Control on sediment and organic carbon delivery to the Arctic Ocean revealed with space-borne synthetic aperture radar: Ob′ River, Siberia

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ABSTRACT

An important control on river biogeochemistry and sediment load is the process of water exchange between primary channels and the flood plain, particularly in low-relief areas containing lakes, ephemeral channels, and other aquatic ecosystems. Flood-plain exchange may be a dominant process on the lowland rivers of Arctic Russia, which are among the world's largest in water discharge yet are strikingly deficient in their delivery of sediment to the Arctic shelf. Temporal synthetic aperture radar (SAR) amplitude and interferometric images of the Ob' River, Siberia, reveal a time-varying limnological network controlling water, sediment, and nutrient exchange between flood-plain wetlands and the main channel. The amount of hydrologic exchange decreases by one order of magnitude from June to September, enhancing sedimentation over as much as 90% of the flood plain and enriching channel waters with colloidal organic carbon. This observation, combined with Russian field measurements of water discharge and sediment load, indicates that a major sediment sink on the lower Ob' flood plain may be responsible for the low amount of sediment delivery by the Ob' River to its estuary and the Kara Sea.

INTRODUCTION

River runoff plays a major role in the fresh-water budget of the Arctic Ocean, which receives nearly 10% of the world's river runoff into an enclosed basin that occupies only 6% of the global ocean surface area (Steele et al., 1996). In Russia, combined flows from the Yenisei, Lena, and Ob' Rivers deliver 1540 km^3 of fresh water each year to the Arctic Ocean, ranking them sixth, eighth, and thirteenth, respectively, among the world's largest rivers in flow volume (Meade, 1996). However, despite their very large discharges, these rivers have sediment yields much lower than the world average (Meade, 1996; Bobrovitskaya et al., 1996; Gordeev et al., 1996). Mean sediment concentrations of the Lena and Ob' Rivers are less than those of the Yukon and Mackenzie Rivers by about a factor of 10, yet the total organic carbon content of the Russian rivers is about as high as that of their North American counterparts (Telang et al., 1991). Current hypotheses explaining low sediment loads from the Ob' and other Siberian rivers include storage on flood plains (Bobrovitskaya et al., 1996; Gordeev et al., 1996) and low erosion rates due to lack of topographic relief (Gordeev et al., 1996; Milliman and Syvitsky, 1992). Furthermore, it is acknowledged that primary productivity on Arctic continental shelves may be limited by the seasonal depletion of nutrients (Grebmeier et al., 1995), but the importance of Eurasian river inputs of sediment and nutrients to shelf biodiversity and primary productivity remains a major unanswered question in Arctic system science (Forman and Johnson, 1996).

The Russian Federation contains the largest and least-studied Arctic land mass. It contributes about 85% of the total terrestrial runoff to the Arctic Ocean (Aagaard and Carmack, 1989), but its general inaccessibility and sheer size limit field study of much of its area. Satellite remote sensing is perhaps the only practical way to regularly observe its hydrological processes at the regional to continental scale. This approach has been used to study the interconnectivity of water bodies on the Mackenzie River delta (Mouchot et al., 1991), the fate of water and sediment on the Mississippi (Gomez et al., 1995), Missouri (Izenberg et al., 1996) and Amazon (Mertes, 1994; Hess et al., 1995; Mertes et al., 1996) flood plains, and the shape of the Nile (Stern and Abdelsalam, 1996). This paper describes temporal inundation patterns on the Ob' River flood plain, Siberia, identified through the use of temporal synthetic aperture radar (SAR) amplitude and interferometric data acquired by the European Space Agency's ERS-1 and ERS-2 satellites. In order to study processes affecting water quality just prior to the river's entry to the

Figure 1. Location of lower Ob' River, Siberia, study area.

Arctic shelf, images were acquired from a 100 × 100 km area within 200 km of the river's entry to the Ob' estuary and Kara Sea (Fig. 1).

