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Deposition and flux of sediment from the Po River, Italy: An idealized and wintertime numerical modeling study

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ABSTRACT

Recent studies of sediment dynamics and clinoform development in the northern Adriatic Sea focused on winter 2002–2003 and provided the data and motivation for development of a detailed sediment-transport model for the area near the Po River delta. We used both idealized test cases and more realistic simulations to improve our understanding of seasonal sediment dynamics there. We also investigated the relationship between physical processes and the observed depositional products; e.g. the accumulation of sediment very near the Po River distributary mouths. Sediment transport near the Po River was evaluated using a three-dimensional ocean model coupled to sediment-transport calculations that included wave- and current-induced resuspension, suspended-sediment transport, multiple grain classes, and fluvial input from the Po River. High-resolution estimates from available meteorological and wave models were used to specify wind, wave, and meteorological forcing.

Model results indicated that more than half of the discharged sediment remained within 15 km of the Po River distributary mouths, even after two months of intensive reworking by winter storms. During floods of the Po River, transport in the middle to upper water column dominated sediment fluxes. Otherwise, sediment fluxes from the subaqueous portion of the delta were confined to the bottom few meters of the water column, and correlated with increases in current speed and wave energy. Spatial and temporal variation in wind velocities determined depositional patterns and the directions of sediment transport. Northeasterly Bora winds produced relatively more eastward transport, while southwesterly Sirocco winds generated fluxes towards both the north and the south. Eastward transport accounted for the majority of the sediment exported from the subaqueous delta, most likely due to the frequent occurrence of Bora conditions. Progradation of the Po River delta into the Adriatic Sea may restrict the formation of the Western Adriatic Coastal Current, increasing sediment retention at the Po delta and reducing the supply of sediment to the Apennine margin. A positive morphodynamic feedback may therefore be present whereby the extension of the delta into the Adriatic increases sediment accumulation at the delta and facilitates further progradation.

1. Introduction

1.1. Sediment-transport processes

The primary factors controlling delta growth and morphology are rates of fluvial sediment supply and dispersion by waves and currents (Wright and Coleman, 1973; Wright, 1985). For many modern river systems, reduced sediment supplies have increased the dominance of marine dispersal and led to active delta retreat. Examples include the Nile (Frihy, 1996), Godavari (Malini and Rao, 2004), Danube (Mikhailov and Mikhailova, 2003) and Ebro (Mikhailova, 2003). The Po River delta, however, exhibits a supply-dominated morphology and has advanced a total of ~30 km during the last 500 years, due to both anthropogenic control of the river channels and changes in the sediment supply (Nelson, 1970; Oldfield et al., 2003; Correggiari et al., 2005a,b). Continued deltaic progradation implies that the supply of sediment by the Po overwhelms the physical processes acting to disperse it.

Active sediment-transport processes on deltas and their adjacent shelves can be classified as resuspension by waves and currents (Passega et al., 1967; Sternberg and Larsen, 1976; Butman et al., 1979), gravity driven flows (Mulder and Syvitski, 1995; Sternberg et al., 1996; Traykovski et al., 2000; Wright and Friedrichs, 2006), and fluvial advection with settling from river plumes (Geyer et al., 2004). Bed shear stresses generated from waves and currents act to suspend sediment (Smith, 1977; Grant and Madsen, 1979). In many coastal

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environments, including offshore of the Po delta, waves dominate bed shear stresses during periods of significant sediment resuspension (Cacchione et al., 1995; Drake and Cacchione, 1985; Fain et al., 2007; Sternberg and Larsen, 1976). Observational studies have also shown that episodic storms dominate sediment fluxes in many coastal environments, including the Po delta region (Fain et al., 2007; Ogston and Sternberg, 1999; Sherwood et al., 1994). The majority of sediment flux in such storm-driven systems occurs during short-lived and energetic conditions, which are present a small fraction of the time (Sherwood et al., 1994; Cacchione et al., 1999; Mulder et al., 2003).

1.2. Adriatic sea

The Adriatic is an epicontinental sea located between Italy and the Balkans, and is connected to the Mediterranean Sea by the Otranto Strait (Fig. 1). The northern Adriatic, that north of Rimini, is very shallow (<50 m). Artegiani et al. (1997) and Poulain (2001) documented the prominent counterclockwise gyre that persists in the northern Adriatic. The southward flowing Western Adriatic Coastal Current (WACC) begins near the Po delta and extends south, past the Gargano Peninsula. It is driven by a combination of barotropic pressure gradients, wind stresses, and buoyancy inputs (Orlic et al., 1992; Artegiani et al., 1997; Zavatarelli et al., 2002).

Two distinct wind regimes, Bora and Sirocco, dominate conditions in the Adriatic and influence basin-wide circulation (Orlic et al., 1994; Lee et al., 2005). Cold, dry northeasterly Bora winds form distinct bands due to funneling through the Dinaric Alps on the east coast of the Adriatic Sea (Orlic et al., 1994). Siroccos are warm, wet, southeasterly winds that generally strengthen from west to east (Pasaric and Orlic, 2004). In the Po delta region, Bora winds favor downwelling, while Sirocco winds favor upwelling (Kourafalou, 2001). Bora winds intensify the WACC, extending the freshwater plume as far as the Gargano Peninsula, 450 km from the Po River (Orlic et al., 1994). Sirocco winds, in contrast, reduce the coastal current speed and can increase water levels in the northern Adriatic (Orlic et al., 1994).

