) bPSi fluxes, (g) FPC fluxes, and (h) contribution of copepod and appendicularian fecal pellets to the FPC fluxes obtained from August 2002 to June 2003 and from July 2004 to July 2008 in the eastern Fram Strait. The black diamonds indicate the location of the sediment trap along the oceanographic mooring transect. The light gray areas represent the mooring turnover periods.

warming of the Atlantic Water on phytoplankton and zooplankton communities.

4.1. Before the warm anomaly

During the first weeks of sampling in fall 2002, a decrease in water temperature, POC export, bPSi fluxes, and FPC fluxes indi-

cated the end of the productive period and the beginning of winter. Export fluxes remained very low until March when a small increase in POC fluxes suggested the start of the productive season in spring. An increase in bPSi fluxes at the end of April and in May indicated the development and export of a diatom bloom, which contributed to the highest POC export of that sampling year at the end of May. The southward displacement of the ice edge into



**Fig. 3.** Average (a) volume and (b) width of copepod and appendicularian fecal pellets exported during spring/summer and fall of each sediment trap deployment period in the eastern Fram Strait.

the area above the sediment trap likely triggered the onset of the diatom bloom, as ice melt typically promotes diatom blooms in the marginal ice zone by producing strongly stratified surface water (Peinert et al., 2001; Fortier et al., 2002; Sakshaug, 2004; Lalande et al., 2007). Because zooplankton fecal pellets sink rapidly (Turner, 2002), a pronounced increase in FPC fluxes 15 days after the increase in bPSi fluxes suggests that zooplankton biomass was low until it rapidly increased at the end of May, most likely indicating the seasonal ascent of copepods in the region. A similar increase in FPC fluxes was measured at the end of May by another sediment trap deployed at a distance of ~5 km from the current sediment trap (Lalande et al., 2011), supporting the hypothesis of the seasonal ontogenetic migration of copepods at the end of May in the eastern Fram Strait.

The unusual increase in ice concentration at the beginning of June 2003 was attributed to the formation of a cyclonic eddy at the ice-edge, a recurrent feature in the eastern Fram Strait (Wadhams and Squire, 1983; Johannessen et al., 1987; Lalande et al., 2011). In addition to distributing ice over an area of 30–40 km diameter for a 20–30 day period, the cyclonic motion of an ice-edge eddy transport warm Atlantic Water beneath the ice, creating an upwelling in the core of the eddy and downwelling on the outer edges (Johannessen et al., 1987; Niebauer and Smith, 1989). The formation of the ice-edge eddy rapidly modified the composition of the POC flux in June 2003 and likely contributed to the rapid dominance of appendicularian fecal pellets in the FPC flux (Lalande et al., 2011). Appendicularians were either advected with the Atlantic Water or were better adapted to take advantage of a rapid change in water mass and presumably phytoplankton composition due to their higher rates of ingestion than copepods (Hopcroft et al., 2005; Lalande et al., 2011). In the present

study, the FPC flux composition also shifted from a dominance of copepod pellets to a dominance of appendicularian pellets at the onset of the ice-edge eddy in the first week of June, providing further support to the hypothesis that mesoscale eddies can affect the composition of the POC flux over a large area.

An abrupt and large increase in POC, bPSi and FPC fluxes was observed a few weeks after the beginning of the following deployment period at the end of July–beginning of August 2004. These elevated fluxes indicated the occurrence of a diatom bloom that was immediately grazed upon by zooplankton and contributed to a large export of POC before the onset of the warm anomaly period. This late summer bloom may have been the second bloom in 2004 as repeated blooms are a common feature during spring and summer in the marginal ice zone of Arctic seas (e.g. Arrigo and van Dijken, 2004; Richardson et al., 2005). For example, Richardson et al. (2005) reported a *Phaeocystis* bloom in June and a diatom bloom in August in the Greenland Sea in 1999. Stratification from solar heating rather than from ice melt likely triggered a phytoplankton bloom earlier in the productive season in 2004, as ice was absent in the region for the complete spring and summer period. These results indicate that the presence of ice is not mandatory for the occurrence of a large POC export event in the eastern Fram Strait.

