Bio-mooring arrays and long-term sediment traps: key tools to detect change in the biogeochemical and ecological functioning of Arctic marine ecosystems

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Summary

Through the transfer of carbon from the surface to the deep ocean via the passive sinking and active transport of organic material, the biological pump is a key global process for the regulation of atmospheric CO_2. Over the last decades, studies relying on sediment traps and other bio-devices moored over an annual cycle in the Arctic Ocean helped to resolve how the Arctic biological pump is operating and how it is responding to global change. Here, we provide a short review of the pioneer work done in the 1980-90's and we present key knowledge gained on Arctic ecosystem functioning with a series of case-studies conducted in the 2000's on the basis of bio-moorings: (1) carbon export in response to warm anomalies in the main Arctic gateway, the Fram Strait; (2) ecosystem-level analyses in Beaufort Sea from a vertical flux perspective; (3) the importance of lateral processes for sinking flux events in the Central Basin; and (4) the impact of zooplankton life-cycle strategies on the biological pump in fjord-like systems. We also identify regional challenges and potential future research avenues in terms of new sampling tools and coordination for the development of an Arctic biogeochemical observatory network aligned with global initiatives. As such, this paper represents a call to sustain and further develop observing activities that rely on bio-mooring arrays in the Arctic Ocean over the next decade. By capturing the full seasonality of ice-covered environments, we argue that bio-moorings are one of the most powerful approaches to distinguish natural variability from actual shifts that might affect the structure and function of Arctic marine ecosystems in response to human-induced changes.

1.0 Introduction

The biological pump is the process by which organic carbon derived from biological productivity in the surface ocean is transported to depth via both passive and active mechanisms (Figure 1). This downward export of organic material lowers the concentration of carbon dioxide (CO_2) at the sea surface and creates an indraft of carbon from the atmosphere to the ocean. Globally, this process is so important that if the biological carbon pump would stop, the concentration of atmospheric CO_2 would naturally more than double over a time-period of roughly 1000 years (Sigman and Hain, 2012). The two main engines of the biological pump are: (1) the passive flux of sinking particulate organic carbon (POC) typically comprised of phyto-debris, zooplankton detritus and marine snow aggregates (e.g. Sampei et al., 2004; Forest et al., 2008a; Lalande et al., 2011); and (2) the active vertical migration of zooplankton followed by subsequent egestion and respiration at depth (e.g. Berge et al., 2009; Darnis and Fortier, 2012). While the magnitude of primary production (PP) is dictated by the amount of available nutrients and light (Tremblay and Gagnon, 2009), the strength of the biological pump is further controlled by the plankton community composition and by trophic interactions within the lower food web (Forest et al., 2011; Reigstad et al., 2011). Studying the factors that drive the efficiency of the biological pump lies thus at the intersection of biogeochemistry and ecology. This is particularly true as vertical POC fluxes serve as the main food source for benthic organisms, which in turn typically leave a minor fraction of POC for burial and actual sequestration in the sediment.

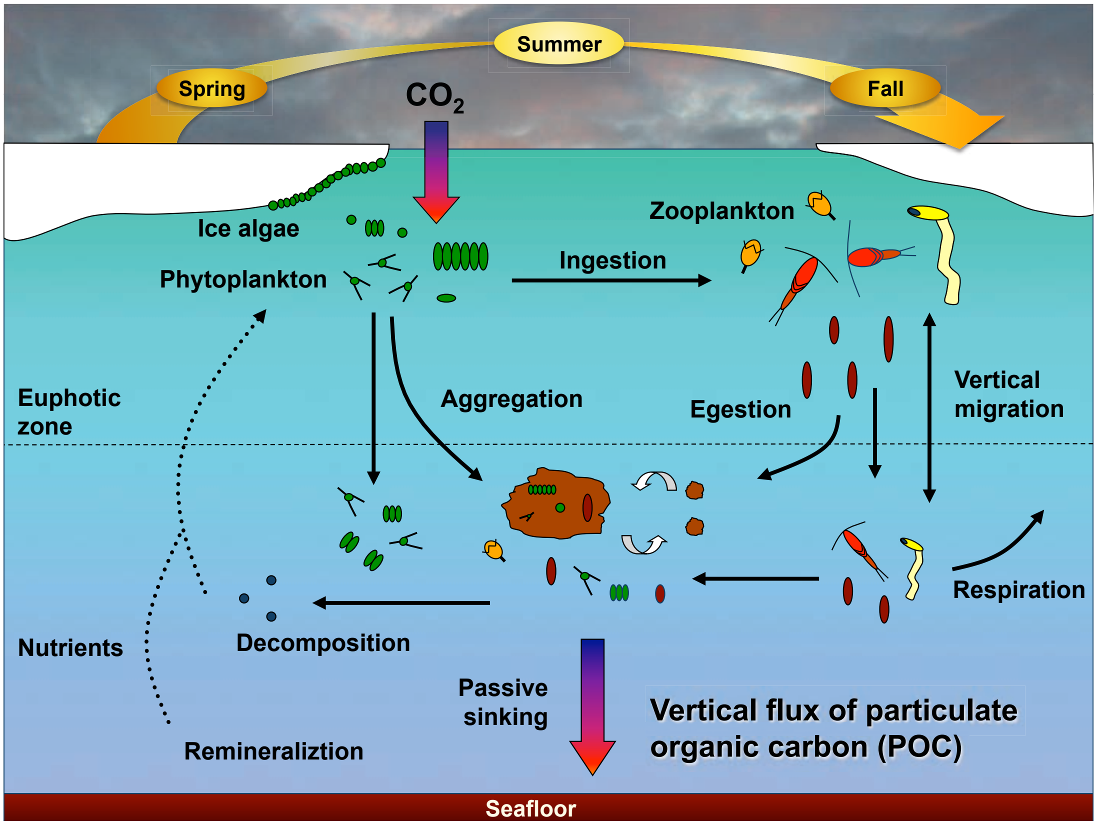

Figure 1. Simplified schematics of the processes that mediate the biological carbon pump in the Arctic Ocean. The two main processes discussed in this paper are: (1) the gravitational sinking of POC under the form of phyto-debris, zooplankton detritus and aggregates; and (2) the vertical migration of zooplankton that subsequently respire and egest carbon at depth. Figure adapted from Ducklow et al. (2001) and Wassmann et al. (2004).

