Continental Shelf Research 101 (2015) 1–21

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

# Physical forcings and intense shelf–slope fluxes of particulate matter in the halocline waters of the Canadian Beaufort Sea during winter

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ARTICLE INFO

*Article history:*
Received 17 November 2014
Received in revised form
10 March 2015
Accepted 18 March 2015
Available online 28 March 2015

*Keywords:*
Physical oceanography
Sea ice
Shelf–slope exchange
Mesoscale eddies
Sediment traps
Arctic biogeochemistry

ABSTRACT

Resolving the mechanisms that support the transfer of particulate matter across the shelf–slope interface is a key issue for the sustainable development of marine resources along continental margins. A better comprehension of shelf–slope exchanges is particularly needed in the Arctic Ocean given the intensification of human activities and rapid environmental changes in this region. Here, we use three years of physical and biogeochemical data collected with tautline moorings deployed from September 2009 to August 2012 over the slope of the Mackenzie Shelf to identify the processes that drive the lateral transport of particulate matter off the shelf. The main dataset consists of particle flux time-series collected with automated sediments traps deployed on moorings at ~80 and ~180 m depth over the mid-slope. We detected a strong vertical discrepancy in the magnitude of particulate mass fluxes that were 20–600% higher at ~180 m than at ~80 m, and up to ~1500% greater during the winter season alone. The high fluxes at ~180 m depth were linked to several sedimentation events occurring from November to May each year, which were not captured by the upper ~80 m traps. These differences corroborate previous studies that documented active transport of resuspended material near the bottom across the shelf-break and in the mid-water column over the slope. Consideration of particle fluxes along with synchronous current time-series, water column properties and meteorological data revealed that thermohaline convection and storm winds act as the main mechanisms underlying resuspension and transport processes. Their combination drives mesoscale eddy formation, downwelling flows and current surges that are characterized by moderate to high velocities (~20–80 cm $s^{-1}$) sufficient to mobilize sediments. Turbidity near the shelf-break and particle fluxes over the slope were particularly enhanced in winter 2011 (mass fluxes up to ~2 g $m^{-2}$ $d^{-1}$) when a persistent downwelling-favorable wind regime and a large production of winter water were observed. Overall, the amount of winter water events correlated significantly ($R^2$=0.76) with the magnitude of mass fluxes collected at ~180 m. Our analysis revealed a complex pattern of mean currents over the slope facilitating instabilities, frontal structures, shear and eddying motion. Additional work is needed on erosion mechanisms in the bottom boundary layer and their relationship to regional and mesoscale circulation and eddy activity over the upper slope.


## 1. Introduction

Understanding the atmospheric and oceanic processes that drive the transport of particulate matter from shallow shelves to the deep ocean is a key consideration for coastal sediment budgets and for the investigation of marine biogeochemical cycles (Liu et al., 2010). While a typical objective of land–ocean interaction studies is to quantify and characterize the sediments and chemical compounds supplied to the shelf environment by riverine flows, eolian inputs or coastal erosion (Rachold et al., 2000; Schlünz and Schneider, 2000), relatively little is known about the remobilization of shelf materials and their potential transport to the slope and beyond (e.g. Lorenzoni et al., 2009; Hwang et al., 2010). The increasing exposure of continental shelves to additional stressors that include local and global industrial activities, tourism and the

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http://dx.doi.org/10.1016/j.csr.2015.03.009
0278-4343/

effects of climate change, heightens the need to understand both the source and sink mechanisms of shelf materials. This topic is currently a priority in marine research given the uncertainties with respect to pathways, redistribution mechanisms and quantity of inorganic and organic matter transiting through the global margin spatial domain (Jahnke, 2010). The necessity of better constraining shelf–slope–basin exchange is not only important for the assessment of baseline conditions and related variability in the coastal zone, but also essential to anticipate the possible interactions of ocean boundary processes with new environmental features brought by human, sidereal or geological forcing mechanisms (Valiela, 2009) and their impact on the global ocean.

A better understanding of particulate matter fluxes across the Arctic Ocean shelf–slope system is particularly needed given its disproportionate role when compared with other shelves worldwide. Although the Arctic Ocean accounts for only 3% of the global ocean area, approximately 36% of its surface area consists of shallow shelves with less than 200 m depth. Consequently, the Arctic Ocean comprises roughly 20% of the world's continental shelves (Macdonald et al., 1998) and is pervasively influenced by terrigenous inputs delivered through large rivers, eroding shoreline and thawing permafrost (see Stein and Macdonald, 2004; and Smith, 2010, for reviews on sediment and organic carbon budgets in the Arctic Ocean). The Arctic shelf system is also particularly sensitive to changing environmental conditions, including ongoing modifications in the hydrological and cryogenic cycles owed to climate change (e.g. sea ice decline, permafrost destabilization, increased riverine discharge, shifts in atmospheric and wind patterns) as well as growing human activities such as oil and gas exploration and development (e.g. Forbes, 2011; Gautier et al., 2011; IPCC, 2013; Ogi and Rigor, 2013). Given the important connectivity of the Arctic Ocean shelf system with its basin interior (Smith, 2010), alterations of physical and biogeochemical processes near the coast and along the continental margin could thus swiftly and markedly affect water column properties, geochemical cycling and ecosystem dynamics of the central Arctic Ocean (Honjo et al., 2010).