METHODOLOGY AND RESULTS

SAR is uniquely suited to study Russian Arctic rivers because of its high sensor resolution (~25 m), ability to penetrate clouds and darkness, and the very large size of these rivers (the Ob' flood plain is as wide as 50 km). However, the greatest limitation of SAR for detecting open water is caused by surface waves generated by wind or turbulence. The resulting increase in surface roughness can raise backscatter amplitude values to levels similar to those from surrounding terrestrial areas, making lakes and rivers difficult or impossible to see in the radar imagery (e.g., of the nearly 100 ERS-1 and ERS-2 SAR images examined in this study, only 12 were sufficiently wind free for easy classification of open-water surfaces). To mitigate this problem, we have supplemented the SAR amplitude data time series with phase-coherence images derived from interferometric image pairs acquired one day apart during the 1995 ERS-1 and ERS-2 tandem mission. The interferometric correlation coefficient is a measure of the accuracy of the interferometric phase; its value decreases with temporal surface change and/or increasing volume scattering (Wegmuller and Werner, 1995). Open-water surfaces are characterized by extreme temporal phase decorrelation because they are constantly in motion. Therefore, the aggregate phase return over a water surface for a first acquisition date is radically different from the phase return for a second acquisition, yielding low phase coherence. If the surrounding land surface yields sufficiently high coherence to provide a contrast with the low coherence from water surfaces, flood-plain channels and lakes can be effectively mapped regardless of clouds, darkness, wind, or turbulence. Only one-day interferometric pairs were used in order to minimize the effect of temporally changing water level on the derived phase-coherence images. One-day pairs also yield much higher levels of phase coherence from surrounding terrestrial surfaces.

Figure 2 compares two tandem-mission SAR amplitude images of the Ob' River, along with the corresponding phase-coherence image. Note that water bodies obscured by wind in the amplitude data are revealed in the phase-coherence image. This method was used to check whether areas classified as "water" in the SAR amplitude images are truly flood-plain water bodies. The procedure confirmed that (1) only wind-free amplitude data are effective for mapping inundation along rivers and (2) connectivity maps (see below) derived from wind-free amplitude data provide a close representation of hydrologic linkage on inundated flood plains.

In order to clearly delineate areas of the flood plain that actively exchange with primary or secondary river channels, SAR amplitude and phase-coherence images were processed in a geographic information system to build a connectivity map for each image. A connectivity map delineates only those water bodies that are linked to primary or secondary channels by the flow of surface water, unlike inundation maps that show both isolated water bodies (e.g., oxbow lakes) and interconnected streams. This map serves to separate flood-plain water bodies that are connected to channels from those that are not. Active exchange areas may then be easily