Understanding how the biological pump in the Arctic Ocean responds to warming, sea ice reduction and increased terrigenous inputs is a critical issue for our comprehension of shifts in the Arctic marine realm and for the implications with respect to the global climate system. However, monitoring synoptically the biogeochemical and ecological factors that govern the biological pump in the Arctic Ocean over seasonal to multi-year time-scales is not an easy task. Remote sensing offers theoretically a powerful approach to measure the large-scale variability of PP and the potential export during the open-water period. But given that the cloud cover over the Arctic is intensifying (Stroeve et al., 2012; Bélanger et al., 2012), that PP might increasingly take place under a thin and ponded ice cover (Frey et al., 2011; Arrigo et al., 2012), and that the chlorophyll maximum appears to deepen in some areas (McLaughlin et al., 2010), it is obvious that a satellite-based approach could provide only a partial measure of the phenomena that will drive the future Arctic Ocean carbon cycle. Likewise, many studies speculated on the functioning of the Arctic biological pump on the basis of snapshot datasets obtained within a very limited time-window, typically the late summer period when nutrients are exhausted in the surface layer and when PP is low (e.g. Cai et al., 2010a, b; Jutterström and Anderson, 2010; Else et al., 2013). Such studies partly ignored the extreme seasonal variability of Arctic ecosystems and dismissed the transient export events that might be of key importance for particle transport from surface to depth (e.g. Reigstad et al., 2008; Lalande et al., 2009b; O'Brien et al., 2011; Sampei et al., 2012; Boetius et al., 2013). In fact, the reality of the biological pump in the Arctic Ocean is indeed one that could oscillate from extreme inefficiency to very high carbon export rates, depending on the location, depth and timing of flux collection (e.g. Yu et al., 2010; Nishino et al., 2010; Honjo et al., 2010; Forest et al., 2012; Gustafsson and Andersson, 2012; O'Brien et al., 2013).

A complete picture of carbon export in the Arctic Ocean can thus be only obtained through the deployment of *in situ* moored instruments that record the biological pump over the annual cycle. In a perfect observing system, these instruments would travel freely with ocean circulation under the ice cover in order to capture "lagrangially" the transport of carbon to depth (cf. Owens et al., 2013). However, such technologies do not exist yet for ice-covered seas and we still have to rely on fixed moorings (i.e. ice-tethered or bottom-anchored) to build-up annual time-series of vertical carbon export. As such, the primary tool to quantify and characterize the temporal variability of the biological pump remains the sequential sediment trap. Despite being affected by several methodological caveats (Buesseler et al., 2007), this device has proven to be a relatively low-cost and efficient sampling gear to capture the signal of the biological pump via the collection of sinking matter. Sediment traps are especially valuable when attached to a mooring line along with a suite of bio-optical sensors and acoustic recorders that can estimate, for instance, light and nutrient availability, algal and non-algal POC inventories, as well as zooplankton diel migration. Such integrated bio-mooring arrays are possibly the most complete detection systems that could be deployed in the Arctic Ocean with the aim of following fluctuations in physical forcing, plankton activity, carbon export and sediment transport, when accepting compromises with regard to spatial variability. Actually, we believe that they represent one of the most powerful approaches to distinguish natural variability from real trend or shift in Arctic marine ecosystem functioning over the current phase of rapid environmental changes.

This white paper represents a call from an "early career perspective" to sustain, develop and coordinate observing activities that will rely on bio-mooring arrays and long-term sediment traps in the Arctic over the next decade. We specifically aim at addressing three major objectives:

(1) To provide a short overview of the pioneer work related to sequential sediment traps and biological pump monitoring conducted across the Arctic Ocean (defined as the area above 66°N) during the decades of the 1980's and 1990's;
(2) To present key knowledge gained on Arctic ecosystem functioning through a suite of case-studies on the passive and active downward carbon export measured with mooring arrays equipped with sediment traps and bio-sensors over the 2000's;
(3) To identify geographical gaps and propose new research avenues in terms of coordination and novel sampling tools and analyses for the development of an Arctic biogeochemical observatory network aligned with global initiatives.

2.0 Early deployments of particle-interceptor traps in the Arctic Ocean

Pioneer works on sinking particle fluxes recorded with sequential sediment traps moored in the Arctic during the 1980's include Hargrave et al. (1994), Bauerfeind et al. (1994) and Bodungen et al. (1995) – conducted, respectively, off Axel Heiberg Island north of the Canadian Arctic Archipelago, and in the Norwegian and Greenland seas. Those three studies provided evidence for the important role of zooplankton-phytoplankton interactions in shaping the magnitude and timing of the major export flux events. Interestingly, they also illustrated the influence of resuspension (lithogenic particles) and across-slope lateral transport in punctuating at times the nature of sinking material.

Early deployments of moored traps were also done within the framework of the Northern Oil and Gas Action Plan (NOGAP, 1987-88) across the Mackenzie Shelf (Beaufort Sea). From this project, Forbes et al. (1992) evaluated the zooplankton swimmer composition of trap samples and found a close relationship between the pteropod *Limacina helicina* and the variability in sea ice coverage. Two decades later, O'Brien et al. (2006, 2011, 2013) published a series of thorough geochemical analyses conducted on sinking particles collected within NOGAP, and related them to their full hydrographical and climatic context. This suite of key papers represents a major advancement in our understanding of sediment dynamics in river-influenced Arctic shelf systems. In particular, these were among the first studies to document the episodic transport of particles beyond the shelf edge and toward the basin within bottom and mid-water nepheloid layers, as well as through eddies, upwelling-downwelling flows and other dynamic ocean features.

Over the 1990's, time-series sediment trap experiments have been carried out though numerous research projects/groups such the Northeast Water Polynya (NEW, 1992-93), the Polarstern Expeditions of the Alfred Wegener Institute for Polar and Marine Research (AWI, 1994-96), the Ice Ocean Environmental Buoy (IOEB, 1996-98), and the International North Water Study (NOW, 1997-99).

From the NEW project, two companion papers have been published. Ramseier et al. (1997) and Bauerfeind et al. (1997) made a link between the ice cover and the seasonal variability of vertical particle fluxes. In particular, they showed the significant contribution of houses and feces of appendicularians to total POC flux in that so-called NEW polynya that appears to be affected by a steady decline in its extent since the 1990's and is almost non-existent since 2007.

From the AWI expeditions, Fahl and Nöthig (2007) investigated the seasonal variability of lithogenic matter, $CaCO_3$, opal and POC fluxes at the almost permanently ice-covered slope of the Lomonosov Ridge. They pointed out the importance of sediment input from the Laptev Sea for the sediment accumulation on the Lomonosov Ridge on geological time scales. Using a similar suite of analyses, Bauerfeind et al. (2005) characterized the content of sediment traps samples collected over the Greenland Shelf and confirmed that the environmental setting of this region favors the formation of organic–mineral aggregates during spring and summer.

From the IOEB project, Hwang et al. (2008) and the review paper of Honjo et al. (2010) characterized the variability of under-ice vertical fluxes using ice-tethered moorings deployed in the Canada Basin and Chukchi Rise, with an emphasis on lithogenic matter, aluminum fraction, organic content, and POC radiocarbon signature. The main result from this deployment was to confirm that the vertical POC flux at 120 m was very low (~0.1 g C m^{-2} yr^{-1}) while the POC flux at 3067 m depth measured a few years later was ~40 % higher than that at 120 m depth at a close location. These results set the stage for a further in-depth analysis of the linkages between the lateral transport of material from the margins and the deep flux in the central Arctic basins.

