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Connectivity patterns of coastal fishes following different dispersal scenarios across a transboundary marine protected area (Bonifacio strait, NW Mediterranean)

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ABSTRACT

The Strait of Bonifacio constitutes one of the rare transboundary Marine Protected Areas (MPA) of the Mediterranean Sea (between Sardinia, Italy and Corsica, France). Based on the hypothesis that no-take zones will produce more fish larvae, compared to adjacent fished areas, we modeled the outcome of larvae released by coastal fishes inside the no-take zones of the MPA in order to: (1) characterize the dispersal patterns across the Strait of Bonifacio; (2) identify the main potential settlement areas; (3) quantify the connectivity and the larval supply from the MPAs to the surrounding areas. A high resolution hydrodynamic model (MARS 3D, Corse 400 m) combined to an individual based model (Ichthyop software) was used to model the larval dispersal of fish following various scenarios (Pelagic Larval Duration PLD and release depth) over the main spawning period (i.e. between April and September). Dispersal model outputs were then compared with those obtained from an ichthyoplankton sampling cruise performed in August 2012. There was a significant influence of PLD to the connectivity between coastal areas. The synchronization between spawning and hydrodynamic conditions appeared to be determinant in the larval transport success. Biotic and abiotic parameters affecting the dispersal dynamic of fish larvae within the Strait of Bonifacio were identified and synthesis maps were established as a tool for conservation planning.

1. Introduction

1.1. Larval dispersion & early life history traits of fish

Most coastal marine fish species have a bipartite life cycle, divided in a relatively sedentary juvenile/adult stage and a dispersive pelagic early life stage (eggs/larvae) (Heath, 1992; Leis, 2002). Dispersal distances of Early Life stages of Fish (ELF) can reach up to 10–100s' of km, as shown in previous studies on reef fishes (McCleave et al., 1987; Kinlan and Gaines, 2003; Cowen et al., 2006; Purcell et al., 2009). The dispersal process of ELF is thus generally considered to be the principal driver of population connectivity and subpopulation persistence in marine fish populations (Cowen and Sponaugle, 2009). The replenishment of subpopulations will greatly rely on the recruitment process of newly settled individuals (Doherty and Fowler, 1994; Hastings and Botsford, 2006; Hjort, 2014). However, more recent studies have provided the evidence that dispersal distances of ELF are less important than previously thought and that local recruitment plays an important role in the larval supply of coastal fish populations (Shanks, 2009; Saenz-Agudelo et al., 2011). The larval dispersal is in fact a complex process difficult to predict as it relies on physical factors, such as the advection and diffusion, but also on biological

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factors (Werner et al., 1996; Pineda et al., 2007), such as egg buoyancy, Pelagic Larval Duration (PLD), availability of food and predation pressure operating at different spatial and time scales (Scheltema, 1986; Pineda et al., 2009) as well as on the behavior of ELF linked to their swimming and orientation abilities (Leis and Lockett, 2005; Leis, 2006; Staaterman et al., 2012).

1.2. The Mediterranean Sea and its marine protected areas

The Mediterranean Sea is one of the world's marine biodiversity hotspot (Bianchi and Morri, 2000; Coll et al., 2010) and concentrates between 4 and 18 % of known marine species (Mouillot et al., 2011). It is also one of the most impacted ecosystems by fisheries (Tudela, 2004) and considered as a highly vulnerable sea (Cognetti and Curinigalletti, 1993; Coll et al., 2012). With the aim to sustainably protect and to ensure marine biodiversity and related ecosystem goods and services, following the Convention on Biological Diversity and the Barcelona Convention, a target of 10% protection of the marine and coastal Mediterranean waters representative of the Mediterranean diversity has been set to reach by 2020 (Olsen et al., 2013). To date, 677 Marine Protected Areas (MPAs) have been identified in the Mediterranean Sea covering 87 500 km^2, i.e. 1.1% of the sea surface of the Mediterranean and up to 4.6%, including the Pelagos Sanctuary for marine mammals (Gabrié et al., 2012). Marine Protected Areas are particularly suited management tools for coastal areas, as they protect simultaneously the living resources from extraction, but also the essential habitats on which they rely (Agardy, 1994). Since the implementation of the first MPA around 1920–1930 along the Californian coasts (Sobel and Dahlgren, 2004), evidence has been provided by MPAs around the world, that these management tools induce biological responses, mainly increasing the densities of populations, biomass, average organism size and diversity (Halpern and Warner, 2002; Halpern, 2003).