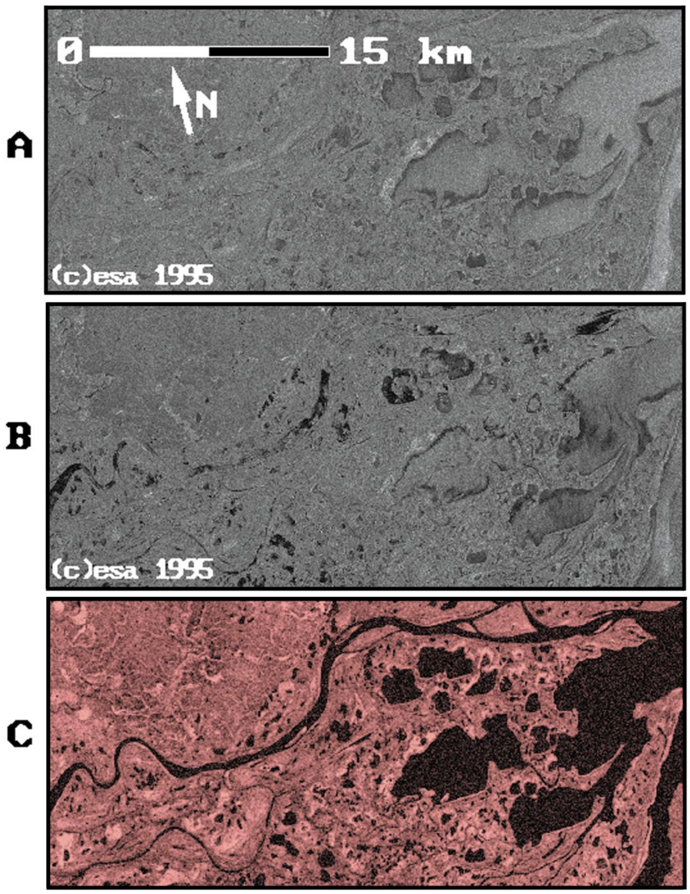

Figure 2. Synthetic aperture radar amplitude and phase-coherence close-ups of Ob' River flood plain. Each image is 15 km × 15 km. Water bodies are difficult to see in amplitude images (A and B) because of increased radar backscattering from wind-generated waves. This problem is eliminated in corresponding phase-coherence image (C). Processing steps included baseline estimation from orbit data, precision registration of interferometric image pairs to registration accuracy of 0.2 pixels or better, interferogram generation, and estimation of interferometric correlation (Wegmuller and Werner, 1997). Correlation was computed within 3 × 3 moving window.

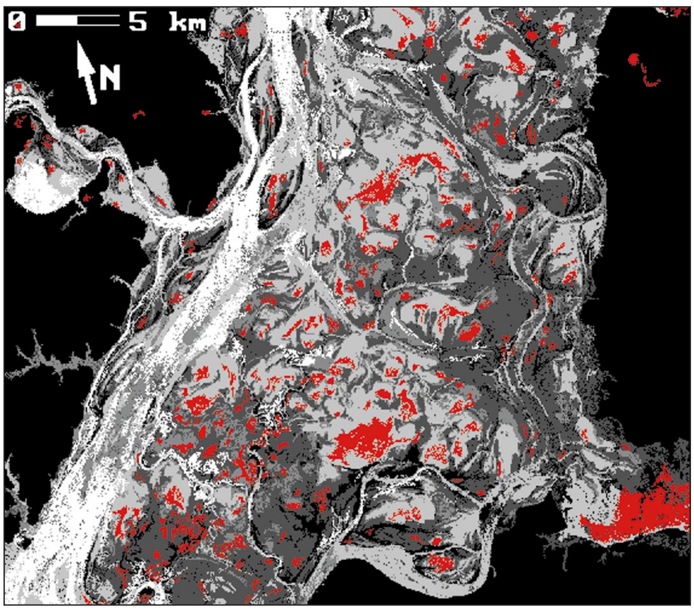

Figure 3. Temporal connectivity map for Ob' River flood plain, derived from synthetic aperture radar amplitude images acquired June 11, July 16, August 4, and September 8, 1993. Active flood plain is about 30 km wide. Black areas are above flood plain. Darkest gray tone (present over most of flood plain though sometimes "covered" by lighter tones) indicates areas connected in only one of four satellite images (June 11, for this particular image). Successively lighter gray tones represent areas connected in two, three, or four satellite images. In places, lighter gray tones overlie darker tones, thus dark tones actually cover greater area than lighter. This image demonstrates seasonal shrinkage in extent of flood-plain exchange. Exchange is most extensive during spring flooding (darkest gray tone). Detached flood-plain lakes do not appear in this image, except for those present on September 8 (in red). Processing steps included 3 × 3 Lee-Sigma filtering, supervised classification, eight-connected proximity analysis, and composite overlays of temporal images.

identified by excluding isolated water bodies from the connectivity map (to identify closed aquatic ecosystems, isolation maps of detached water bodies may also be constructed). By overlaying connectivity maps for different times (Fig. 3), we are able to view fluctuations in the location and areal extent of water exchange, and thus sediment and nutrient exchange, across the flood plain over time. The four connectivity maps overlaid to form Figure 3 were created from SAR images acquired between June and September, the time period when most of the annual flow occurs (Fig. 4). Isolated flood-plain lakes do not appear in Figure 3, except for those present at the end of summer (in red). This approach serves to illustrate the strong seasonal variability in hydrologic linkage on the Ob' flood plain. When optimal satellite baselines (the physical distance between the sensor positions at the times of image acquisition) and short satellite revisit times are available, it is particularly beneficial to use interferometric phase-coherence images to construct these connectivity maps. Phase-coherence images generally provide the clearest delineation of open-water surfaces and are best suited for automated classifications of connectivity and detachment.