From the NOW project, three papers have been published: Hargrave et al. (2002) and Sampei et al. (2002) presented for the first time the temporal and spatial variability of vertical particle fluxes in a region still considered as one of the most productive areas of the Arctic Ocean. The full suite of geochemical and microscopic analyses (fecal pellets, phytoplankton cells) conducted on the trap samples collected in NOW suggested an important spatial redistribution of particles due to advection. As seen in other coastal Arctic systems, sediment resuspension and lateral transport of fragmented sinking particles were subjected to pelagic remineralization processes. In a second-level analysis, Sampei et al. (2004) estimated the retention of surface POC by combining measurements of fecal pellets flux, *in vitro* fecal pellets production rates and data on the zooplankton community structure. These analyses suggested that retention processes due to coprophagous feeding behaviors of zooplankton (i.e. fragmentation process on fecal pellets) were important in the control of the magnitude of POC fluxes.

All the above studies on vertical fluxes conducted in the 1980-90's (with many more described in Wassmann et al., 2004) were of relatively short durations (≤2 years), but can be seen as the only baseline information that we have on the biological carbon pump in the Arctic Ocean prior to the rapid changes that occurred over the last 15 years (with the exception of paleo-proxies). Data from these projects are now stored into numerical archives and their usage should be maximized with the aim of benchmarking the current phenomena (e.g. shifts in biological productivity, increase in resuspension) that are linked to the impact of global warming on the Arctic Ocean, as generally done within the recent case-studies presented in the next section.

3.0 Case studies from the last decade: challenges, pitfalls and key advancements

3.1 Arctic-Subarctic connections: particulate carbon fluxes across gateways

As the Arctic Ocean is rapidly changing due to climate warming, some key areas to monitor are the major gateways between the Arctic and Subarctic ecosystems. The HAUSGARTEN observatory, located in the eastern Fram Strait approximately 120 km west of Spitsbergen, has been maintained by AWI for more than a decade (Soltwedel et al. 2005). Long-term sediment traps have collected sinking particles in this gateway between the Atlantic Ocean and the Arctic Ocean since 2000, providing the longest time-series of export flux measurements for an Arctic marine ecosystem. This unique long-term dataset allowed us to gain important knowledge on the potential impact of climate warming on the biological pump due to the fortuitous deployment of sediment traps before, during, and after an anomalously warm Atlantic Water inflow observed from 2005 to 2007 in the eastern Fram Strait (Figure 2).

During the 2005-2007 warm anomaly period, a decrease in the export of biogenic particulate silica (bPSi), a proxy for diatoms, reflected a shift from a dominance of large diatoms to a dominance of coccolithophores in the export fluxes (Bauerfeind et al., 2009; Lalande et al., 2013). In addition to the export of smaller phytoplankton cells, 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 zooplankton grazing and fecal pellet production (Lalande et al., 2013). A few episodes of enhanced bPSi and fecal pellet fluxes when sea ice was present during the warm anomaly indicated that the absence of ice was a key parameter inhibiting diatom and fecal pellet export in the eastern Fram Strait. The presence of ice promoted the export of bPSi, which subsequently increased fecal pellets and POC fluxes and produced efficient export events. The similar amounts of POC exported at ~200 m before, during, and after the warm anomaly period indicate that the warm conditions did not cause intensified retention in the eastern Fram Strait, but rather a change in the composition of the material exported (Lalande et al., 2013). Overall, the export of smaller phytoplankton cells and smaller zooplankton fecal pellets observed during the warm anomaly period in the eastern Fram Strait represent changes to expect in Arctic ecosystems under warmer conditions and could have important implications for the biological pump of the Arctic Ocean.

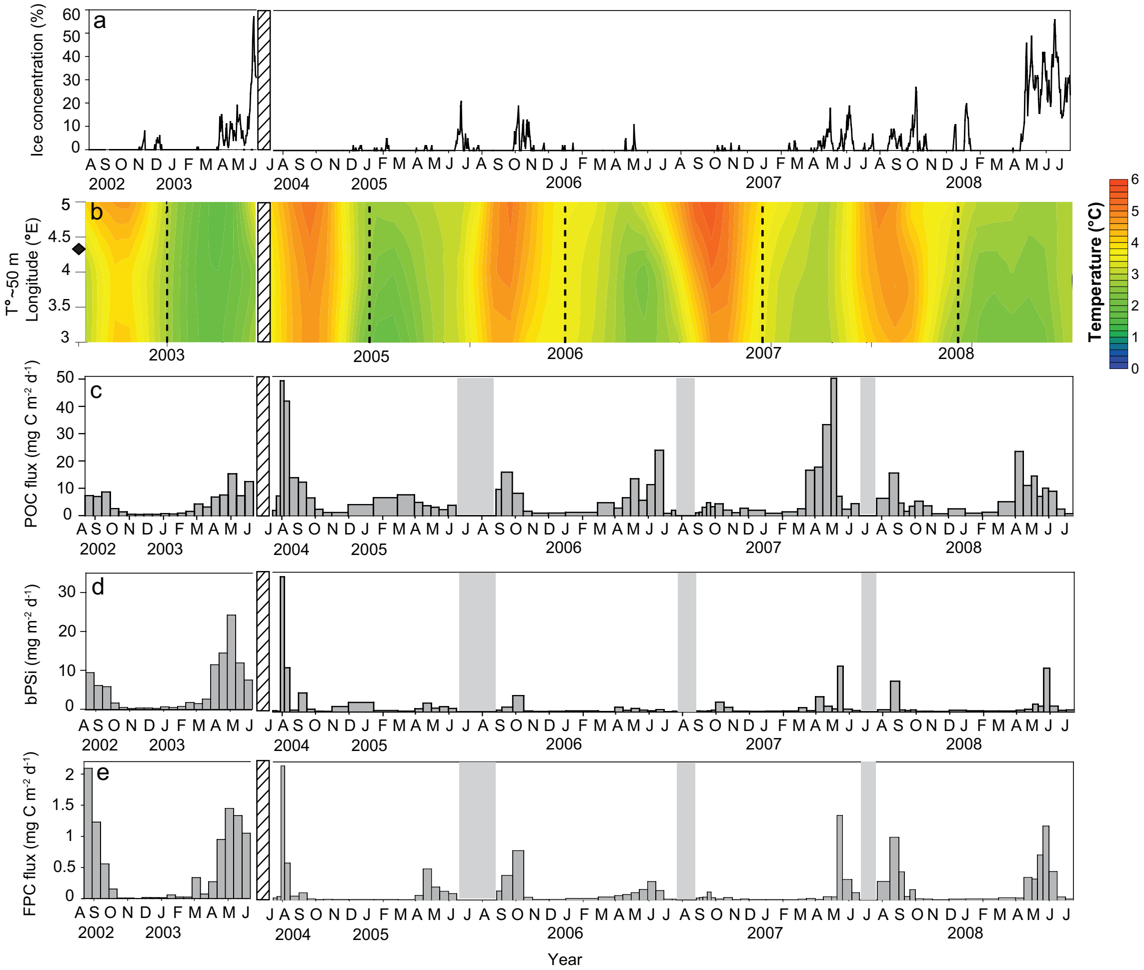

Figure 2. (a) Satellite-derived daily sea ice concentration averaged over the sampling region (78°30–79°30 N; 2°30–6°30 E), (b) Hovmöller diagram of monthly averaged water temperature measured at ~50 m, (c) POC fluxes, (d) bPSi fluxes, and (e) FPC fluxes obtained from August 2002 to June 2003 and from 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. Adapted from Lalande et al. (2013).