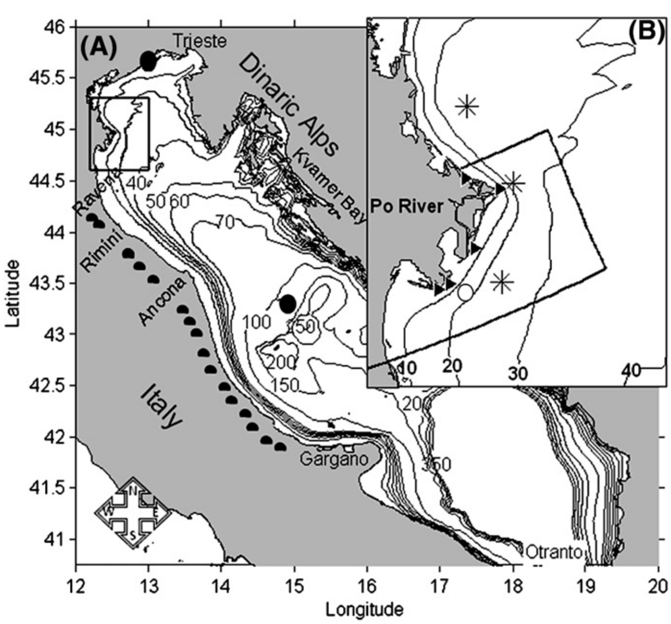

Fig. 1. The Adriatic Sea (A) and the Po River delta (B). Bathymetry is contoured in meters. (A) The Apennine Mountains are represented by half circles. The Bora wind index (Fig. 2) was calculated between the two solid circles. (B) The inset shows the Po River delta in more detail, with the study area delineated by the rectangle. Po River mouths are marked by triangles, and are the Maestra, Pila, Tolle, Gnocca, and Goro; from north to south. Waves for Fig. 2 were analyzed at locations marked by stars. Fig. 8 presents data from Traykovski's et al. (2007) tripod, which was located at the open circle.

1.3. Po River and the subaqueous delta

The Po River dominates discharges into the Adriatic Sea. Its mean freshwater discharge of 1500 $m^3\ s^{-1}$ accounts for almost a third of the total freshwater input (Raicich, 1994). A sediment discharge of 15 million metric tons per year (t yr^{-1}) makes the Po River the largest single sediment supplier to the Adriatic Sea, although rivers south of the Po combine to supply twice as much, about 32 million metric tons per year (Cattaneo et al., 2003). Over an annual cycle, the river typically experiences two peak discharges, first in the winter due to precipitation, and a second in the spring resulting from combined snowmelt and precipitation. Po River discharge occurs through five distributary mouths. From north to south these are the Maestra, Pila, Tolle, Gnocca, and Goro (Fig. 1), each of which provides about 3, 61, 12, 16, and 8% of the freshwater discharge, respectively (Nelson, 1970). Estimates made using the HYDROTREND model indicated the Pila mouth delivers ~73% of the suspended sediment (Syvitski et al., 2005). Data showed this sediment is composed of 23% sand, 70% silt, and 7% clay (Nelson, 1970). Sediment discharged from the Po River accumulates near the distributaries (Fox et al., 2004a; Wheatcroft et al., 2006). The delta advanced at a rapid rate, ~47 m yr^{-1}, until at least 1970. Since then, however, the shoreline has been stable, presumably due to sand mining from the river (Nelson, 1970; Correggiari et al., 2005a,b).

Wave heights during winter, roughly October through February, frequently reach two to three meters on the subaqueous portion of the Po River delta (Nelson, 1970; Traykovski et al., 2007). Suspended-sediment concentrations generated by these waves have been reported to be as high as 50 g L^{-1} at the sea bed (Traykovski et al., 2007). The Po subaqueous delta is characterized by weak tides, with an average tidal range of only 60 cm, with tidal currents in the northern Adriatic reaching 25 cm s^{-1} (Nelson, 1970). Wind- and buoyancy-driven currents on the Po delta vary seasonally in response to wind patterns (Nelson, 1970; Artegiani et al., 1997; Traykovski et al., 2007). Observations on the southern Po subaqueous delta in winter 2002–2003 showed sediment transport to be predominantly alongshore towards the southwest (Fain et al., 2007; Traykovski et al., 2007). Also, satellite and water-column data and basin-scale numerical models imply an eastward transport of sediment in the northern Adriatic gyre during winter 2002–2003 (Lee et al., 2005; Mauri et al., 2007; Harris et al., 2008).

Significant flooding of the Po River occurred in November and December, 2002. The flood lasted for about three weeks, had a peak freshwater discharge of 7960 $m^3\ s^{-1}$, and delivered an estimated 14 million metric tons of sediment (Syvitski et al., 2005; Syvitski and Kettner, 2007). Both Bora and Sirocco winds occurred during this flood. This interval coincided with a field experiment on the Po River subaqueous delta as part of the Po and Apennine Sediment Transport and Accumulation (PASTA) project (see Nittrouer et al., 2004).

Previous research has focused on observing both long- and short-term sediment deposition and accumulation on the Po subaqueous delta. This work found significant sediment deposition close to the distributary mouths in as little as 4 m of water (see Frignani and Langone, 1991; Cattaneo et al., 2003; Fox et al., 2004a; Palinkas et al., 2005; Palinkas and Nittrouer, 2007). Sediment grain size distributions showed predominantly silt and clay around the Po River subaqueous delta with a coarsening towards the northeast. (Goff et al., 2006; Palinkas and Nittrouer, 2007). Seismic studies have highlighted the variation in delta morphology and progradation through time (Correggiari et al., 2005a). Tripod and water-column observations have provided insight into sediment properties and the timing and magnitude of sediment fluxes. Fine sediment aggregation was found to vary in space and time, with sediment alternating between single grains (<36 μm), microflocs (36–133 μm), and macroflocs (<133 μm) (Mikkelsen et al., 2006). Fain et al. (2007) and Traykovski et al. (2007) both observed periods of high sediment flux that coincided with periods of intense Bora or Sirocco winds. These observations of