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Current surges and seabed erosion near the shelf break in the Canadian Beaufort Sea: A response to wind and ice motion stress

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ABSTRACT

Estimating the erosion potential of seabed sediments and the magnitude of the resulting suspended load in relation to current dynamics near the shelf break is a key issue for better understanding shelf-slope sediment transport. On the outer Mackenzie Shelf (Canadian Beaufort Sea, Arctic Ocean), a thin and discontinuous veneer of recent surficial clays overlie old glaciomarine sediments that further pinch out at the shelf edge. Gas and fluid venting is known to underlie part of sediment instability in the area, but recent mooring-based measurements also indicate that sediments near the shelf break are recurrently remobilized by strong subsurface currents. Here, we relate storms to the development of current surges that resulted in the abrupt resuspension of sediments at two locations along the shelf break. Near-bottom concentrations of suspended sediments were estimated using the acoustic backscatter of high-frequency acoustic Doppler current profilers deployed from September 2011 to September 2013 as part of the Beaufort Regional Environmental Assessment (BREA) program. Near-bottom currents near the shelf edge (140 to 150 m isobaths) were characterized by recurring episodes of elevated velocities (instantaneous speeds up to ~40-50 cm s^{-1}) that were extensions of current surges (~60-80 cm s^{-1}) occurring in the core of the shelfbreak jet located at ca. 90-120 m. Sudden peaks in suspended sediments (above 100 g m^{-3}) corresponded closely with current surges in the near-bottom boundary layer (<10 m) implying the local erosion of surficial sediments and the rapid advection or redeposition of the resuspended sediments. A range of apparent threshold velocities from 18 to 36 cm s^{-1} was calculated based on the relationship between suspended sediment concentrations and near-bottom current speeds. Two meteorological scenarios were identified to explain the current surges underlying these erosion events at the shelf edge: (1) Pacific or Arctic-born low pressure systems that propagate into the southern Beaufort Sea and are associated with intense downwelling-favorable westerly winds. These amplify the eastward-setting shelfbreak jet along the upper slope, such as in September 2012 when successive cyclones developed during the record-low sea ice extent. (2) The persistence of a high-pressure system over the Beaufort Sea that causes strong upwelling-favorable easterly winds and a strengthening of anti-cyclonic ice motion. This induces a reversal of the shelfbreak jet to the west and a subsequent eastward-directed relaxation flow when the winds fade, such as during the major ice fracturing events of January to March 2013 that were associated with strong and persistent current speeds.

1. Introduction

Understanding sediment transport processes at the boundary of continental margins is essential to linking the source and fate of particulate matter from shallow shelves to the deep sea (Liu et al., 2010). The land-ocean transfer of terrigenous material has implications for sediment mass balance budgets, but also for the biogeochemical fluxes of carbon and nutrients that shape the functioning of pelagic and benthic food webs beyond the shelf edge (e.g. Jefferies, 2000; Schlacher and Connolly, 2009; Forest et al., 2013; Pusceddu et al., 2013). Sediment transport studies on the outer shelf and upper slope are typically based on seabed geomorphological characteristics and often make use of sub-bottom profiler images and sediment texture data to infer deposition and erosion mechanisms (e.g. Cunningham et al., 2005; Noda and TuZino, 2007; Saint-Ange et al., 2014). The focus of such studies is usually oriented toward the role of geological processes, which in turn support the interpretation of sediment mobilization and pathways. However, a water column perspective on cross-shelf sediment transport is also needed given that oceanographic forcings can play a key role in

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determining sediment fluxes and the foundation conditions of the seabed (e.g. Hernández-Molina et al., 2011; Urgeles et al., 2011; Palanques et al., 2012). In particular, there is a strong need for more studies targeting the bottom boundary layer (BBL) near the shelf break where strong currents, associated for example with breaking internal waves, upwelling/downwelling circulation and solitons, may interact with the seabed (e.g. Quaresma et al., 2007; Thiem and Berntsen, 2009; Lamb, 2014). The shelf break is also an active region where mesoscale eddies that have the potential to impinge on sediments and carry suspended matter over long distance may be generated as a result of baroclinic instabilities and density fronts (e.g. Spall et al., 2008; O'Brien et al., 2011, 2013; Watanabe et al., 2014).