The additional deployment of a sediment trap at high temporal resolution at the HAUSGARTEN observatory revealed that the onset of a cyclonic ice-edge eddy, a common feature along the ice edge in the Fram Strait, caused a rapid shift in the composition of the export fluxes due to the advection of warm Atlantic Water (Lalande et al., 2011). These results confirm that warmer conditions affect the biological pump in Arctic waters.

The changes in the magnitude and composition of the export fluxes recently observed at the HAUSGARTEN observatory confirm that long-term measurements are necessary to accurately monitor this rapidly changing ecosystem. Similar long-term observatories are urgently needed in other Arctic gateways to improve our understanding of the impact of climate change on Arctic marine ecosystems. Long-term measurements of export fluxes are particularly required in the Bering Strait to monitor the influence of the Pacific Water inflow on the biological pump and to evaluate if similar changes in the composition of the material exported also occur under warmer conditions in this region.

3.2 Ecosystem-level analyses on Arctic shelves from a vertical flux perspective

Roughly 85% of the PP in the Arctic Ocean takes place over shallow shelves (<200 m depth), which account for about 55% of the Arctic Ocean area (Stein and Macdonald, 2004). As such, Arctic shelves represent a perfect setting to investigate ecosystem structure and function on the basis of long-term trap data. The analysis of trap samples acquired on Arctic shelves and in their periphery is not an easy work. In these regions, the heterogeneity of sinking particles and the variability in their total mass over a 1-year cycle is simply tremendous. Episodic sinking of ice algae and filamentous phyto-aggregates, fecal pellets of different shapes, sizes and degradation states, presence of unidentifiable mucous material, resuspended matter from the seafloor, fine particles coming from intermediate nepheloid layers, and sometimes an enormous quantity of zooplankton swimmers, are all examples of what can be found in traps deployed in shallow waters. This nevertheless provides a wide-open window on the complex physical and biological processes occurring in coastal Arctic systems. Tedious geochemical and microscopic analyses are needed to quantify the various POC flux components. And ancillary data are necessary to explain the hydrographical and ecological reasons behind their variability. As a result, very few studies have undertaken so far exhaustive analyses combining all those elements.

The Canadian Arctic Shelf Exchange Study (CASES) 2003-2004 in the Beaufort Sea provided the opportunity to document for the first time the seasonal variability of downward POC fluxes within a full ecosystem framework. Results from CASES are primarily summarized in Forest et al. (2007, 2008a) and Sampei et al. (2009b, 2011). The key knowledge gained there was the development of a conceptual model of the biological pump across the shelf-slope interface that would operate via two alternative modes (Figure 3). The first mode dominates in spring-summer when autochthonous processes derived from PP and herbivorous food web activities foster labile POC fluxes. The top-down control of POC fluxes by heterotrophs during this period is usually strong, but high POC fluxes associated with upwelling-favorable conditions and ice-edge areas can be at times measured. The second mode operates mainly in fall-winter, as a consequence of thermohaline convection, wind stress, downwelling, current surges, and eddies, that develop during episodes of autumnal storms, phases of ice growth and under ice cover. In these periods, increases in vertical POC fluxes are indeed observed and are associated with the resuspension of shelf sediments and the advection of both terrigenous and marine particles from the benthic layer. Hence, the displacement of marine carbon from the shelf to the deep basin is an unsuspected mechanism by which the Arctic biological pump operates during the polar night.