#### 4.2. During the warm anomaly

A long period without a marked increase in bPSi fluxes coincided with the warm anomaly period that began in late 2004 and peaked in September 2006, reflecting a decrease in the export and probably in the production of diatoms with the increase in water temperature. In fact, phytoplankton fluxes obtained from 2000 to 2005 from the same long-term sediment trap time-series indicated that the abundance of diatoms declined considerably in 2005, leading to a dominance of coccolithophores in the last year of sampling (Bauerfeind et al., 2009). Diatoms are cold water and ice-associated organisms, while coccolithophores such as *Emiliania huxleyi* are known to prefer warm waters (Tyrell and Merico, 2004). *E. huxleyi* blooms occur during positive temperature anomalies in the Atlantic Water inflow to the southern Barents Sea (Smyth et al., 2004), it is therefore likely that coccolithophore blooms were recurrent during the warm anomaly in the eastern Fram Strait. The lack of elevated bPSi fluxes from the start of the warm anomaly up to May 2007 concurs with the reduced importance of large phytoplankton cells caused by the high surface temperature anomaly observed during the El Niño episode of 1997–1998 off Chile (Escribano et al., 2004; Iriarte and González, 2004), Oregon (Corwith and Wheeler, 2002), and British Columbia (Harris et al., 2009), as well as during the warm anomaly of 2005 off Washington (Kudela et al., 2006). A shift from a dominance of large diatom cells to a dominance of small coccolithophore cells is also consistent with recent observations that rising water temperature favors the growth of small phytoplankton cells (Morán et al., 2010; Hilligsøe et al., 2011).

Similarly to diatom fluxes, the export of fecal pellets remained low from the start of the warm anomaly up to May 2007, except for a short period at the end of September–beginning of October 2005 when FPC flux increased above  $0.5 \text{ mg C m}^{-2} \text{ d}^{-1}$  and a simultaneous small increase in bPSi fluxes was observed. These increases in bPSi and FPC export were likely initiated by the advection of ice into the area during a few weeks, which may have caused sufficient ice melt to stratify warm surface waters and trigger diatom production. However, the rapid decline in sunlight at that time of year likely prevented the occurrence of a diatom bloom, and the increase in bPSi and FPC fluxes may instead be attributed to the rapid sedimentation of diatoms released from the melting sea ice and subsequently grazed upon by zooplankton (Michel et al., 1997). This is supported by the observation of

diatoms both as individual cells and inside fecal pellets during a period of elevated bPSi and FPC fluxes. Although calanoid copepods in the region normally descend for hibernation in July (Hirche, 1997; Hirche et al., 2006), Svensen et al. (2011) reported that a large proportion of calanoid copepods of stage CIII were still present in surface waters of the eastern Fram Strait in September, possibly due to a second spawning or to the advection of a second generation with the Atlantic Water. The large proportion of copepods in total zooplankton biomass during September explains the increased copepod fecal pellet fluxes observed with increased bPSi fluxes during this period. Apart from this short period of increased fluxes, the low FPC fluxes observed during most of the warm anomaly period may reflect a decrease in fecal pellet production due to a decline in large diatom cells, which is in agreement with observations of reduced zooplankton production in warmer waters where phytoplankton cells are smaller (Hilligsøe et al., 2011).

Interestingly, the average volume of exported fecal pellets also decreased during the warm anomaly. Fecal pellet volumes were significantly lower in fall 2005 and spring/summer 2006 than in other periods sampled due to significantly smaller fecal pellet widths during these periods. The export of smaller pellets suggests that the proportion of small-sized zooplankton increased during the warm anomaly, similar to observations made off Chile during the 1997–1998 El Niño event (González et al., 2000a; Escribano et al., 2004). This higher proportion of small-sized zooplankton may reflect a shift in the zooplankton community composition during the warm period, comparable to the increased abundance of warm water zooplankton species observed during the 1997–1998 El Niño event off central California (Marinovic et al., 2002). In the eastern Fram Strait, a shift from the dominance of the copepod *Calanus glacialis* to a dominance of the smaller copepod *Calanus finmarchicus* is probable under warmer conditions, as *C. finmarchicus* is favored by higher temperature while water temperatures  $>5^{\circ}\text{C}$  induce dormancy in *C. glacialis* (Hirche and Kosobokova, 2007). The smaller copepod pellet size may therefore reflect a dominance of *C. finmarchicus* during the warm anomaly. However, because fecal pellet size also varies with food concentration and composition (Turner, 2002; Ploug et al., 2008), the decrease in average fecal pellet sizes may instead have been caused by the near absence of large diatom cells during the 2005–2006 deployment period, and the cause for reduced fecal pellet sizes remains debatable. Because fecal pellet composition and size determine their sinking velocity (Ploug et al., 2008), smaller fecal pellets have lower sinking rates and are more easily retained in the upper water column, further contributing to the reduction of FPC fluxes during the warm anomaly.

An increase in bPSi and FPC export was observed in May 2007 when the water temperature was still anomalously high. For the first time since the start of the warm anomaly, ice cover persisted in the region above the sediment trap during April and May, presumably producing sufficient stratification to cause a short diatom bloom, or potentially releasing diatom resting spores and diatom cells in the water column (Michel et al., 1997; Róžańska et al., 2008). The increased bPSi and FPC fluxes in the presence of ice suggest that the absence of ice during the warm anomaly inhibited the export of diatoms and fecal pellets. A second increase in bPSi and FPC fluxes was observed before the end of the warm anomaly in September 2007 when ice was again present in the region, further stressing the importance of ice for the export of large phytoplankton cells and fecal pellets. Overall, the increased bPSi and FPC fluxes in May and September 2007 indicated that diatom and fecal pellet export returned to pre-anomaly conditions once ice cover was sufficient in the region, in accordance to the rapid recovery in phytoplankton size structure, biomass, and productivity observed following the onset of upwelling after the El Niño event (Iriarte and González, 2004; Kudela et al., 2006).

