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Research papers

Observed and modeled surface Lagrangian transport between coastal regions in the Adriatic Sea with implications for marine protected areas

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ABSTRACT

Surface drifters and virtual particles are used to investigate transport between seven coastal regions in the central and southern Adriatic Sea to estimate the degree to which these regions function as a network. Alongshore coastal currents and cyclonic gyres are the primary circulation features that connected regions in the Adriatic Sea. The historical drifter observations span 25 years and, thus, provide estimates of transport between regions realized by the mean surface circulation. The virtual particle trajectories and a dedicated drifter experiment show that southeasterly Sirocco winds can drive eastward cross-Adriatic transport from the Italian coast near the Gargano Promontory to the Dalmatian Islands in Croatia. Southeasterly winds disrupt alongshore transport on the west coast. Northwesterly Mistral winds enhanced east-to-west transport and resulted in stronger southeastward coastal currents in the western Adriatic current (WAC) and export to the northern Ionian Sea. The central Italian regions showed strong connections from north to south, likely realized by alongshore transport in the WAC. Alongshore, downstream transport was weaker on the east coast, likely due to the more complex topography introduced by the Dalmatian Islands of Croatia. Cross-Adriatic connection percentages were higher for east-to-west transport. Cross-Adriatic transport, in general, occurred via the cyclonic sub-gyres, with westward (eastward) transport observed in the northern (southern) arms of the central and southern gyres.

1. Introduction

The European Union (EU) mandated the formation of networks of marine protected areas (MPAs) to achieve good environmental status in EU waters by 2020 (Fenberg et al., 2012). Ocean currents play a fundamental role in the dispersal stage of many marine organisms (Cowen et al., 2007; Gawarkiewicz et al., 2007; Pineda et al., 2007; Treml et al., 2008), and transport by ocean currents can affect the degree to which MPAs function as a network (Corell et al., 2012; Largier, 2003; Puckett et al., 2014). However, the small sizes of marine larvae and propagules complicate direct tracking from spawning to settlement/recruitment (Gaines et al., 2007; Largier, 2003), though progress has been made in this area (Langård et al., 2015). Drifters and/or virtual particle trajectories often serve as simplified indicators of larval and propagule pathways in studies of hydrodynamic connectivity (Lugo-Fernández et al., 2001; Tang et al., 2006; Tilburg et al., 2006; Hare et al., 2002; Andrello et al., 2013; Rossi et al., 2014; Di Franco et al., 2012a; Pujolar et al., 2013).

This paper, therefore, uses surface drifters and virtual particles to investigate surface transport between regions in the central and southern Adriatic Sea (Fig. 1a) to determine if Lagrangian transport could impact the degree to which these MPAs and their surroundings function as a coherent network. This paper focuses entirely on surface Lagrangian transport of passive drifters and

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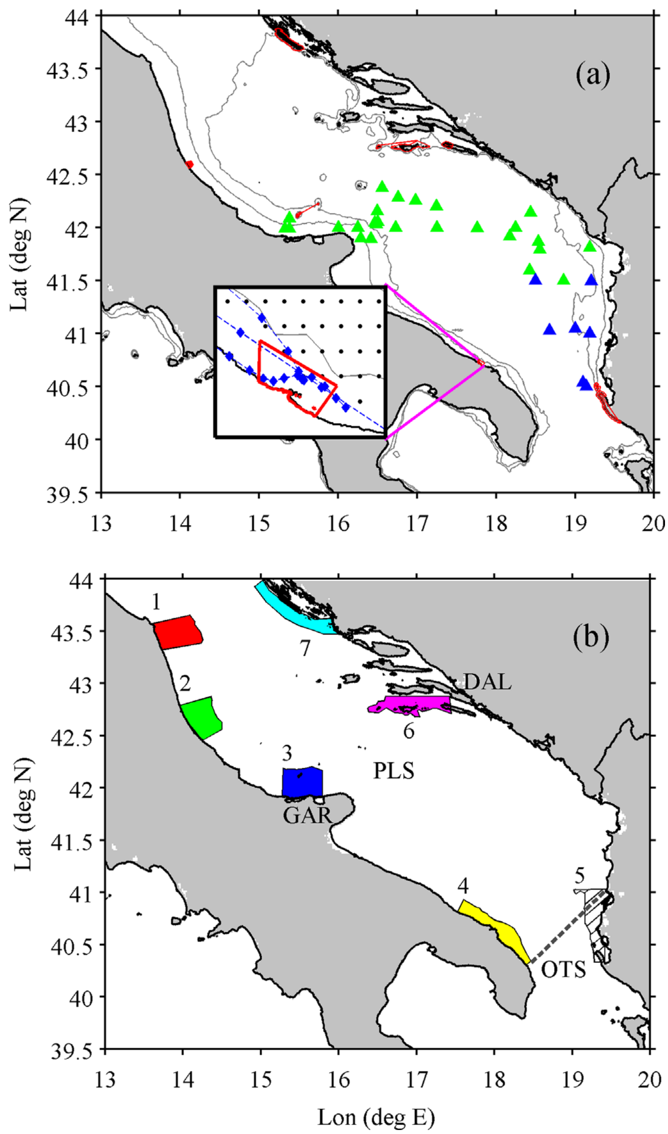

