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Estuarine, Coastal and Shelf Science 65 (2005) 61–73
ESTUARINE COASTAL AND SHELF SCIENCE
www.elsevier.com/locate/ECSS

The turbidity maximum zone of the Yenisei River (Siberia) and its impact on organic and inorganic proxies

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Received 18 May 2004; accepted 27 May 2005
Available online 5 July 2005

Abstract

A general overview of the processes taking place in the summer mixing zone of the fresh Yenisei River water with the marine waters of the Kara Sea is given in this study, with special emphasis on the interaction between bulk (total suspended matter), inorganic (Fe, Mn) and organic (suspended organic carbon, suspended nitrogen) proxies. Within the mixing zone, a zone of enhanced turbidity (maximum turbidity zone) was observed comparable to studies in other rivers. Flocculation of particles due to changes in salinity and hydrography cause this maximum turbidity zone, and resuspension additionally enhances the turbidity in the near-bottom layers. Organic matter behaves conservatively in the mixing zone in terms of its percentage of suspended matter. It, however, undergoes degradation as revealed by amino acid data. Inorganic, redox- and salinity-sensitive, proxies (Mn, Fe) behave non-conservatively. Dissolved iron is removed at low salinities (<2) due to precipitation of iron oxyhydroxides and adsorption of manganese on suspended particles, enhancing the Mn/Al ratio of the suspended matter in the same zone. At higher salinities within the mixing zone, Fe/Al and Mn/Al ratios of the suspended particles are depleted due to resuspension of sediment with lower Fe/Al and Mn/Al ratios. Dissolved manganese concentrations are significantly higher in the near-bottom layers of the mixing zone due to release from the anoxic sediment. All things considered, the Yenisei River mixing zone shows patterns similar to other world's rivers.

Keywords: mixing zone; turbidity maximum; carbon cycle; Arctic Ocean; Kara Sea

1. Introduction

Estuaries occupy less than 10% of the ocean's surface (Lisitsyn, 1995), but play an important role in the global cycle of divers substances (e.g. organic matter, nutrients, metals). Estuaries and coastal areas trap significant quantities of suspended and dissolved matter and, thus, act as filter between the terrestrial and the marine realm. Mixing of riverine freshwater and marine saline water and the associated changes in physicochemical properties lead to physical, chemical and biochemical processes affecting the dissolved and suspended load of the river. During the late 1970s, a broad interest in the processes taking place in the mixing zone arouse (e.g. Cronin, 1975; Wiley, 1976, 1978; Kennedy, 1980, 1982, 1984). Despite the large number of studies, some of the processes in estuaries are still not well understood. Some parts of the river load seem not to be affected by

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0272-7714/$ - see front matter
doi:10.1016/j.ecss.2005.05.007

the estuarine processes, whereas others are trapped or mobilized in the mixing zone. This ability of estuaries to remove or retain material in solution and suspension makes estuaries important in terms of environmental questions.

During the last decades, studies about the removal and mobilization processes were carried out in several estuaries (e.g. Lena River, Gordeev and Shevchenko, 1995; Cauwet and Sidorov, 1996; St. Lawrence River, Bewers and Yeats, 1978, 1979; Cossa and Poulet, 1978; Gobeil et al., 1981; Hamblin, 1989; Lucotte, 1989; Changjiang River, Milliman et al., 1985; Cauwet and Mackenzie, 1993; Jiufa and Chen, 1998). A zone of maximum turbidity is generally observed in estuaries at the convergence of the downstream flowing surface water and the upstream flowing salt wedge of marine water (Bowden, 1984). This zone is characterized by high concentrations of suspended matter, higher than upstream in the river or downstream in the estuary. The estuarine circulation pattern has an effect on the location and strength of the turbidity maximum zone. This site of high suspended matter concentrations provides an ideal site for physical, chemical and biological reactions between dissolved and particulate species as well as interactions among particulate species, so that much of the riverine material is deposited.

Lisitsyn (1995) calculated that in what he calls the "marginal filter", about 93–95% of the suspended and about 20–40% of the dissolved riverine material is deposited worldwide. He slightly modified his statement for the Polar Regions where rivers drain areas of permafrost and are more influenced by seasonal variations, e.g. by ice cover and snow during winter. Lisitsyn (1995) distinguishes between two different marginal filter regimes in the Ob and Yenisei rivers: (a) a short summer regime with the main part of water and solid material delivered to the Kara Sea; and (b) a rather long winter regime with low water and suspension discharges. He further introduces a so-called ice marginal filter: during ice production, the saline water forms dense plumes sinking in the water column and transporting some of the marginal filter sediment away from its initial position.

In this study, we intend to characterize the processes taking place in the Yenisei River estuary and compare these findings with the adjacent Ob River estuary as well as with rivers from other non-polar regions. However, as all our data originate from the short Arctic summer period, we are only able to evaluate the summer situation.

2. Study area

The Kara Sea is one of the Arctic shelf seas of Northern Siberia (Fig. 1). The central and the eastern parts of the Kara Sea are dominated by the Ob and Yenisei estuaries (= Yamal Plateau) with a characteristic depth of 25–30 m. More than one third of the total freshwater discharge to the Arctic Ocean is into the Kara Sea, mainly via Ob and Yenisei rivers (Aagaard and Carmack, 1989).

The Yenisei River draining into the Kara Sea is Siberia's largest river with a drainage area of $2.58 \times 10^6\ km^2$ and a length of 3844 km (Milliman and Meade, 1983; Milliman, 1991; Telang et al., 1991; Gordeev, 2000). The Yenisei bed crosses igneous basement rocks and fills two large reservoirs in its upper reaches, and flows through the West Siberian Plain in regions of permafrost in its lower reaches. Along the banks, the taiga is gradually replaced by forest tundra. The freshwater discharge to the Kara Sea is highly seasonal with the main discharge occurring during spring and summer, part of which occurs while the Southern Kara Sea is ice-covered. The Kara Sea is almost entirely ice-covered from October to May (e.g. Pavlov and Pfirman, 1995) with only a small narrow polynya north of the fast-ice zone remaining ice-free due to prevailing offshore winds (Pavlov and Pfirman, 1995; Harms et al., 2000). During the summer months, deep water supplied from the central Arctic Ocean forms a stable salt wedge having salinities > 30 in the Yenisei River.

Large amounts of river suspension have built up thick packages of sediments mostly in the outer estuary and the southernmost Kara Sea (Dittmers et al., 2003; Stein and Fahl, 2004). It has been assumed that the major amount of organic carbon deposited in the Kara Sea is of riverine origin (Stein and Fahl, 2004, and references therein).

3. Data used for this study

In order to get detailed information on the processes taking place in the mixing zone of river and sea water, we combine different data from the Yenisei River estuary. Most of the data were obtained within the framework of the German-Russian SIRRO project (Siberian River Run-Off) on three *RV Akademik Boris Petrov* cruises between 1997 and 2000 (Matthiessen and Stepanets, 1998; Matthiessen et al., 1999; Stein and Stepanets, 2000, 2001). Additionally, sediment surface samples from the international *RV Dmitriy Mendeleev* expedition in 1993 (Lisitsyn and Vinogradov, 1995) were used in this study. All suspended and dissolved matter samples are from the *Akademik Boris Petrov* 2000 cruise in order to avoid effects due to different conditions in different years. Nevertheless, surface sediment samples originate from different years as they are not affected by interannual variations.