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Po River plume pattern variability investigated from model data

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ABSTRACT

The Adriatic Sea is a semi-enclosed basin located in the NE part of the Mediterranean Sea and it is strongly influenced by riverine inputs. In its northern sub-basin the freshwater plume of the Po River, together with those of numerous smaller rivers, plays a fundamental role in driving the physical and biogeochemical processes of the whole basin. In this paper we characterize the surface plume structure and identify its patterns and temporal variability on seasonal and inter-annual scales relating it to its major forcings (i.e., river discharges and winds). To perform this analysis, a 3D hydrodynamic numerical model was implemented over the whole Adriatic for the period 2003–2010 and the resulting outputs were analyzed through a series of statistical tools. The inter-annual and seasonal averages of Sea Surface Salinity (SSS) fields show that the average patterns are composed of a coastal plume, wider or narrower depending on the season, that flows southward of the Po River mouths. The first two modes of the Empirical Orthogonal Functions (EOF) analysis show a similar distribution with a cumulative explained variance up to 60%; the third mode, instead, presents a plume shape that extends well into the basin. To obtain a more detailed representation of the plume, a 2×3 Self-Organizing Map (SOM) analysis was performed over the surface salinity fields. Two antithetic patterns were depicted: (i) a small plume confined to coastal areas, typical of low discharges and/or Bora wind events and (ii) a wider plume that extends into the basin, typical of high river discharges and/or Sirocco winds. The comparison between wind regimes, riverine inputs and the time series of the SOM's Best Matching Units (BMU) suggested that, on long time scales, river discharges represent the dominant forcing in defining the plume size and surface pattern, while on time scales of few days the plume dynamics are modulated mostly by the wind structure.

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1. Introduction

Riverine discharges and the freshwater plume that they produce on the continental shelf are important drivers of the coastal dynamics and processes both from a physical and biological point of view. The fluvial plume structure depends on many different factors, some of them are here briefly recalled: outflow angle (Garvine, 1999); Coriolis force (Chao and Boicourt, 1986); ambient background currents and water column structure (Fong and Geyer, 2002; Hickey et al., 2005); bathymetry and seabed morphology (Chao, 1988a, b); tidal forcing for a modulation effect (Guo and Valle-levinson, 2007; MacCready et al., 2009) and local winds (Choi and Wilkin, 2007; Liu et al., 2009). The latter have been generally identified as the leading forcings both on short (Chao, 1988b; Otero et al., 2008; Marques et al., 2009) and longer (Chao, 1988b; Fong and Geyer, 2001; Xia et al., 2007) time scales, due to the narrowing/expanding of the plume offshore extent depending on the downwelling/upwelling direction of the resulting currents.

Generally speaking, freshwater that reaches an ocean basin forms a buoyant water mass with low density which, in an idealized condition with negligible external forcing, tends to develop in a recirculating bulge structure located in the proximity of the river mouth (Fong and Geyer, 2001). This formation tends to expand until the occurrence of an external forcing changes its dynamics (Fong and Geyer, 2001). In a more realistic scenario, i.e., in presence of external forces, the bulge usually turns anticyclonically under the effects of the Coriolis force and propagates, accordingly to the winds fields, along the shore as a wind stress and buoyancy driven coastal current. The propagation continues until mixing processes with ambient water dissipate the plume buoyancy (Garvine, 1999).

The buoyancy inputs associated with a river plume may affect the whole receiving basin, developing lateral gradients and hence circulation features. Riverine waters are an active way of transport for sediments and nutrients of land origin: the former are relevant for sediment budgets, coastal morphodynamics and for the fate of contaminants interacting with cohesive sediments; the latter can play an important role in many ecological aspects of the continental shelves, like maintenance of fish stocks, sustainability of larval and nursery habitats, eutrophication, hypoxic/anoxic events and harmful algal blooms.

Within the Mediterranean Sea, the Northern Adriatic Sea is presently an area where river plumes have a significant influence. It is a epicontinental basin located in the north-eastern part the Mediterranean Sea that lays between the Italian peninsula and the

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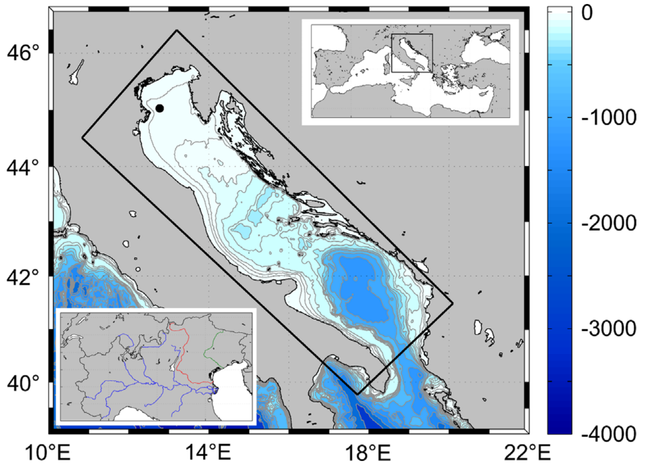

Fig. 1. The Adriatic Sea bathymetry and its location in the Mediterranean Sea. The Black box shows the hydrodynamical model domain; the black dot is the site used to extract the wind data. In the low-left inset are shown the paths of three main NA rivers: Po (blue), Adige (red) and Isonzo (Green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Balkans (Fig. 1). The basin has a complex bathymetry that divides the shallow northern part (having dynamics typical of a continental sea surrounded by mountains) from a deeper southern region (having characteristics closer to those of an open sea). The whole Adriatic basin is generally divided into three areas (Artegiani et al., 1997a): the Northern sub-basin (Northern Adriatic Sea, NA, having the dynamics typical of a continental sea surrounded by mountains) up to the 100 m isobath is an extended continental shelf with a gentle slope toward south-east; the Middle Adriatic, located between the 100 m isobath and the Pelagosa sill, with the Pomo depressions (250 m depth) and an average depth of 130 m; and the Southern Adriatic, a deep basin with a pit deeper than 1200 m, with the characteristics close to those of an open sea.