#### 4.3. After the warm anomaly

An increase in ice concentration when water temperature declined in spring 2008 also resulted in an increase in bPSi, FPC, and POC fluxes in May 2008. Although the warm anomaly period was at that time over, the magnitude and duration of the increase in bPSi and FPC export were similar to those observed during the previous spring when the water temperature was still anomalously high, further suggesting that the presence of ice had a larger influence on export fluxes than water temperature. The increased ice concentration and proportion of appendicularian fecal pellets at the end of April–beginning of May and at the end of May suggest the onset of an ice-edge eddy when the ice edge moved southward over the sampling area, similar to the eddy observed in June 2003. Daily ice concentration maps from April to July 2008 showed the intermittent presence of an ice-edge eddy in the vicinity of the sediment trap (data not shown), further indicating that ice-edge eddies are recurrent features in the region.

#### 4.4. Conclusions and implications

Long-term measurements of export fluxes in the eastern Fram Strait revealed a decrease in the export of large diatom cells during the warm anomaly period of 2005–2007. This suggests that the shift from a dominance of diatoms to a dominance of coccolithophores observed in 2005 at the beginning of the warm anomaly probably persisted for the rest of the warm period (Bauerfeind et al., 2009). Lower export fluxes of smaller zooplankton fecal pellets were also observed during the warm anomaly, either the result of the increase in water temperature inducing a shift in zooplankton community composition towards a dominance of small-sized zooplankton, or the effect of a shift in phytoplankton composition on grazing and fecal pellet production. These results are similar to the dominance of small-sized phytoplankton, lower diatom fluxes, and shift in zooplankton community composition observed during the 1997–1998 El Niño event (Escribano et al., 2004; Iriarte and González, 2004; Romero et al., 2001; Corwith and Wheeler, 2002; Harris et al., 2009). However, lower bPSi and FPC fluxes were not associated with reduced POC export in the eastern Fram Strait, as increases in POC fluxes were still observed during the warm anomaly. This indicates that the warm anomaly did not lead to intensified retention as expected by model predictions reported by Forest et al. (2010), but rather to a change in the composition of the material exported, with a larger proportion of unidentified POC being exported during the warm anomaly.

A few episodes of enhanced bPSi and FPC fluxes when sea ice was present during the warm anomaly indicated that the absence of ice cover was a key parameter inhibiting diatom and fecal pellet export in the eastern Fram Strait. The presence of ice cover promoted the export of bPSi, which subsequently increased FPC and POC fluxes and produced efficient export events, as is typical for diatom-dominated ecosystems (Boyd and Newton, 1999; Buesseler et al., 2007). The strong correlation obtained between bPSi and FPC fluxes ( $r = 0.832$ ,  $p < 0.01$ ) confirms that the presence of diatoms promoted the export of fecal pellets. Conversely, the export of bPSi was also enhanced by the export of diatom cells encapsulated into fecal pellets through grazing, an export mechanism also observed off northern Spitsbergen and in the Antarctic Polar Front region (Andreassen et al., 1996; Dagg et al., 2003). Overall, the rapid and frequent changes in the magnitude and composition of the export fluxes observed in the eastern Fram Strait confirm that long-term measurements are necessary to accurately monitor this changing ecosystem.

In addition to the 2005–2007 warm anomaly, another warm anomaly entered the Arctic Ocean through Fram Strait in 1999–2000, suggesting that these features are recurrent (Beszczynska-Möller et al., 2012). Furthermore, the mean temperature of the

Atlantic Water entering the Arctic Ocean increased at a rate of 0.06 °C/year from 1997 to 2010, implying that further warming may be expected, should the trend continue (Beszczynska-Möller et al., 2012). This inflow of warmer Atlantic Water is likely to contribute to increased sea ice melting west and north of Svalbard, although ice cover extent in this region is also governed by solar radiation and ice drift due to wind stress (Walczowski and Piechura, 2011). Indeed, higher southward ice drift velocities due to stronger geostrophic winds caused an increase in ice export in 2005–2008 in the Fram Strait (Smedsrud et al., 2008; Smedsrud et al., 2011). Therefore, whether or not the warm anomaly induced the decline in ice cover in 2005–2006, the reduced fluxes observed during this period represent changes to expect in Arctic ecosystems under warmer conditions. This could have important implications for benthic communities, as a change in the composition of the downward export of organic matter is likely to affect food supply to the benthic ecosystem (Klages et al., 2004; Wassmann et al., 2004; Grebmeier et al., 2006).

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