DISCUSSION

The SAR-derived series of connectivity maps reveal an annual flood-plain inundation cycle as the dominant fluvial process occurring along the Ob' River upstream of its entry to the Gulf of Ob' and Kara Sea. Flood-plain lakes, anastamosing channels, and wetlands linked in a seasonally regulated network serve as sites for sediment deposition and also are believed to be rich sources of organic nutrients (Shiklomanov and Skakalsky, 1994). During periods of maximum water exchange, such networks are known to have a significant impact on water and nutrient delivery downstream (Shiklomanov and Skakalsky, 1994) and to control flood-plain plant ecology (Borodulin et al., 1978). Like most Arctic rivers, flows in the high-latitude parts of the Ob' are seasonally controlled and closely follow the annual temperature cycle (Fig. 4). Similar to the Pechora, Yenisei, Lena, and Indigirka Rivers, peak discharge of the Ob' occurs in late May or early June, and at least half of the total annual flow occurs during this spring flood period (Gordeev et al., 1996). We found that during peak flows, more than 90% of the flood-plain lakes actively exchange with primary and secondary river channels, then steadily detach as discharges subside. The active exchange area involves nearly the entire flood plain (~1000 km^2, i.e., darkest gray tone, Fig. 3) in the spring but steadily shrinks over an order of magnitude (to ~110 km^2, i.e., light gray tone, Fig. 3) by September. In the spring, sediment-laden flood waters are filtered through ~1000 km^2 of marshy flood plain, enhancing sediment deposition and storage while enriching the amount of organic debris delivered to the Ob' estuary. Our interpretation of a major sediment sink on the lower Ob' flood plain is supported by Russian suspended-sediment measurements that reflect substantial load reduction through the study reach (Bobrovitskaya et al., 1996, 1997). Although water discharge increases as the Ob' flows north from Belogor'ye to Salekhard, there is a net decrease in the total sediment load between these two stations (Fig. 5). The study reach is situated immediately upstream of the Salekhard measurement station.

The study area may be described as an anastomosing, or "Type 1 cohesive sediment anabranching river" (Nanson and Knighton, 1996). Anastomosing rivers are often associated with rapid sediment aggradation (Smith and Smith, 1980; Smith, 1986; McCarthy et al., 1991). Mechanisms for removing sediment from the transport system include various stages of crevasse splays and deposition of fine-grained facies in levees, shallow lakes, abandoned splay channels, and interchannel flood plains (Smith et al., 1989). Evidence for carbon enrichment in the Ob' River has been supported by its being regarded as a "black" river, suggesting enrichment in organic colloidal material (Telang et al., 1991). This presumption has been confirmed by recent ship measurements, which show that the Ob' River is much more enriched in colloidal organic carbon (337 µ*M*) than the Yenisei (121 µ*M*) River (Dai and Martin, 1995). Measurements from the Lena River show 30%–50% organic matter in total dissolved load during the annual spring flood (Cauwet and Sidorov, 1996), although caution must be exercised when comparing the Lena and Ob' Rivers, because they have quite different hydrological settings.

Our results indicate that the hydrology and flood-plain geomorphology of large Arctic rivers play a critical role in determining the composition of channel waters prior to their entry to the Arctic coastal zone. In estuarine systems, further "filtering" of river water is likely to occur in a wedge-shaped mixing zone prior to delivery to the Siberian shelf (Mann and Lazier, 1991). For the Ob', formation of a very stable pycnocline with well-defined separation between river inflows and cold Arctic sea water is demonstrated by a good correlation between salinity and temperature (Dai and Martin, 1995). Within this mixing zone sediment settling may be further enhanced by the presence of fast ice cover, which in the Ob' estuary is known to remain in place during the spring flood (Pfirman et al., 1996). Colloidal organic carbon has also been seen to flocculate in this estuary (Dai and Martin, 1995), complicating direct estimates of riverine carbon inputs to the Arctic shelf. River waters exiting the Ob' estuary are usually routed eastward into the coastal Siberian current. Low-salinity shelf waters are seasonally mixed (primarily by brine ejection from sea-ice formation), resulting in lateral ventilation of the Arctic Ocean from its shelves (Aagaard