The NA is a river-dominated and very dynamic coastal system with a close coupling between the physical forcing and riverine inputs (Spillman et al., 2007). Due to the high amount of freshwater discharges (daily average of about 5500 m^3/s) it is generally considered a dilution basin; such elevated inputs have a significant effect both on the physical and biogeochemical properties of the basin (Zavatarelli et al., 1998). In the NA the Po River delta system (daily mean discharge of 1500 m^3/s, with minimum and maximum daily mean discharges of 100 m^3/s and 11550 m^3/s, Falcieri, 2012), and the nearby Adige and Brenta Rivers, with their discharges located less than 50 km away from the Po River delta, produce a single freshwater plume that can influence not only the NA but also the whole Adriatic. The development of a strong buoyancy gradient is one of the major drivers of the general (Ludwig et al., 2009) and coastal (Kourafalou, 2001; Carniel et al., 2012) circulation and water column structure of the Adriatic Sea; moreover, through the freshening of coastal waters, riverine inputs have a direct influence on the formation processes of the Northern Adriatic Dense Waters (NAdDW). Sediments and nutrients carried by rivers sustain primary production near the Po mouth (Bethoux and Gentili, 1999), under the plume, in frontal areas (Danovaro et al., 2000), and can lead to the development of intense phytoplanktonic blooms that can boost hypoxic and anoxic events (Zavatarelli et al., 1998). The Po River plume in the NA has been recognized as a variable but highly productive area (Fonda Umani, 1996) that shows a significant negative correlation between salinity and nutrient concentration (Marini et al., 2008). It appears therefore clear that the understanding of the spatial and temporal variability of the plume is an issue of high importance. Their knowledge would be helpful in disentangling the different contributions that affect the dynamics of the NA, even more in the perspective of its elevated sediment deposition (Sclavo et al., 2013) and nutrients inputs.

Two major horizontal patterns of evolution of the Po plume have been identified in literature: along the Italian coasts toward South (clear signals of its presence can be found well South of Ancona, e.g. Artegiani et al., 1997b) or across the basin towards the Istrian Peninsula (Kourafalou, 2001). In both cases the vertical structure of the plume is very variable, determined by many forcing and ranging from a thin surface lens to the whole water column depth.

Even if there are numerous modeling studies focusing on the Adriatic Sea, to our best knowledge a model-based assessment of the inter-annual variability and pattern of the Po River plume, albeit semi-quantitative, has not been yet attempted. To fill this gap we modeled the Adriatic Sea in a long term run configuration (2003–2010) using the Regional Ocean Modeling System (ROMS) and statistically analyzed the resulting surface salinity fields. All the previously cited factors influencing the plume dynamics (outflow angle, Coriolis force, ambient background currents, bathymetry, tidal forcing, winds, marine density stratification) are considered in the numerical model. In this paper we therefore present a series of considerations, based on a statistical analysis, and maps that describe the most common patterns of the Po plume, both on a yearly and seasonal basis.

This paper is structured as follow: Section 2 describes the hydrodynamical model, its configuration and the statistical tools used; Section 3 describes and discusses statistical results that will be summarized in Section 4 together with some further considerations.

2. Methods

2.1. Plume definition

River plumes can be defined as “plumes of buoyant water […] produced by the inflow from a coastal buoyancy source” (Garvine, 1999) and can be identified by the presence of foam, debris lines and significant color and property gradients (Garvine and Monk, 1974). The fate of a plume is to be slowly dispersed along its path on the continental shelf and, since it does not present clear edges, it is not so straightforward to unambiguously identify a plume from the surrounding ambient waters. In numerous modeling studies a single cut off in salinity has been used to mark the plume limit: Kourafalou (2001) in the Adriatic sea used 37.8 and 38.4, Choi and Wilkin (2007) choose 32 for the Hudson River, in the Columbia River plume Liu et al. (2009) set the limit to 29 while Burla et al. (2010) for the same river used 28. Reasons for a threshold approach are multiple and very often justified by the local dynamics; however, in search for a more objective method, a more articulated approach was proposed in Otero et al. (2008), where the authors used as a reference salinity the surface value found over the maximum horizontal gradient of the Mixed Layer Depth (MLD). For the North-West Iberia shelf they identified as a reference value for the front between the plume and the ambient water the surface isohaline of 35.6.

Following this less subjective approach to identify the plume area, instead of using a single threshold defined *a priori* and with the scope to have more physically sound value, we tested the methodology proposed by Otero et al. (2008) and Otero et al. (2009), and obtained a value close to 36. However it should be recalled that in the case of the NA, due to a water column structure that alternates periods of well stratified waters to periods of completely mixed water column the MLD is not always present and results were not statistically significant (not shown). We also

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