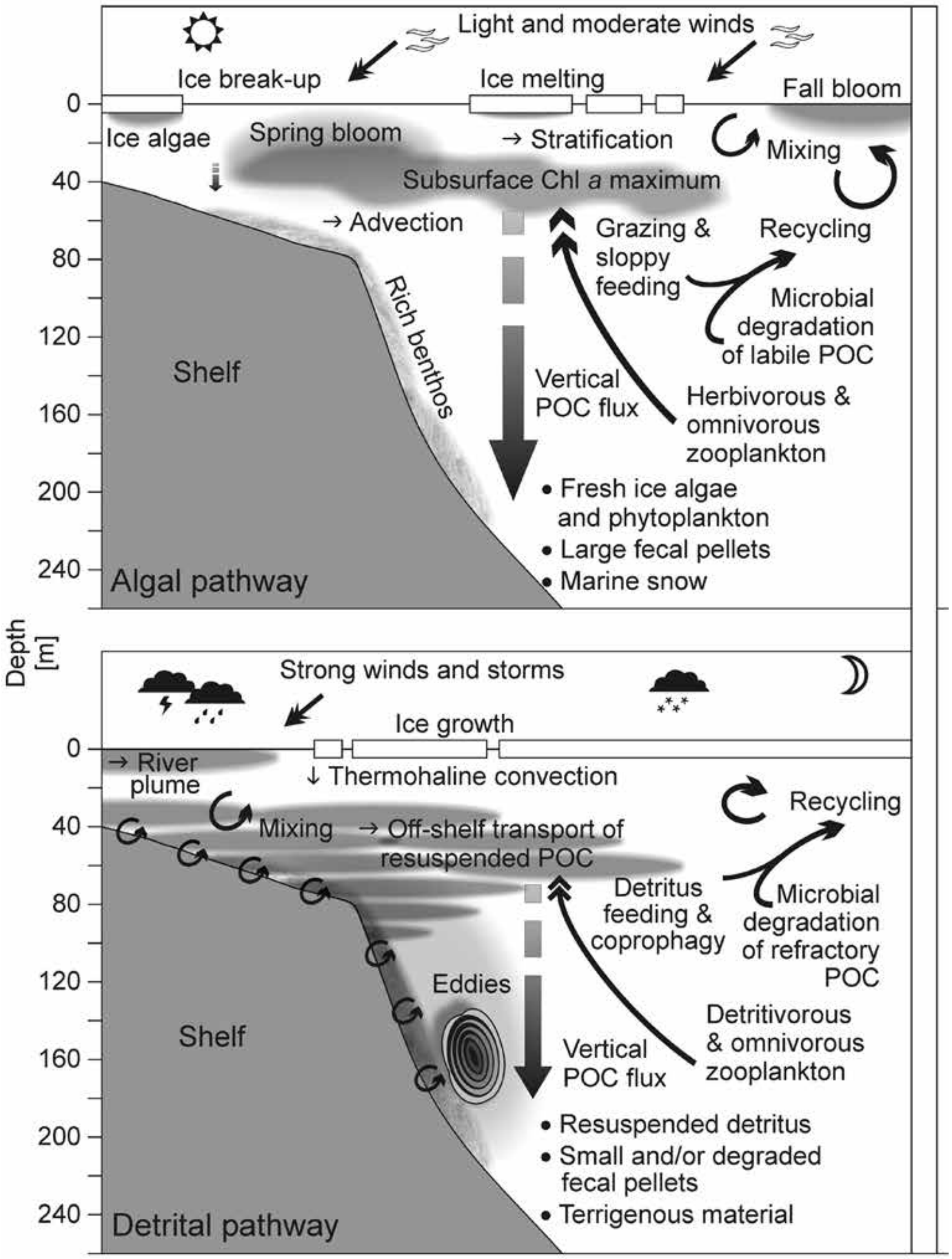

Figure 3. The double nature of the biological pump functioning in the Arctic Ocean. Top panel: the traditional "algal pathway" that dominates in spring-summer and which proceeds following PP and herbivorous food web activities (cf. Figure 1). Lower panel: the lateral pumping of resuspended POC (marine and terrigenous) from the shelf to the basin ("detrital pathway") that dominates mainly in fall-winter under the forcing of downwelling flows (windstorms), brine rejection and cascading of particle-rich dense water across the slope, and subsurface eddies with increased particle concentration that propagate under ice cover. Figure adapted from Forest et al. (2008a).

More recently, sediment trap datasets, still being collected in the Beaufort Sea as part of ArcticNet, were used in further ecosystem-level analyses. First, a synthesis of the planktonic food web structure and function in the Amundsen Gulf in 2008 used the downward export measured with a long-term sediment trap at ~100 m depth to constrain an inverse model of biogenic carbon flows (Forest et al., 2011). This analysis confirmed that the ongoing decline in Arctic sea ice might promote the growth of pelagic communities, but is unlikely to increase enough the productivity of the lower food web to support new harvestable fishery resources in the offshore domain. These results illustrated also that the pelagic food web might overall benefit from sea ice decline at the expense of the short-term biological pumping of CO_2, but uncertainty regarding this hypothesis remains large. In a subsequent work, Forest et al. (2012) conducted an integrative analysis of the spatial variability and biophysical determinants of vertical POC fluxes across the Mackenzie Shelf in 2009. This multivariate analysis has been performed on the basis of a geospatial model of downward POC fluxes constructed by combining sediment trap data with the size-distribution of particles (17 classes from 0.08-4.2 mm) measured by an underwater particle camera. This work demonstrated convincingly that vertical POC fluxes across the Arctic shelf system are patchy and determined by both environmental forcings and food web function. It further provided a robust case study to demonstrate how mooring-based measurements can be used in statistical analyses in order to extract the backbone information from the multiple and often heterogeneous datasets collected over an oceanographic campaign.

3.3 The Arctic lateral biological pump: insights from the Central Arctic Basin

Dynamics of particle fluxes in the marginal ice zone (MIZ) of the deep Arctic basins is far less well studied compared with the continental margins. Two methods of sediment trap mooring have been used to collect sinking particles in the central basins. Two sediment traps tethered to floating sea ice collected samples at relatively shallow depths (120 m and 200 m) while they were hovering with the drifting ice in the Canada Basin and at the Chukchi Rise in 1996-1998 as part of the IOEB program (see section 2.0 and details in Honjo et al., 2010). In 2004-2005, a bottom-anchored mooring equipped with a sediment trap was deployed in the deep Canada Basin (St. A, 75°N, 150°W; bottom depth 3824 m, trap depth 3067 m) enabling the collection of sinking particles at the deepest depth ever sampled by a sediment trap across the Arctic basins (Hwang et al., 2008). This trap was deployed on a hydrographic mooring operated by the Beaufort Gyre Exploration Project (Proshutinsky et al., 2009) for a year in the MIZ of the Canada Basin. Later on in 2007, the program extended its temporal and spatial coverage and included three traps on a mooring at St. A and one trap each at two more stations (78°N, 150°W, 74°N, 140°W) (Hwang et al., in prep.). The analysis of particles collected by the various traps deployed in the basin environment revealed the unique characteristics of the organic carbon cycling and biological pump system in this "cryopelagic" environment (Honjo et al., 2010). In brief, the efficiency of the biological pump in the Canada Basin was very low and sinking material in the deep ocean interior was dominated by the lateral supply of aged POC (Figure 4).

Furthermore, the POC flux to the deep trap did not reflect the temporal variation in biological production in the surface water. Surprisingly, the highest particle fluxes were observed mainly in winter when the surface was covered with sea ice (Figure 4). Radiocarbon analysis of sinking POC revealed that the freshly-produced POC presumably settling from the overlying water column accounted for a substantial fraction of the downward flux only in summer when absolute values in POC fluxes were extremely small. The average radiocarbon content of sinking POC expressed in $\Delta^{14}C$ was –217 ‰ (equivalent to an apparent ^{14}C age of ~1900 years) indicating that the organic matter was already very old when incorporated into sinking particles in the central Arctic. Prevalence of aged POC in the deep interior of the Canada Basin was also observed for suspended POC even in summer (Griffith et al., 2011). Such dominance of old POC in the water column has many implications for the bottom dwelling suspension feeders and deep benthos, such as for food quality and selective uptake and/or digestion (Purinton et al., 2008).