An increasing number of studies have highlighted the strong link between the Arctic Ocean shelf and the slope/basin system with respect to water flows and particulate matter fluxes. Williams et al. (2014) recently reviewed the control of ocean circulation by shelf-break exchange processes in the Chukchi and Beaufort seas. The shelf–basin connection is best exemplified by Pacific water that enters the Arctic Ocean through the Bering Strait, subsequently steered by topography through the Chukchi Sea, and on reaching the shelf-break is believed to turn east causing a shelf-break current along the slope. Then, Pacific water (and western Arctic shelf water in general) can enter the deep basin via subduction (Timmermans et al., 2014) and eddies generated through instabilities in the shelf-break jet (Spall et al., 2008). Mesoscale eddies in the Beaufort and Chukchi seas are now recognized as an important mechanism for transporting particulate matter from the shelf to the slope and basin environments, thus contributing to both the land–ocean transfer of terrigenous material and to the biological pumping of carbon to depth (Forest et al., 2008; Honjo et al., 2010; O'Brien et al., 2011, 2013; Watanabe et al., 2014). During winter, the bottom-intensified and slowly-decaying configuration of the shelf-break jet raises the possibility that the Pacific water is mainly routed toward the Canadian Archipelago (Williams et al., 2014), thus enhancing the presence of the shelf-break current and related eddy generation activity to the east – as observed by Barber et al. (2010).

Wind-driven transport of Pacific and/or Chukchi and Beaufort shelf water is another key mechanism for transferring shelf material toward the Arctic basin. Wind conditions in the western Arctic are typically dominated by an easterly component due to the occurrence of a high atmospheric pressure system located over the Beaufort Sea, which promotes coastal upwelling conditions. This setting entrains surface waters offshore where they subsequently downwell due to Ekman pumping associated with the rotation of the wind field of the Beaufort Sea High (Yang, 2009; Pickart et al., 2013). Direct "coastal downwelling" related to a strong westerly wind regime is about four times less frequent than coastal upwelling events (Pickart et al., 2013). Coastal downwelling is usually caused by an Arctic-born storm that has the capacity to reverse the Beaufort Gyre (Lukovich and Barber, 2006) and accelerate the transport of Pacific water to the east as part of the shelf-break current (Pickart et al., 2013). Upwelling–downwelling cycles driven by winds and moving sea ice are thought to be an important operative factor for transporting suspended shelf sediments and marine particles toward the basin interior (O'Brien et al., 2011), especially when large Arctic cyclones may transit across the region to cause intense downwelling.

Another key process that has been hypothesized to play a major role in the transport of shelf material off the margin is the cascading of dense winter water formed over the shelf that flows downhill and eventually crosses the shelf edge and intrudes over the slope (Backhaus et al., 1997; Forest et al., 2007; Jackson et al., 2015). During ice formation phases, a substantial amount of brine is rejected which results in the production of cold, salty dense water that sinks to depth. This process is particularly effective in polynyas and flaw-lead systems within which dynamic and thermodynamic forcings by the atmosphere and the ocean recurrently flush sea ice, thus generating local "ice and brine factories" in the middle of a more consolidated and thicker ice cover (Barber and Massom, 2007). In shallow flaw-lead polynya systems along the Arctic margin, the combination of dense water formation (i.e. thermohaline convection), the production of frazil-ice crystals and wind/wave-induced Langmuir circulation are among the most efficient hydrodynamic factors which lead to the enhancement of currents and have potential to resuspend, uplift and entrain fine particles in the water column (Dethleff, 2005). O'Brien et al. (2011) determined that bottom currents must exceed 19–36 cm $s^{-1}$ to resuspend material from the seabed of the Mackenzie shelf depending on the sediment type. Such thresholds can be reached in Langmuir circulation cells within which downward velocity may attain 22–27 cm $s^{-1}$ under wind speeds of 7–10 m $s^{-1}$ (Weller and Price, 1988). Once resuspended, particles in the bottom boundary layer may propagate down the shelf with the cascading dense water and intrude within the mid-water column over the slope along the isopycnals where they form intermediate nepheloid layers (Forest et al., 2007). These features have been repeatedly observed across shelf-break areas in the Arctic (Wegner et al., 2003; Ehn et al., 2012; O'Brien et al., 2013) and at lower latitudes (McPhee-Shaw et al., 2004; Inthorn et al., 2006; Lorenzoni et al., 2009), although the mechanism of their formation (e.g. dense-water advection, intermittent current surges, internal waves) might differ from one region to another.

In the current study, we analyze three years of mooring data (September 2009–August 2012) collected over the slope of the Mackenzie Shelf in the southeastern Beaufort Sea (Arctic Ocean). We use a combination of sediment trap measurements, current profiler records, water property data, and ancillary information on sea ice and wind dynamics, to relate recurrent and intense sedimentation events to the potential physical processes (or ensemble of processes) that might have generated them. Our main objective is to characterize a series of 11 particle flux events (~3–4 per year) and their concomitant environmental forcings, which provide further evidence that most of the lateral particle transport across the Arctic shelf-break occurs at depth primarily during winter. In particular, we revisit the hypothesis of Forest et al. (2007) that pointed to ice thermodynamics through thermohaline convection