One future target identified within the framework of the Barcelona Convention, will be to design networks of MPAs at a seascape scale rather than isolated MPAs at a regional or national scale (Olsen et al., 2013). These MPA networks will consist of individual MPAs sufficiently interconnected to provide genetic, demographic and ecological stepping-stones. According to the IUCN-WCPA (International Union for Conservation of Nature – World Commission on Protected Areas), the synergistic operation of these interconnected MPAs will help to implement more efficiently their ecological aims (Olsen et al., 2013). At present, the designation and the size of MPAs is still very uneven across Mediterranean countries, being mostly located in the northern basin (96% in Spanish, French, Italian and Greek waters). These MPAs range between 0.003 and 4000 km^2, but most of them are small ranging between 11 and 25 km^2.

In a context promoting ecological coherent MPA networks in the Mediterranean, an international marine park was established in 2012 in the Strait of Bonifacio – SB (PMIBB, 2012) which separates the island of Corsica (France) and of Sardinia (Italy). This marine park links together both the French MPA of the "Bouches de Bonifacio" and the Italian MPA of the "Archipelago de la Maddalena" and constitutes nowadays one of the rare transboundary MPAs of the Mediterranean Sea (Gabrié et al., 2012).

The general purpose of this work was thus to characterize the effects of the hydrodynamic system of the SB on larval dispersal in order to provide fundamental guidelines for the marine spatial planning in the recently established international marine park of the SB. Based on the hypothesis that no-take zones or MPAs with enhanced protection will produce more fish larvae, compared to adjacent fished areas, due to a higher reproductive output and fitness and a denser population of spawners/brood stock, we modeled the outcome of larvae released by coastal fishes inside the areas of enhanced protection of the SB in order to: (1) characterize the dispersal patterns across the SB, (2) identify the main potential settlement areas, and (3) quantify the connectivity and the larval supply from the MPAs to the surrounding areas. Larval dispersal was modeled following various scenarios in order to investigate the effect of the seasonal variability and of biological parameters of early life stages, such as the pelagic larval durations (PLDs) and the egg type (benthic or pelagic). Additionally, dispersal patterns were compared with those obtained by a larval dispersal model based on the distribution of fish larvae issued from a sampling campaign.

2. Material and methods

2.1. Study area and hydrographic conditions

The Strait of Bonifacio (SB) is a 13 km wide strait separating the islands of Corsica in the North and of Sardinia in the South, located at the meeting-point between the western Mediterranean and Tyrrhenian basin (Fig. 1). Straits are considered as naturally formed passage, narrow enough to constrain surface flows (Astraldi et al., 1999). These choke points are characterized by high seasonal variability of currents (Astraldi et al., 1999). Due to its geomorphological configuration, bathymetry and the presence of numerous islands and islets, the SB is a complex area in term of currents (Gérigny, 2010). These currents have an average intensity of 0.5 m s^{-1} and can reach up to 1.46 m s^{-1} (Gérigny et al., 2011). The general circulation in this area is mainly influenced by two prevailing orographically controlled winds, a western wind (52–54% of the winds) and an eastern wind (26%); (De Falco et al., 2011).

Across the marine park of the SB, various protection levels are applied (Sorgente et al., 2012), where gears and the fishing catches are limited (artisanal fishing, spear fishing), depending on the levels of protection. In the enhanced protection areas of the MPA, all recreational fishing activities are forbidden. The SB counts in total seven distinct enhanced protection areas, each of them include small fully protected zones where all kinds of fishing activities are prohibited.

Habitat mapping in the SB shows that rocky substratum and *Posidonia oceanica* sea grass are the predominant habitat types between 0 and 30 m depth (Pasqualini et al., 1998), which is the bathymetric preferendum for most Mediterranean coastal fish species (Harmelin-Vivien et al., 1995). *P. oceanica* seagrass meadows are particularly dense and extensive along the coasts of the Island of Corsica compared to other coastal French Mediterranean areas (Pasqualini et al., 1998). *P. oceanica* sea grass meadows are recognized to be essential habitats for many coastal fishes at the adult stage (Bell and Harmelin-Vivien, 1982; Moranta et al., 2006; Kalogirou et al., 2010), but are also perceived as an important nursery habitat for the early life stages (Garcia-Rubies and Macpherson, 1995; Harmelin-Vivien et al., 1995).

2.2. Larval dispersal modeling

2.2.1. Biophysical model

Larval dispersal was modeled using Ichthyop, a coupled biophysical Lagrangian particle tracking tool (Lett et al., 2008). The CORSE-400 m hydrodynamic model is based on the MARS-3D code, the 3D hydrodynamic Model for Application at the Regional Scale (Lazure and Dumas, 2008). CORSE-400 m was implemented with a configuration of 400 m horizontal resolution and 30 sigma layers, which covers the entire Corsican Island, the SB and the most southern part of Sardinia Island. CORSE-400 m takes its boundary conditions on the North-western Mediterranean configuration –