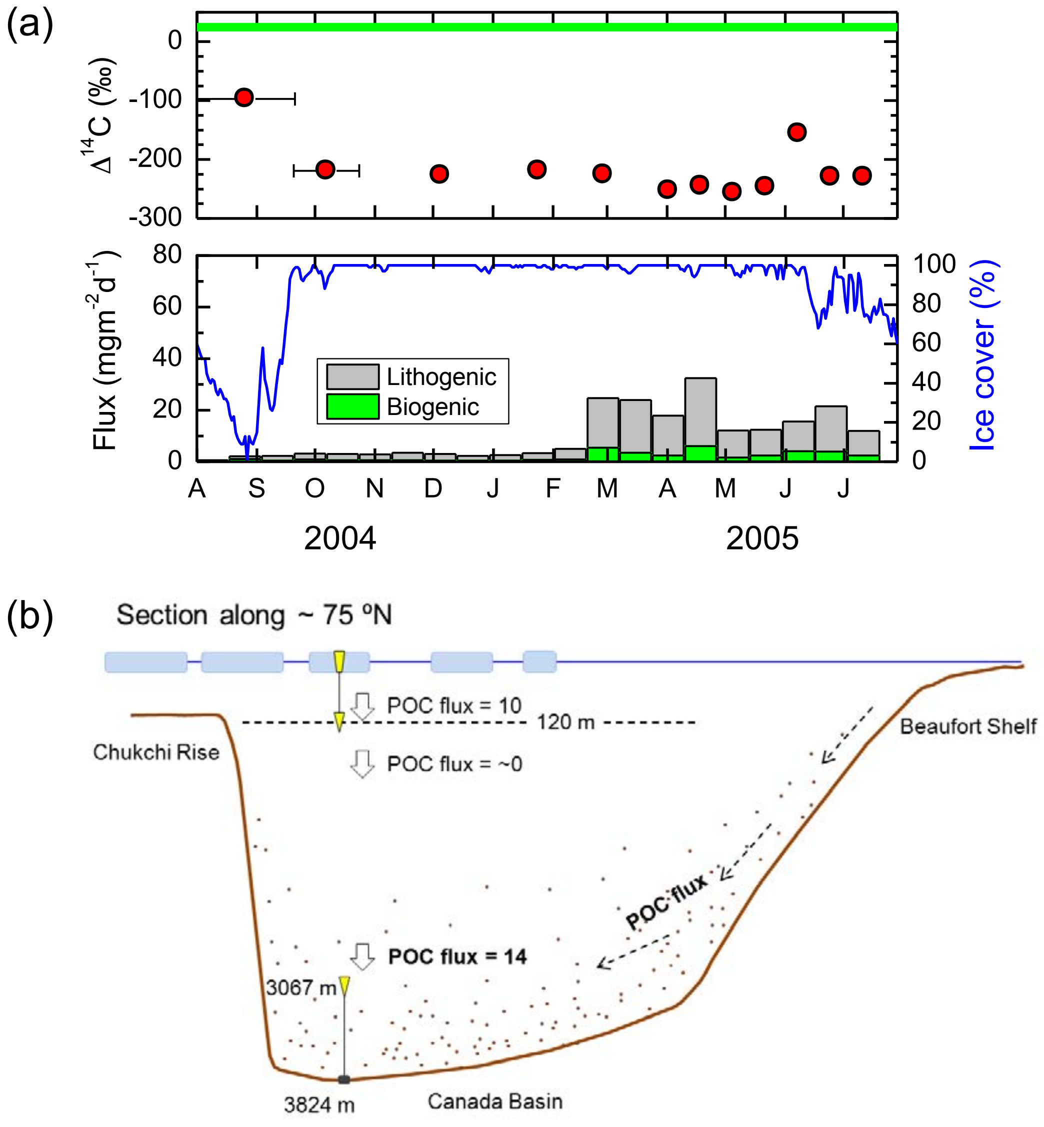

Figure 4. (a) Particle flux to the 3067 m trap at Station A in the central Canada Basin, and the corresponding $\Delta^{14}C$ values of sinking POC and ice concentration (modified from Hwang et al., 2008). The horizontal bar denotes a presumed $\Delta^{14}C$ value of freshly produced POC. (b) A schematic diagram of POC cycling (values are in mmol C m^{-2} yr^{-1}) in the Canada Basin that further illustrates the importance of lateral processes in driving the flux of sinking particles in the deep basins (modified from Honjo et al., 2010).

The vertical position of the trap (~800 m above bottom) and the lack of strong currents that could induce the local resuspension of bottom material into the trap pointed toward a long-distance transport of fine particles from the surrounding margins to explain the observations (Hwang et al., 2008). However, provenance of the laterally supplied particles and mode of transport to the deep interior of the Canada Basin begin only to be understood. A narrow range of $\delta^{13}C$ and C:N ratios in sinking particles during the high flux periods imply that the particles are not likely to have originated from several locations (Honjo et al., 2010). Studies of biomarkers (Belicka et al., 2004; Yunker et al., 2005) and clay mineralogy (Darby et al., 2011) may shed light on revealing their origin (e.g., marine vs. terrestrial). The apparent correlation between high particle flux and the northward current direction implies that once fine particles are resuspended on the margin, they are transported along the northward current, a part of the Beaufort Gyre. Preliminary data at three depths at St. A (nominally, 2000, 3000, and 3800 m) showed higher particle flux at the deepest traps, implying that particles were transported along the sea floor in clouds whose thickness was such that they influenced the 1000 m trap as well (Hwang et al., in prep.). Possible mechanism for shelf-basin export are the eddies shed from the Beaufort shelf (Mathis et al., 2007; Spall et al., 2008; O'Brien et al., 2011, 2013), but it is not certain whether these eddies are actually capable of transporting particles over extended periods. Another process might be the cascading of dense water created by brine rejection during ice growth over the shelf and that could entrain particles obliquely along the slope (Forest et al., 2007, 2008b; Pasqual et al., 2010). Further work is utterly needed to elucidate the role of eddies, cascading water and other downwelling flows in carrying particles from the Arctic shelf to the deep central basins.

Currently, the biological pump does not appear to operate efficiently in the cryopelagic Canada Basin (Figure 4). Honjo et al. (2010) hypothesized that the retreat of sea ice in summer would not immediately result in enhanced PP in the region newly exposed to the atmosphere. Consistently, low biological productivity in summer was reported for such scenario in the central Canada Basin (Cai et al., 2010b). As the summer retreat of sea ice becomes a routine phenomenon in the central Canada Basin, the physical environment may change and thus the interplay between wind-driven mixing, freshwater content, nutrient supply, and light availability. In this context, it is obvious that sediment traps can diagnose the effect of environmental changes on ecosystem structure and productivity. Continued monitoring of particle fluxes in this sensitive region over the next decade will be essential to detect any significant trend in the functioning of the biological pump system. In addition, analyses of biogeochemical properties of sinking particles such as radiocarbon of POC will provide critical information whether the enhanced summer time POC flux (if it happens) is derived from fresh PP or from the lateral advection of old refractory particles.

3.4 The impact of zooplankton life-cycle strategies on the Arctic biological pump

Diel vertical migration (DVM) of zooplankton is a characteristic feature of the world's oceans and lakes, and has been claimed to be the largest synchronized movement of biomass on the planet (Hays, 2003). Since the phenomenon was first detected almost two centuries ago in 1817 (Cuvier, 1834), there have been numerous studies into both the adaptive significance of this behavior and the ecosystem consequences (for two reviews, see Hays, 2003 and Ringelberg, 2010). Research on DVM has focused both on the proximate and the ultimate explanations of the behavior (e.g. Lampert 1989; Ohman, 1990), as well as implications to the ecosystem regarding trophic interactions and the biological pump of carbon (e.g. Buesseler et al., 2008). A migration of animals to the surface layer at night allows zooplankton to feed in food-rich waters with reduced likelihood of detection by visual predators (predator-avoidance hypothesis), whereas during daytime they seek refuge in the darkness of the deep (see references above). Vertical migration of zooplankton enhances downward transport of organic and inorganic carbon through fecal pellet production at depth and decoupling of grazing and respiration. This phenomenon has successfully been studied using a combination of moored acoustical instruments and sediment traps. Acoustics have the potential to detect migrating organisms on a daily basis, whereas, by capturing the descending biomass over seasons, sediment traps have proven to be useful over annual time-scales. In a series of papers (Cottier et al., 2006; Willis et al., 2006, 2007) from Kongsfjorden on Svalbard (Norway, 78°N), a combination of moored sediment traps and acoustics (ADCPs) were used to study bio-physical coupling processes, demonstrating e.g. the impact of advection on local zooplankton communities in the fjord throughout the year.

