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Sediment transport by sea ice in the Chukchi and Beaufort Seas: Increasing importance due to changing ice conditions?

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Abstract

Sediment-laden sea ice is widespread over the shallow, wide Siberian Arctic shelves, with off-shelf export from the Laptev and East Siberian Seas contributing substantially to the Arctic Ocean's sediment budget. By contrast, the North American shelves, owing to their narrow width and greater water depths, have not been deemed as important for basin-wide sediment transport by sea ice. Observations over the Chukchi and Beaufort shelves in 2001/02 revealed the widespread occurrence of sediment-laden ice over an area of more than 100,000 km^2 between 68 and 74°N and 155 and 170°W. Ice stratigraphic studies indicate that sediment inclusions were associated with entrainment of frazil ice into deformed, multiple layers of rafted nilas, indicative of a flaw-lead environment adjacent to the landfast ice of the Chukchi and Beaufort Seas. This is corroborated by buoy trajectories and satellite imagery indicating entrainment in a coastal polynya in the eastern Chukchi Sea in February of 2002 as well as formation of sediment-laden ice along the Beaufort Sea coast as far eastward as the Mackenzie shelf. Moored upward-looking sonar on the Mackenzie shelf provides further insight into the ice growth and deformation regime governing sediment entrainment. Analysis of Radarsat Synthetic Aperture (SAR) imagery in conjunction with bathymetric data help constrain the water depth of sediment resuspension and subsequent ice entrainment (>20 m for the Chukchi Sea). Sediment loads averaged at 128 t km^{-2}, with sediment occurring in layers of roughly 0.5 m thickness, mostly in the lower ice layers. The total amount of sediment transported by sea ice (mostly out of the narrow zone between the landfast ice edge and waters too deep for resuspension and entrainment) is at minimum 4×10^6 t in the sampling area and is estimated at 5–8 $\times 10^6$ t over the entire Chukchi and Beaufort shelves in 2001/02, representing a significant term in the sediment budget of the western Arctic Ocean. Recent changes in the Chukchi and Beaufort Sea ice regimes (reduced summer minimum ice extent, ice thinning, reduction in multi-year ice extent, altered drift paths and mid-winter landfast ice break-out events) have likely resulted in an increase of sediment-laden ice in the area. Apart from contributing substantially to along- and across-shelf particulate flow, an increase in the amount of dirty ice significantly impacts (sub-)ice algal production and may enhance the dispersal of pollutants.

Keywords: Sea ice; Ice rafting; Ice drift; Coastal processes; Shelf sedimentation; Arctic

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1. Introduction

Research over the past two decades has established that sediment-laden or "dirty" sea ice is a common phenomenon in the Arctic Ocean and its marginal seas. While the entrainment of sediments into newly grown sea ice had been reported in early, mostly anecdotal reports (see discussion in Pfirman et al., 1990), more recent icebreaker expeditions (Larssen et al., 1987; Pfirman et al., 1989; Reimnitz et al., 1993a; Nürnberg et al., 1994; Eicken et al., 2000; Tucker et al., 1999) and shore-based research (Osterkamp and Gosink, 1984; Kempema et al., 1989; Dethleff et al., 1993; Macdonald et al., 1995; Stierle and Eicken, 2002) have demonstrated that sediment-laden ice appears to be a common phenomenon. At the same time, detailed analysis of sediment cores obtained throughout the Arctic revealed that sediment transport by sea ice has been dominating the sedimentation regime in the Arctic Ocean and the Greenland Sea in the recent geological past (Clark and Hanson, 1983; Bischof and Darby, 1997; Nørgaard-Pedersen et al., 1998; Behrends, 1999). Apart from transferring organic carbon (including high fractions of terrigenous carbon, Eicken, 2003), sea-ice transport of sediments plays an important role in the redistribution and dispersal of pollutants (Lange and Pfirman, 1998) and is of importance for sea-ice microbial communities (Junge et al., 2004). Due to the sensitivity of ice optical properties to even small concentrations of opaque impurities the entrainment of sediments impacts the surface energy balance of the ice cover and significantly reduces the fluxes of short-wave radiation into the underlying water (Warren, 1984; Light et al., 1998; Frey et al., 2001).

The details of the entrainment process are still not well understood, although field work (Osterkamp and Gosink, 1984; Kempema et al., 1989; Reimnitz et al., 1993b; Stierle and Eicken, 2002), lab experiments (Reimnitz et al., 1993c; Ackermann et al., 1994; Lindemann, 1999; Smedsrud, 2001), and modeling (Sherwood, 2000; Smedsrud, 2002) have resulted in some progress in the recent past. From this work, it appears that sediment entrainment into sea ice requires resuspension of sediments during episodes of frazil ice formation. Work by Kempema et al. (1989) also suggests that the interaction between frazil crystals and the seafloor may promote resuspension of particulates. The degree of interaction between frazil ice and resuspended sediment particles depends on a number of parameters (grain size, wave height, water depth, current speed, initial stratification), but generally sediment entrainment is limited to water depths shallower than 30 m and is most effective in water depths less than 20 m (Reimnitz et al., 1987; Kempema et al., 1989; Sherwood, 2000). The potential role of anchor ice formation in dislodging sediments from the seafloor (Reimnitz et al., 1987) as well as the filtration of turbid water by ice slush at the surface (Ackermann et al., 1994) are not well understood but are assumed to be of lesser quantitative importance.

The broad, shallow Siberian shelves with fall ice formation over vast stretches of the seasonally ice-free marginal seas provide ideal conditions for the entrainment and export of sediments (Reimnitz et al., 1994; Eicken et al., 2000). Field observations (Lindemann, 1999; Dethleff et al., 1993, 2000), remote sensing (Eicken et al., 2000; Huck et al., submitted), analysis of sea-ice trajectories and modeling (Pfirman et al., 1997) as well as deep-sea sediment cores (Nørgaard-Pedersen et al., 1998; Behrends, 1999) underscore the importance of ice transport of sediments from the Siberian shelves. In contrast, the Chukchi and Beaufort shelves (Fig. 1), with comparatively narrow width and deeper waters, the lack of an extensional sea-ice drift regime, and—until very recently—a predominance of perennial ice, appear to be less important as source areas of sediment-laden sea ice (Reimnitz et al., 1993a, 1994; Eicken, 2003). Nevertheless, based on an analysis of ice-transported mineral grains, Darby (2003) concluded that the Banks Island shelf in the eastern Beaufort Sea represents an important source area. A recent study of the carbon and sediment budget of the Mackenzie shelf established that the role of sea-ice transport of organic carbon and particulates is a major unknown, with more data and insight required for closure of the budget (Macdonald et al., 1998).

With the exception of a pioneering study by Reimnitz et al. (1993b) comprising field work and remote sensing, little work other than studies of processes at individual localities (Barnes et al., 1982; Osterkamp and Gosink, 1984; Kempema et al., 1989) has been completed on sediment transport by sea ice in this region of the western Arctic. In contrast, a larger number of icebreaker expeditions (Larssen et al., 1987; Pfirman et al., 1989; Nürnberg et al., 1994; Eicken et al., 1997, 2000), land-based or airborne studies (Dethleff et al., 1993), and remote