The resuspension, entrainment and seaward advection of shelf bottom material is increasingly recognized as an important component of particulate matter cycling in the Arctic Ocean system (Forest et al., 2007, 2015; Hwang et al., 2008; Honjo et al., 2010; Macdonald et al., 2015; Magen et al., 2010; Mucci et al., 2008; Smith, 2010; O'Brien et al., 2011, 2013; Watanabe et al., 2014). This is partly due to the inherent characteristics of this ocean, which is comprised of 36% of shallow shelves less than 200 m (~20 % of the world's continental shelf) and is pervasively influenced by large riverine sediment outputs, accelerating permafrost thawing, and coastal erosion (Macdonald et al., 1998; Stein and Macdonald, 2004; Smith, 2010). In the Canada Basin, time-series sediment traps provide evidence that 80% of the settling material at 3000 m depth is of lithogenic nature and dated to about 1900 years (Hwang et al., 2008). The latter particles represent in fact the oldest suspended matter ^{14}C values out of a large radiocarbon database covering all Earth's oceans (Hwang et al., 2010), which suggests active transport of resuspended material from the shelf to the basin in the Arctic Ocean (see also the review of Macdonald et al., 2015). Recent particle flux measurements by epipelagic sediment traps moored in the Canadian Beaufort Sea demonstrate that intense events of shelf-slope sediment transport recurrently occur near the bottom across the shelf break and in the mid-water column over the slope (Forest et al., 2007, 2015). These events appear to be driven by downwelling-favorable wind storms and the cascading flow of dense winter water down the shelf, which both represent mechanisms able to entrain material from the shelf BBL toward the margin and beyond. It is also hypothesized that some of the strong particle flux events originate directly from sediment resuspension and dispersal taking place near the shelf break following short-lived current surges and mesoscale eddy development in the shelfbreak jet (cf. Forest et al., 2008).

The main objective of this study is to characterize the spatial-temporal variability of sediment fluxes within the BBL near the shelf break in the Canadian Beaufort Sea and to understand the underlying forcing factors. The focus is on the coupling between ocean currents and near-bottom suspended sediment concentrations during well-defined seabed erosion events. Oceanographic data from instruments deployed on taut-line moorings at two locations near the shelf edge (150 m isobath) from September 2011 to September 2013 (Fig. 1, Table 1) are used to develop estimates of sediment fluxes in the lower 10 m of the water column. Suspended sediment concentrations are obtained through the inversion of the acoustic backscatter signal from 1-MHz acoustic Doppler current profilers as based on a relationship linking the acoustic backscatter and suspended sediment concentrations obtained from a laser scattering and transmissometer diffraction system. Examination of suspended sediment time-series in conjunction with current speed reveals that strong sediment erosion events can occur at multiple occasions over the year as a response to current surges propagating along the shelf break. The intensifications of the along-slope current speed are caused by enhanced wind and/or ice motion stress developing during storms passing over the Canadian Beaufort Sea. These results are used to assess the envelope of threshold velocities for upper slope sediment resuspension and to develop annualized

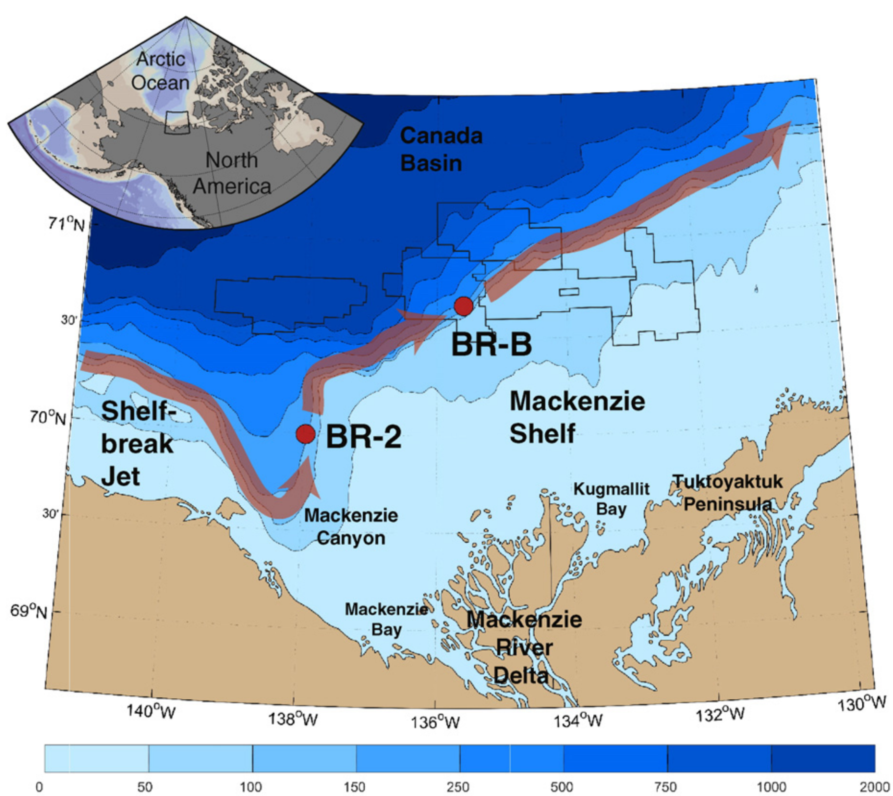

Fig. 1. Bathymetric map of the Mackenzie Shelf in the southeastern Beaufort Sea (Arctic Ocean) with position of BR-2 and BR-B moorings deployed over 2011-2013 near the shelf break. The location of the eastward shelfbreak jet that is expected to flow on the upper slope is schematized on the map. Offshore lease areas are also delineated on the map. See Table 1 for the details on mooring instrumentation.