Marine ecosystem processes are direct consequences of the complex behaviors and interactions between organisms, many of which are driven by the physical environment. Accordingly, the classic paradigm of Arctic marine ecology suggests that most biological processes stop during the polar night at high latitudes due to low food availability and the lack of light (Smetacek, 2005; Piepenburg, 2005). Recently research carried out in the Svalbard archipelago using moored arrays of acoustics and sediment traps challenged this assumption by presenting evidence of both active and synchronized diel vertical migration (DVM) of zooplankton during the polar night (Berge et al., 2009, Figure 5). Although the human eye perceives the polar night at these latitudes as being continuous and characterized by total darkness, the new data indicate that Arctic zooplankton nevertheless respond to variations in the very low light levels. This unexpected behavior under the extreme conditions of the Arctic winter challenges our fundamental understanding of sensory capabilities of high latitude fauna, and suggests potentially significant consequences of this finding (Søreide et al., 2010). Furthermore, a study (Wallace et al., 2010) based on two complete years of moored acoustic data (2006-08) from two Arctic fjords in the Svalbard archipelago reported a continuous signal in zooplankton vertical migration that had strong variations in characteristics between both seasons and the two fjords. These findings included very strong and fully synchronized vertical migration signals during polar twilight (October/November –March/April). Based on this, they concluded that current reduction of Arctic sea ice (Stroeve et al., 2012) is likely to have an indirect, but substantial, impact on zooplankton vertical migration and the associated vertical carbon flux.

DVM is not the only one intricate process by which zooplankton contribute positively to the biological carbon pump. Two recent studies have pointed out that the sinking of intact copepod carcasses (i.e. copepods died recently in the water column before sinking into the trap) can contribute substantially to vertical POC fluxes (Sampei et al. 2009a, Sampei et al. 2012). The carcass flux is a grossly ignored component of the POC flux, resulting in the underestimation of the total POC flux. The contribution of dead copepods to the annual export POC flux can be significant (up to 36%) from the surface mixed layer (Sampei et al., 2009a; Sampei et al., 2012). Those studies also indicated that a peak in carcass POC flux (equivalent to the POC flux in the productive spring-summer period) could recurrently occur during winter due to the massive death of large female calanoid copepods after spawning in February. Since these copepod carcasses are suspected to be rich in lipid content, this POC flux potentially represents a major food/substrate for heterotrophs to sustain their activity in the water column during winter (Sampei et al., 2012).

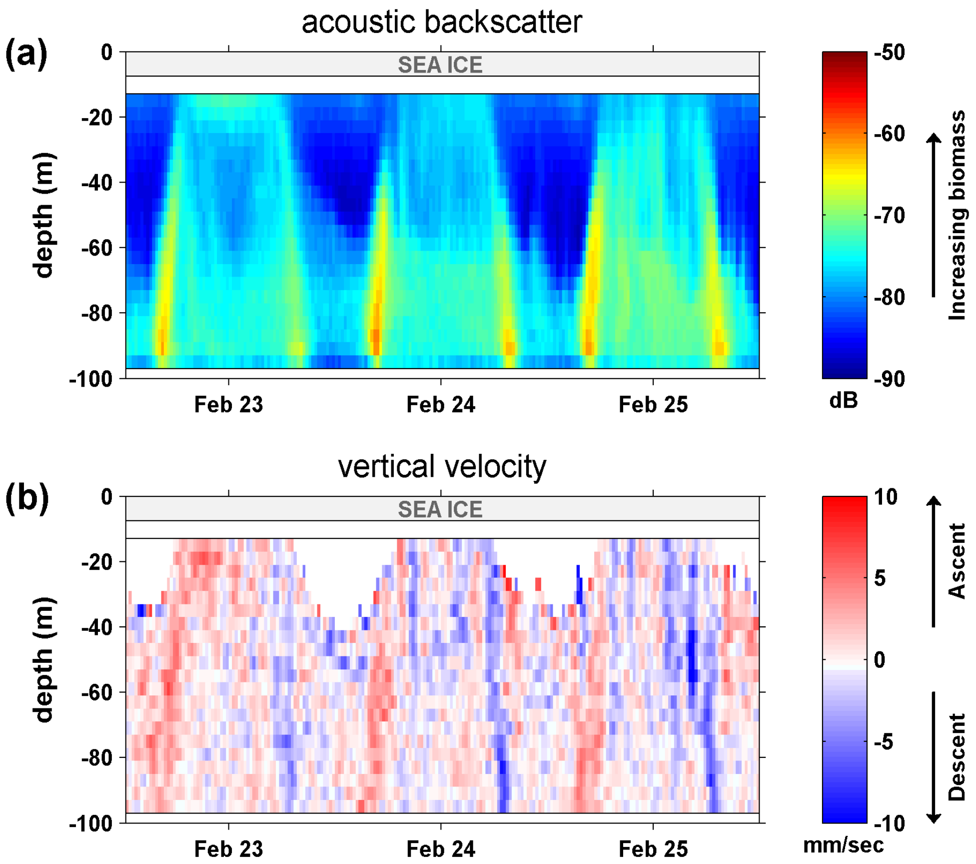

Figure 5. Acoustically detected DVM signal in the water column from Rijpfjorden (Svalbard, at 80°N) in February 2007 (a) backscatter (Sv values) recalculated as biomass following Cottier et al. 2006: warmer colours (red) indicate higher biomass (b) vertical velocity: warmer (red) colours upward movements, colder (blue) downwards movements of biomass in the water column. During this period the sun is about to reach above the horizon, but the fjord was covered by up to 1m of ice and snow. Measurements later in the season revealed that less than 1% of the available light penetrated through the ice and snow, leaving the underlying water column in a twilight state long into the spring.

4.0 Recommendations for future research avenues

4.1 Geographical gaps and logistical constraints of bio-mooring deployments

As described above, bio-mooring arrays equipped with sediment traps have been deployed so far in the Fram Strait, at numerous locations across the Canadian Archipelago, in the southeast Beaufort Sea, over some areas of the outer Eurasian shelves, in the deep Canada Basin, and in a few fjords of Svalbard. However, all of these regions, with the noteworthy exception of Fram Strait, have suffered from multiple setbacks in the maintenance of time-series over the last decades. They nonetheless constitute a rich and unique data collection upon which scientific papers and syntheses can be elaborated for years to come. Already, repeated measurements over the multi-annual time-scale in these regions have provided evidence for change in ecosystem functioning (e.g. Lalande et al., 2009b; Forest et al., 2010). However, although the time-series acquired until now provided insights into the state of the Arctic biological pump (Honjo et al., 2010), some critical anthropogenic impacts on the Arctic marine carbon cycle (e.g. acidification) will still take a few decades to fully emerge. On the one hand, this underscores the need to sustain bio-mooring observatories in the areas where precious historical datasets have been stowed in the form of numerical archives. This is not a simple task, as changes in the physical environment have the possibility to hinder the sustainment of moored observatories. For example, the major effort to moor instruments in Northern Baffin Bay in the mid 2000's as a follow-up to the NOW project (Lalande et al., 2009a) were stopped by massive equipment losses due to a possible increase in iceberg concentration nearby Greenland. On the other hand, this leaves place for further expansion of bio-mooring arrays and targeted sampling of the biological pump, such as in the Makarov and Eurasian basins (as suggested by Nishino et al., 2010), in the Chukchi Sea and Bering Strait (cf. section 3.1), or all through the European and Siberian Arctic shelves – although deploying moorings in the Barents Sea is challenging and risky due to the intensive trawling and ship-traffic in this area (M. Reigstad, pers. com.). Nevertheless, those are key areas to investigate if we truly are to understand and anticipate seasonal and inter-annual changes in biogeochemical cycling and biological pump functioning in response to a warmer and ice-less Arctic Ocean.