Fig. 1. (a) The Adriatic Sea with the CoCoPro drifter launch locations in 2013 and 2015 denoted by green and blue triangles, respectively. MPA boundaries are plotted in red. The 50 m and 100 m isobaths are plotted in gray. Inset: The Torre Guaceto MPA boundary is plotted in red, along with the ROMS grid points in the vicinity (black) and the three drifter trajectories that passed through the MPA (blue). (b) Coastal regions used for transport assessments: (1) Conero (Italy); (2) Torre del Cerrano (Italy); (3) Isole Tremiti (Italy); (4) Torre Guaceto (Italy); (5) Karaburun (Albania); (6) Mljet (Croatia); and (7) Kornati (Croatia). The Dalmatian Islands (DAL), Palagruza Sill (PLS), Gargano Promontory (GAR), and Otranto Strait (OTS) are also indicated. The dashed gray line denotes the southern boundary of the ROMS simulation.(For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

virtual particles and, therefore, is most applicable to the study of buoyant, passive tracers. While we make no attempt to apply our results to the dispersal of a specific species, this study will provide valuable information for resource managers and decision makers about average transit times and the potential for exchange between MPAs and their surroundings in the Adriatic Sea on ecologically relevant timescales (see Section 2.4).

First, we use CODE-type (Davis, 1985) surface drifters deployed in the Adriatic Sea from 1990 to 2015 to compute transit times and the connection percentage between regions (see Section 2.4). The drifters quantify the role of the surface circulation, summarized in Section 1.1, in connecting regions in the Adriatic Sea. While the drifter data provide important quantitative metrics of transport between regions, relatively few data are available and the results are subject to well-documented biases due to drifter mortality (Falco et al., 2000; Poulain and Hariri, 2013) that are partially accounted for in our analysis methods (see Section 2.4).

The second assessment uses a Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams, 2005) simulation of the Adriatic Sea during May–August 2013 and surface winds from the Consortium for Small-Scale Modeling (COSMO) atmospheric model (see Section 2.7) to investigate the effects of wind forcing on transport between regions. We focus on the period May–August 2013 in order to validate virtual particle trajectories from the ROMS simulation with surface drifter trajectories from a dedicated deployment in the central Adriatic Sea (see Section 2.2) during the same time. 115 500 virtual particle trajectories (300 virtual particles released every 24 h from 1 May to 17 July 2013 in five regions) enable computation of statistically robust connection percentages and mean transit times and provide useful qualitative information about transport pathways under different wind conditions. The virtual particle trajectories show that variable wind events do, in fact, influence surface Lagrangian pathways, and should be considered in resource management.

The remainder of this paper is organized as follows. Sections 1.1 and 1.2 review relevant studies of surface circulation and connectivity, respectively, in the Adriatic Sea. The regions, drifter data, ROMS and COSMO configurations, virtual particle tracking scheme, and analysis methods are described in Section 2. Results are presented in Section 3 and discussed in Section 4. We summarize and conclude in Section 5.

1.1. Review of surface transport in the Adriatic Sea

Cyclonic circulation dominates the large scales with northwestward flow on the east coast, in the east Adriatic current (EAC), and southeastward flow on the west coast, in the west Adriatic current (WAC) (Poulain, 1999; Burrage et al., 2009) with significant variability observed over a range of scales, from climatic, seasonal, and synoptic scales (Maurizi et al., 2004). Smaller cyclonic gyres exist in the northern, central, and southern Adriatic (Poulain, 1999). At the synoptic to seasonal timescales considered in this study, the circulation varies in response to air–sea interaction, river runoff, and wind forcing. Wind forcing affects the surface mesoscale circulation and can influence the behavior of river plumes and coastal currents (Orlić et al., 1994; Burrage et al., 2009; Poulain, 1999).

Northwesterly Mistral winds prevail in summer, southeasterly Sirocco winds in winter, and cold, strong northeasterly Bora winds typically occur in winter (Pasarić et al., 2009; Orlić et al., 1994; Bignami et al., 2007). Summertime northwesterly winds tend to be weaker but more steady (Pasarić et al., 2009). Ursella et al. (2006) examined the response of drifters to wind forcing in the northern and central Adriatic Sea using over 120 drifters released from September 2002–November 2003 and found that surface currents responded nearly instantaneously to the wind and were oriented within 15° of the wind vector.

Po river discharge and transient wind forcing, drive the WAC (Bignami et al., 2007; Burrage et al., 2009; Magaldi et al., 2010). Northwesterly and southeasterly winds blow parallel to the coast and, if persistent, lead to downwelling or upwelling, respectively, on the Italian coast. The WAC responds to downwelling-favorable winds by decreasing in width and increasing in vertical thickness (Magaldi et al., 2010; Burrage et al., 2009). Downwelling-favorable winds suppress the formation of instabilities in the WAC but relaxation of downwelling winds and transition to upwelling-favorable winds promote the formation of eddies and filaments through baroclinic instability as the WAC spreads offshore and decreases in vertical thickness (Magaldi et al., 2010; Poulain et al., 2004). Southeasterly winds can drive mixing (Pasarić et al., 2007; Magaldi et al., 2010) and have been observed to reverse the WAC (Orlić et al., 1994; Poulain et al., 2004).