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The role of the Azores Archipelago in capturing and retaining incoming particles

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ABSTRACT

The capacity of the Azores Archipelago to capture and retain incoming particles and organisms that are drifting with the oceanic currents was the main focus of this study. Using the Hybrid Coordinate Ocean Model coupled with the Connectivity Modeling System (an offline Lagrangian tool) a series of experiments were conducted to determine: i) the origin of the particles that reach the archipelago, ii) the capacity of each island sub-group to retain incoming particles and organisms, as well as the iii) oceanographic phenomena that lead to their transport and retention. The Gulf Stream (GS) and the westward propagating eddy corridors were identified as the main transport pathways affecting the Azores region. Eddy Kinetic Energy from altimetry data and Lyapunov exponent analysis suggest that eddies and filaments are the main delivery mechanisms. In the upper mixed layer, the GS and its associated eddies are a predominant regional oceanographic feature injecting particles from the north and west boundaries toward the Azores. The capacity to capture particles of each island sub-group was directly proportional to their size, while the retention time within the Azores region increased with depth, associated with the decrease in velocity of the intermediate water currents. This study opens new prospects to understand transport in the Mid-Atlantic (Azores) region and the islands' role in marine colonization, dispersal, fisheries recruitment and speciation.

1. Introduction

The Azores Archipelago (AZ), located in the middle of the North Atlantic Ocean (37 °–40 °N, 25 °–31 °W), is the most isolated of the Macaronesian Islands (Azores, Madeira and Canary Archipelagos): 580 km north east of Madeira, 1400 km west of Europe, and 2000 km east of North America. It consists of nine volcanic islands disposed in three separate groups (EG—Eastern Group; CG—Central Group; WG—Western Group) (Fig. 1) and several small islets, distributed along a ~600 km tectonic zone, rising from the ocean basin ~4000 m below. As oceanic islands, the AZ are characterized by a narrow or absent island-shelf and its deep waters are punctuated by 461 seamounts. This uneven topography together with its geographic isolation, geologic youth (thought to be of Miocene origin; Briggs, 1970; Schmincke, 1973), small size, temperate climate and the presence of extreme environments associated with hydrothermal vents, allows the existence of different marine ecosystems with habitats where complex marine food webs are assembled, making the AZ a hot-spot of biodiversity in the Atlantic Ocean (Aboim, 2005). However, the dynamics of these microecosystems are poorly understood (Pinho and Menezes, 2009).

Of the 500 fish species identified in this region, around 50–60 are currently exploited by a multi-segmented fishing fleet (Morato et al., 2001), and these marine resources are central to the local economy of the archipelago. These fishing activities, mostly artisanal (Rodrigues, 2008) and small scale (Carvalho et al., 2011), are concentrated in areas less than 600 m deep, restricted to the narrow coastal fringe around the islands and to the nearby banks and seamounts (Menezes, 2003; Silva and Pinho, 2007; Morato et al., 2008; Neilson et al., 2012). These areas represent less than 1% (~7000 km^2) of the nearly one million km^2 (948,439 km^2) corresponding to the Azores part of the Portuguese EEZ (Menezes, 2003). The natal recruitment supplying these fisheries depends greatly on the retention capacity of the islands and seamounts.

The regional oceanography of the Azores Archipelago is governed by the North Atlantic Subtropical Gyre, under the direct influence of the Gulf Stream (GS). Southeast of the Grand Banks, the GS breaks into two branches (Fig. 1b): the North Atlantic Current (NAC), which flows in direction of Northern Europe, and the Azores Current (AzC), which drifts south-westward and crosses the Mid-Atlantic Ridge south of the AZ (Käse and Siedler, 1982; Gould, 1985; Onken, 1993). The AzC is the northern border of the subtropical gyre, and near Madeira

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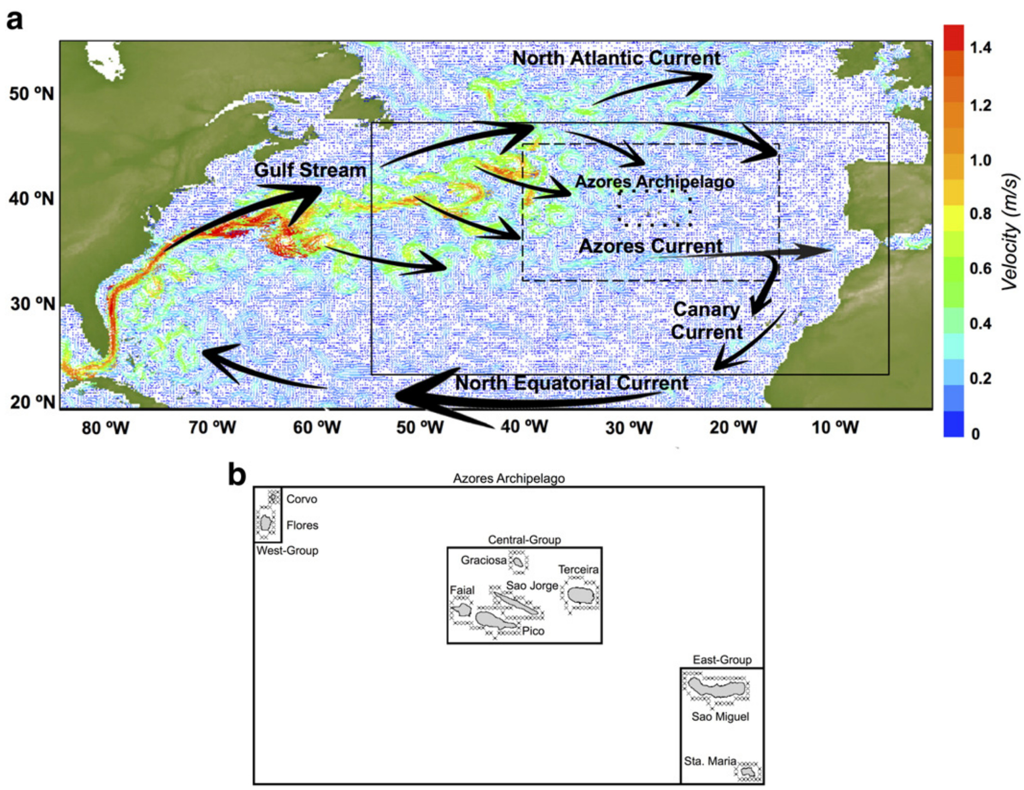