Fortunately, efforts in that direction are taking place. A mooring equipped with sediment traps has been successively deployed and recovered over 2011-12 in the Northwind Abyssal Plain off the Chukchi plateau as part of the JAMSTEC program conducted in the framework of the Japanese-lead Green Network of Excellence (JAMSTEC, 2013). This array has been expanded in 2012 with the addition of one trap mooring in the Chukchi Abyssal Plain with the goal of providing dataset to validate 3D biogeochemical models in addition of monitoring sinking fluxes. On the Eurasian margin, long-term sediment traps were deployed in summer 2012 on both sides of the Gakkel Ridge by AWI with the aim of monitoring export fluxes in the Amundsen and Nansen Basins. Due to the remoteness of these locations, it is logistically impossible for the moment to maintain an observatory in this region. However, it would be important for the community to plan for additional deployments at the same locations to better understand changes occurring with the rapid sea ice decline in the central Arctic Ocean. Additionally, AWI sediment traps will be deployed in summer 2013 on the western side of the Fram Strait to monitor ocean circulation and carbon fluxes in the region where most of the sea ice is drifting out of the Arctic Ocean. The mooring will be maintained for 2 years as part of the German-Russian TRANSDRIFT project to investigate long-term changes in the transpolar system of the Arctic Ocean. Although this is a promising start, longer-term measurements are needed to accurately observe the impact of climate change on Arctic marine ecosystems.

4.2 New observational tools and modelling to track biological pump processes

This review has yet focused on sediment traps and ADCPs to provide information on the magnitude and nature of biological pump mechanisms. New ocean technologies developed for the global ocean are being adapted for ice-covered areas. This is the case for ice-tethered profilers (http://www.whoi.edu/itp), the Arctic equivalent of the Argo floats that measure worldwide basic seawater properties (temperature, salinity, depth) in quasi-real-time. However, biogeochemical properties of the ocean are much more complicated to acquire, as exemplified by the logistical and financial challenges related with the implementation of bio-optical sensors within the global Argo float. Obviously, these issues are multiplied in the Arctic Ocean, for reasons such as the remoteness of the deployment area, the presence of a dynamic ice cover, and near-zero water temperatures that lower the battery efficiency of any autonomous platforms. Hence, it is easy to understand that for the Arctic Ocean, we are far from being able to initiate long-lasting particle flux time-series with instruments like neutrally buoyant sediment traps (e.g. Buesseler et al., 2008; Owens et al., 2013). Nevertheless, the “classic” mooring arrays that are being deployed in the Arctic can be equipped with innovative instruments that would supplement measurements of sinking particles by sediment traps and of other useful variables for carbon flux studies.

Perfect examples of this complementarity are the optical instruments able to measure the size distribution of particles in spaced size-classes. On the lower end of the size-spectrum, the Laser In-Situ Scattering and Transmissometry (LISST; http://www.sequoiasci.com/) is a multi-parameter system capable of measuring particle size-distribution from ~1 to 500 µm. Such instruments represent a powerful approach to measure fine particles propagating horizontally from shallow shelf areas to the deep basins, especially across topographic discontinuities that could favor lateral transport through eddies and downwelling currents. Over 2011-12, the first-ever deployments of LISSTs in the Arctic Ocean have been done at the edge of the Mackenzie Shelf on moorings also equipped with ADCPs and traps as part of a partnership between ArcticNet and the Beaufort Regional Environmental Assessment (BREA) program. Data from these instruments are currently under process, but could potentially provide very valuable information on the seasonal variability of vertical and horizontal fluxes of organic and inorganic particles across the shelf break. Other optical instruments could measure the upper particle size-distribution (0.1-10 mm), a range that typically cover phyto-detritus, fecal pellets, zooplankton debris, and marine snow, which composed the bulk of autochthonous POC export in spring-summer. For instance, the Underwater Vision Profiler (UVP, http://www.hydroptic.com/) appears to be among the most useful devices that could record large sinking aggregates. The UVP provides a robust dataset that enables a direct estimate of vertical POC fluxes (Forest et al., 2012). A moored version of this instrument is available. Furthermore, the process of data and images recorded by the UVP is facilitated by the use of the Zooprocess software supported by a large community of users and for which automatic recognition has been validated for various types of marine particles. Therefore, a “dreamed” bio-mooring specifically designed for particle flux studies in the Arctic Ocean could be one that incorporates sediment traps along with a suite of ADCPs, LISSTs, UVPs, and other standard bio-sensors for light, nutrients and chlorophyll. The series of simultaneous measurements provided by such an integrative bio-mooring array (if successfully deployed and recovered) would definitely be a major step toward the development of ecosystem models that rely on information about PP, carbon export and plankton/particle size-distribution to simulate the functioning of the biological pump (e.g. Stemmann and Boss, 2012).

5.0 Conclusion

Over the last three decades, long-term sediment trap studies helped elucidating how the biological pump in the Arctic Ocean is operating and how it is responding to global change. With the addition of complementary sampling (e.g. ADCPs, turbidity-meters, underwater cameras), sediment traps supported ecosystem-level analyses and a better understanding of vertical, horizontal and trophic carbon fluxes throughout several Arctic regions. Here, our goal was to illustrate with a series of compelling case-studies how bio-moorings arrays are core tools to incorporate within the strategic vision of a coordinated ocean observing program (e.g. global biogeochemical flux initiative, http://gbf-ooi.whoi.edu/). Despite their lack of spatial coverage (in comparison with remote sensing, for example), bottom-anchored and ice-tethered moorings provide a powerful approach to record the full seasonality of Arctic ecosystems and to detect biophysical changes below the ice-encumbered surface layer and across the seasonal ice zone.

Traditionally, the main reason to moor autonomous instruments in the ocean was related to the study of ocean circulation, heat and freshwater fluxes, and to the need to validate 3-D numerical models. Within a system perspective, understanding how the biota living in the physical environment is responding to change is as important as understanding the environment itself. Hence, with the exponential growth of Arctic ecosystem models and the increasing amount of studies targeting the "physical-biological linkages", it is vital to invest part of this effort in the sustainment of bio-devices installed on mooring arrays and other long-term sampling gears. These represent a key support for the validation of biological models and deliver a unique and rich dataset that can be used within a scientific framework that aims at bridging the biogeochemical and ecological aspects of Arctic Change. Such an objective, as outlined by the Arctic in Rapid Transition implementation plan (ART; http://www.iarc.uaf.edu/ART/), is a critical prerequisite for gaining integrated insights into how the different Arctic marine biotopes are impacted and might feedback to the changing Earth System.

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