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The role of eddies on particle flux in the Canada Basin of the Arctic Ocean

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ABSTRACT

Moorings with sequential sediment traps to study downward sediment flux in the Canada Basin of the Arctic Ocean were maintained in 3350 m of water year-round between September 1990 and July 1994. Sediment was collected nominally at 600-m depth and instruments measuring current, temperature, salinity and pressure were placed at several levels between 45 and 1515 m. Total dry weight particle fluxes were low (4.2, 2.1, and 8.2 g m^{-2} a^{-1}) compared to those found in other world ocean basins. Particle flux varied greatly intra-annually. There were peaks during each summer, with differing seasonal timing and particle composition suggesting a correlation with inter-annual differences in summertime ice clearance. In winter, the particle flux was higher if the ice of the preceding summer was light. Enhanced primary production in summers with wider ice-free seas is a possible explanation, but inconsistent with the high lithogenic (LITH) content of most samples: A significant fraction of the particulate organic carbon (POC) content is refractory carbon. Another possibility is that the south-easterly wind pushing ice to the north-west in summers of reduced ice drives the Mackenzie River plume, laden with lithogenic sediment, behind it and out to the mooring site. There is also another factor in play: Peaks in particle flux frequently coincided with eddies, mesoscale circulation features with strongest current well below the surface. The highest measured flux occurred in the winter of 1994, synchronous with a baroclinic eddy which enveloped the mooring for 60 days while rotating cyclonically and moving slowly north-westward. Particles trapped at this time had high LITH and low POC contents, a relatively high molar ratio of biogenic silica to POC and appreciable chlorophyll *a* and phaeophytin pigments. Subsequent trap intervals coincided with the passage of a deeper anti-cyclonic eddy, also on a north-westward trajectory, which deposited material of different composition. These observations demonstrate that an understanding of the lateral transport of sediment by energetic physical phenomena is critical to the insightful interpretation of the particle flux measured with sediment traps at sites remote from the coast in the southern Canada Basin.

1. Introduction

The emerging picture of particle fluxes in Arctic basins is one where old allochthonous carbon and terrestrial material supplied laterally from the shelves and slopes to the deep basin dominates the transport while autochthonous carbon and vertical transport play minor roles. Although exceptionally large quantities of lithogenic suspended particles are supplied episodically to Arctic continental shelves via river inflows and coastal erosion (Rachold et al., 2004), the biological pump within the Arctic interior ocean is anomalously weak (Honjo et al., 2010; Hwang et al., 2008). Particles supplied from land settle to the shelf bottom but are commonly subject to energetic events (e.g., wind, waves, strong currents, internal waves, ice keel gouging), which facilitate resuspension over shelf and slope and transport to the deep basin. Movement of lithogenic sediment to the deep basin also occurs via ice rafting (Rachold et al., 2004), via the spreading of sediment laden river plumes and via slumping of bottom sediments at the shelf edge and the slope (Grantz et al., 1996).

The large-scale circulation features of the Beaufort Sea, the Gyre and the Shelfbreak Jet (Fig. 1), play important roles in sediment transport. The Beaufort Gyre – a large scale, wind-driven anti-cyclonic circulation – carries sea ice and surface waters around Canada Basin and is a vast reservoir of freshwater from runoff and ice melt (Macdonald et al., 1999; Proshutinsky et al., 2002; Plueddemann et al., 1998). Alternating anti-cyclonic and cyclonic anomalies in the Beaufort Gyre occur on approximately a 5–7 year cycle in response to atmospheric oscillations. These cycles play a significant role in Arctic climate variability by accumulating freshwater during times of anti-cyclonic anomaly and releasing freshwater during times of cyclonic anomaly (Proshutinsky and Johnson, 1997; Proshutinsky et al., 1999,

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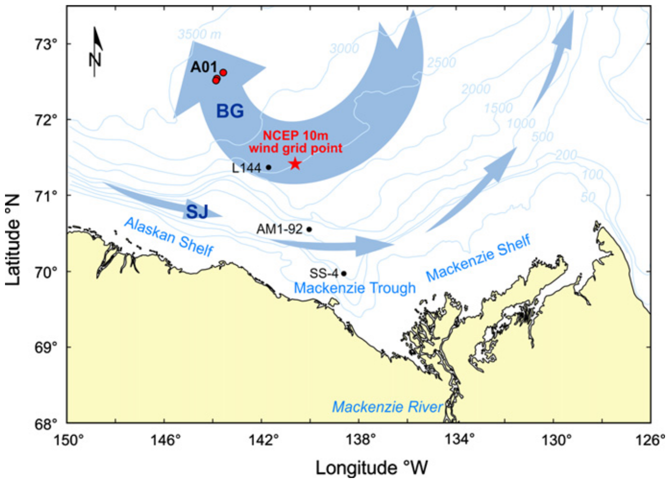

Fig. 1. Location of mooring site A01 (see Table 1) and National Centers for Environmental Prediction (NCEP) grid point (71.426°N 140.625°W). Location of sites from other sequential trap studies (small black dots) are L144 and AM1-92 (O'Brien, 2009) and SS-4 (O'Brien et al., 2006). The large blue arrow labeled BG indicates the dominant direction of the Beaufort Gyre and the smaller blue arrows labeled SJ show the dominant direction of the Shelfbreak Jet. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2002; Morison et al., 2012; Giles et al., 2012). Sediment transport and primary production are closely linked to patterns of freshwater runoff, ice melt, ice drift and wind forcing but we presently have few observational data to inform us about details of those linkages.