Fig. 1. (a) Map of the study area representing the North Atlantic Subtropical Gyre and its associated currents: the Gulf Stream, the North Atlantic Current, the Azores Current, the Canary Current and the North Equatorial Current. The solid line defines the HYCOM domain of this study, the dashed line defines the source box, and the dotted line defines the Azores Box. (b) Zoom of the Azores Box (Azores Archipelago) with the three sub-groups of islands and their respective sink boxes. Black x's represent the release points of the *Backward Experiment*.

(around 16 °W) it splits again in one branch that penetrates the Gulf of Cádiz, and the second one that veers southward feeding the Canary Current (CaC) down the African coast (Johnson and Stevens, 2000). This south branch eventually connects to the westward North Equatorial Current, closing the gyre when it merges with the GS further west (Siedler and Onken, 1996; Tychensky et al., 1998). The AzC is characterized by a complex mesoscale eddy system, generating on its eastward drift eddies and meanders that propagate westward (Le Traon et al., 1990; Stammer, 1997; Richardson, 1983; Fratantoni, 2001; Reverdin et al., 2003; Volkov, 2005). Using merged altimeter data Sangrà et al. (2009) identified two westward propagating corridors of eddies north and south of the Azores Front. Eddies with a life span of more than six months had a zonal dispersive range between 33 ° and 38 °N, some of which originated from the Azores Front.

Several studies have emphasized the impact of the water circulation around small islands and archipelagos on population connectivity, larval dispersal and species assemblages (Jones et al., 1999, 2005; Almany et al., 2007; Burgess et al., 2007; Paris et al., 2007; Hamann et al., 2011; Andutta et al., 2012; Sala et al., 2013); however until now, no study was focused on the Azores region. For this reason, in order to understand the colonization, dispersal, fisheries recruitment and speciation processes, it is necessary to comprehend the oceanographic phenomena that affect the Archipelago. Considering the oceanographic context and location of the Azores, the aim of the present study is to analyze the capacity of these islands to capture and retain incoming particles and organisms that drift with the oceanic currents. There are three questions we address: (i) what is the origin of the majority of the particles that reach the islands? (ii) how do the different island sub-groups contribute to the retention process? and (iii) which oceanographic phenomena affect the transport and retention mechanisms? To answer these questions a series of numerical experiments were performed using the Connectivity Modeling System (CMS), an off-line Lagrangian tool, attached to an ocean circulation model, as described in detail in Section 2. The results of the different numerical experiments are presented in Section 3, and the general discussion and main conclusions are in Section 4.

2. Methodology

For this study the HYbrid Coordinate Ocean circulation Model (HYCOM; http://hycom.org/) was used. HYCOM evolved from the Miami Isopycnic-Coordinate Ocean Model (MICOM) (Bleck and Boudra, 1981; Bleck and Smith, 1990), after the implementation of the hybrid vertical coordinate system (Bleck and Benjamin, 1993). HYCOM solves the hydrostatic primitive equations in a free surface mode. Detailed information about the governing equations, numerical algorithms and the available vertical mixing schemes can be found in Bleck (2002), Halliwell (2004) and Chassignet et al. (2006). This study used the US Navy Research Laboratory (NRL) solutions from a global circulation study, GLBa0.08, experiment 05.8, which has a horizontal grid resolution of ~8 km (1/12°) and 32 vertical layers. The global bathymetry was derived from a quality controlled NRL DBDB2 dataset, and the surface forcing is from Navy Operational Global Atmospheric Prediction System (NOGAPS), which includes wind stress, wind speed, heat fluxes (using the bulk formula), and precipitation. This is a free-run, which does not include data assimilation. Although this is a global model solution, our transport study was focused on the upper 500 m of the Azores Archipelago Subregion, from 32 °N to 45 °N in latitude, and from 40 °W to 16 °W in longitude (“source box”, see below; Fig. 1). In order to contextualize the Basin scale ocean dynamics, enabling broader model-data comparisons, a larger HYCOM domain was contemplate, from 22 °N to 47 °N in latitude, and from 55 °W to 5 °W in longitude. A 3-year solution (2004 - 2006) was considered, enough time to allow particles to travel across the study sub-region.

A comparison of the model with Argo (global array of temperature/salinity profiling floats) profiles, assured a good representation of the