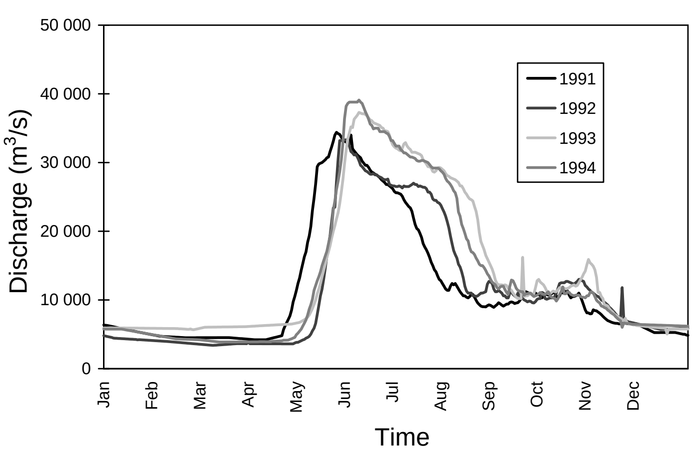

Figure 4. Daily discharge of Ob' River at Salekhard, Siberia, 1991–1994. Annual inundation cycle is remarkably similar each year. Peak flows occur in early June, followed by steady decline through summer. This pattern correlates with shrinkage in flood-plain exchange area (presented in Figure 3). Data source: State Hydrological Institute of the Russian Federal Service for Hydrometeorology and Environmental Monitoring.

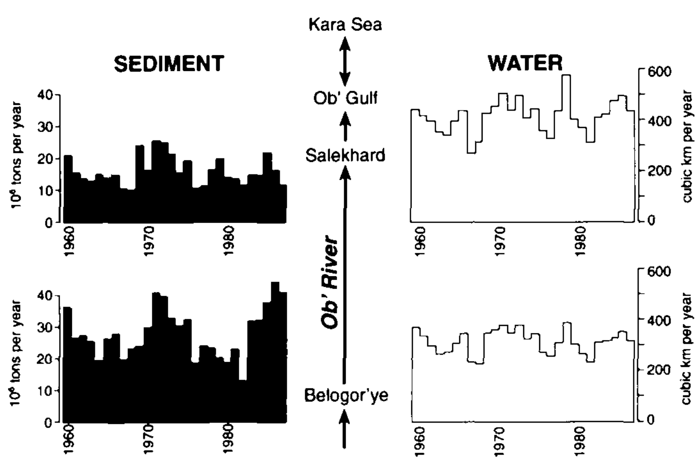

Figure 5. Annual water and sediment discharge in Ob' River, measured at Belogor'ye (upstream) and Salekhard (downstream). Our study area is situated between these two stations. Water discharge increases while sediment discharge decreases through reach. Figure was prepared by R. H. Meade, using data published by Bobrovitskaya et al. (1997).

and Carmack, 1994). Spreading of these shelf waters within the upper Arctic Ocean is thought to take about 10 years (Schlosser et al., 1994). A better understanding of mixing and settling processes in Arctic estuarine, deltaic, and shelf environments is critical to our understanding of the role Arctic Russian rivers ultimately play in the fresh-water, sediment, and carbon budgets of the deep basins of the Arctic Ocean.

CONCLUSION

Spatial analysis of amplitude and interferometric ERS-1 and ERS-2 SAR data supports a flood-plain storage hypothesis (Bobrovitskaya et al., 1996) for the strikingly low sediment load observed for the Ob' River (Meade, 1996; Bobrovitskaya et al., 1996; Gordeev et al., 1996). Patterns of hydrologic exchange are seasonally controlled; peak activity is during the month of June. It is clear that sediment deposition, biogeochemical cycling, and exposure of flood-plain ecosystems to water-borne contaminants will be greatest at this time. Our results also suggest that flood-plain exchange may exert an important control on the timing and volume of organic material, particularly colloidal organic carbon, delivered to the Ob' estuary and the Kara Sea. Remote-sensing study of flood-plain connectivity for other large Russian Arctic rivers should indicate the degree to which their hydrology and geomorphology may control sediment and nutrient delivery to the Eurasian coastal zone of the Arctic Ocean.

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