At the southern perimeter of the Beaufort Gyre the narrow eastward-flowing boundary current, the Beaufort Shelf-break Jet (Pickart, 2004; Nikolopoulos et al., 2009), is strongly influenced by wind, which modulates its speed and forces reversals in its direction of flow (Kulikov et al., 1998, 2004). Nutrient-rich waters of Pacific and Atlantic origin move eastward in this boundary current. Exchanges of water across the shelf break occur at the surface via Ekman transport and at the seabed via up/downwelling driven by surface stress from wind and ice motion (Macdonald and Wong, 1987; Yang, 2009). Upwelling in the southern Beaufort occurs with easterly winds (Carmack and Kulikov, 1998) and may be sensitive to the position of the ice edge relative to the shelf break (Carmack and Chapman, 2003). Sea valleys that cut across the shelf, such as Mackenzie Trough, are preferred locations for such exchanges (Williams et al., 2006, 2008).

The boundary current and its meanders transport suspended material along and beyond the shelf break (Darby et al., 2009; Ashjian et al., 2005). This current is also a source of eddies that have been observed in the Canada Basin (Pickart, 2004; Mathis et al., 2007). Eddies containing water of locally anomalous temperature–salinity correlation are ubiquitous in the Canada and Amundsen basins. They are most commonly observed within the halocline (Krishfield et al., 2002) but also occur below the halocline to depths greater than 1700 m (Aagaard et al., 2008; references therein). Core waters in eddies may contain elevated concentrations of nutrients, organic carbon and suspended particles (Mathis et al., 2007).

The Mackenzie River supplies the Mackenzie shelf with massive inputs of fresh water and suspended sediment. Despite gravitational settling, Mackenzie sediments travel great distances via wind-driven movement of the river plume. Far less obvious, but perhaps more important than these surface processes, sediment is transported and exported in mid- and bottom-nepheloid layers following re-suspension during storms (O'Brien et al., 2006). Sea-bottom gouging by ice keels as deep as 30 m can return sediment to the water column, where it can be frozen into growing ice and travel thousands of kilometers before its release during the thaw (Eicken et al., 2005).

The conditions for and frequency of sediment resuspension from the shelf and slope are not well understood, nor is the frequency with which resuspension results in transport to deep waters. Without such understanding, the impact on sediment processes by climate change effects – on ice cover, weather, river inflow and its dispersal, coastal erosion, resuspension, the biological pump and suspended sediment transport into Canada Basin – will remain enigmatic. Regrettably there are few data that allow study of these processes, which are essential to the understanding of material budgets in the Arctic, e.g., for carbon, silica, and pollutants.

Here we explore physical processes that transport particles to and within deep Arctic basins using data from three annual sediment trap deployments at the 3300 m isobath in the Canada Basin, September 1990, 1992, and 1993. Data from these traps, collected prior to the recent decline in Arctic summertime sea ice, include total solids, organic carbon, total nitrogen, biogenic silica, and pigments. We interpret these time-series in the context of ice conditions, ocean current, temperature and salinity at the moorings and place them within a broader context of weather, ice and river conditions on the adjacent Beaufort shelf.

2. Data and methods

2.1. Station A01 moorings and supporting data

Records of the downward particle flux, seawater temperature and salinity, ocean current and sea ice in Canada Basin were acquired using sequentially sampling sediment traps and electronic recording instruments on submerged moorings in the early 1990s. These were deployed in 1990, 1992, and 1993 at closely spaced stations A01-90, A01-92, and A01-93 near the 3350 m isobath (Fig. 1, Table 1). Two Baker/Milburn sediment traps (Baker

Table 1
Depths of data records recovered from moorings in the Canada Basin (1990–1994) at sites A01-90, A01-92, and A01-93. Instruments are upward looking sonars (ULS), current meters (RCM4 and RCM5) with temperature (T) and conductivity sensors (C), Seacats measuring temperature and conductivity, and sediment traps as described in Section 2.1.

Site **lat/ lon** Start End	**A01-90 72.621 N/143.568 W** September 1990 July 1991 (m)	**A01-92 72.542 N/143.830 W** September 1992 August 1993 (m)	**A01-93 72.517 N/143.866 W** September 1993 August 1994 (m)
ULS	72	28	53
RCM4/5	81	46	60
Plus T&C	81	46	60
SeaCat	83	47	62
RCM4/5	~	67	79
Plus T&C	101	67	79
RCM4/5	~	117	93
Plus T&C	~	117	83
RCM4/5	208	167	139
Plus T&C	208	167	139
SeaCat	209	169	140
RCM4/5	331	296	265
Plus T&C	331	296	265
Sediment trap	**615**	**600**	**568**
RCM4/5	633	598	272
Plus T&C	633	598	572
Sediment trap	**1515**		
Seabed	3339	3375	3370