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How is the surface Atlantic water inflow through the Gibraltar Strait forecasted? A lagrangian validation of operational oceanographic services in the Alboran Sea and the Western Mediterranean

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ABSTRACT

An exhaustive validation of some of the operational ocean forecast products available in the Gibraltar Strait and the Alboran Sea is here presented. The skill of two ocean model solutions (derived from the Eulerian ocean forecast systems, such as the regional CMEMS IBI and the high resolution PdE SAMPA) in reproducing the complex surface dynamics in the above areas is evaluated. To this aim, in-situ measurements from the MEDESS-GIB drifter buoy database (comprising the Lagrangian positions, derived velocities and SST values) are used as the observational reference and the temporal coverage for the validation is 3 months (September to December 2014). Two metrics, a Lagrangian separation distance and a skill score, have been applied to evaluate the performance of the modelling systems in reproducing the observed trajectories. Furthermore, the SST validation with in-situ data is carried out by means of validating the model solutions with L3 satellite SST products. The Copernicus regional IBI products are evaluated in an extended domain, beyond the Alboran Sea, and covering western Mediterranean waters. This analysis reveals some strengths of the presented regional solution (i.e. realistic values of the Atlantic Jet in the Strait of Gibraltar area, realistic simulation of the Algerian Current). However, some shortcomings are also identified, with the major one being related to the simulated geographical position and intensity of the Alboran Gyres, particularly the western one. This performance limitation affects the IBI-modelled surface circulation in the entire Alboran Sea. On the other hand, the SAMPA system shows a more accurate model performance and it realistically reproduces the observed surface circulation in the area. The results reflect the effectiveness of the dynamical downscaling performed through the SAMPA system with respect to the regional IBI solution (in which SAMPA is nested), providing an objective measure of the potential added values introduced by the SAMPA downscaling solution in the Alboran Sea.

1. Introduction

Nowadays, there is a growing interest in monitoring the marine environment, which serves as a stimulus for the scientific development of models that allow the marine prediction and hence better understanding of ocean dynamics and processes. Operational oceanography is a growing field that, based on major scientific advances, is being able to provide services and products for monitoring and forecasting of the ocean. These operational oceanographic products and related services, comprising both observing systems and numerical models, are focused on assessing the real state and dynamics of the seas and on providing predictions of different variables on various time and spatial scales. The operational oceanography products and services are useful not only for the scientific oceanographic community but also for other potential end-users and fields (e.g. fisheries, aquaculture, navigation and ship routing, search and rescue operations, accidental oil spill preparedness and response, harbour operations and design, coastal management, tourism and other), proving unequivocally their contribution to the global societal benefit (Chassignet and Verron, 2006).

The Gibraltar Strait is the natural connection between the Mediterranean Basin and the Atlantic Ocean and a hot spot of the world ocean, from geostrategic and scientific standpoints. The area

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is characterised by a very intense maritime traffic (with an estimated 100,000 ships per year) together with a noticeable port activity (important harbours, such as Bahia de Algeciras, Gibraltar, Tanger and Tanger-Med, are located in the area). It is also a high risk area in terms of oil spill events. All these activities together with an intense human migration entail high number of search and rescue operations in the area. For instance, only in year 2013, 492 emergencies were addressed, involving 3869 people (data from Salvamento Marítimo, the Spanish Search and Rescue Agency, *pers. comm.*). All these facts emphasise the necessity for having efficient operational oceanographic services to monitor and forecast these waters.

From an oceanographic point of view, the Strait is the scenario of a well-studied baroclinic exchange between two basins with different densities. The net loss of freshwater in the Mediterranean Sea, resulting from the evaporation exceeding both precipitation and river runoff effects, represents the main driving force of the circulation through the Strait, which is marked by two counter flowing currents: in the upper layer, warm and relatively fresh Atlantic water (Salinity ~36.2 psu) flows eastward, whereas colder and saltier Mediterranean waters (salinity ~38.5 psu) flows westward as an undercurrent. Various estimations of the transport through the strait resulting from this set-up are provided in Bryden et al. (1994), Send and Baschek (2001), García Lafuente et al. (2007), Soto-Navarro et al. (2010).

A diagram presenting the Alboran Sea surface circulation is shown in Fig. 1. The surface Atlantic water inflow through the Strait and its further flow eastward in the Alboran Sea determine the surface circulation in the area, which is characterised by very strong current regimes and complex dynamics.

This strong Atlantic eastward jet-like current when combined with the topography of the Alboran basin develops a subcritical flow, which evolves into permanent anticyclonic gyres. The Atlantic water jet exhibits a wavelike path around the Western and Eastern Alboran Gyres (WAG and EAG, respectively). Further east, the Almeria-Oran front (Tintoré et al., 1988) separates two water masses: the recent fresh Atlantic water and the saltier Western Mediterranean water. This frontal structure forces the Atlantic flow to move towards the African coast where part of the flow is re-entrained into the Alboran Gyres, whereas some Atlantic water continues its eastward movement, feeding the so-called Algerian Current that flows along the steep bathymetry of the northern African coast (Arnone et al., 1990). Furthermore, the combination of strong tidal effects at the entrance of the Strait, noticeable wind effects, mainly dominated by strong regional westerlies and easterlies regimes, and the existence of re-circulations at both margins of the jet configure a very complex picture of the surface currents in the area; these pose a challenge for modelling. Indeed, there is a long list of works focused on modelling the area and the main processes that configure its dynamics. The modelling research performed in the area has been focused on: the tidal dynamics (Tejedor et al., 1998), the barotropic flows due to the wind and atmospheric pressures (Gomis et al., 2006), simulation of the

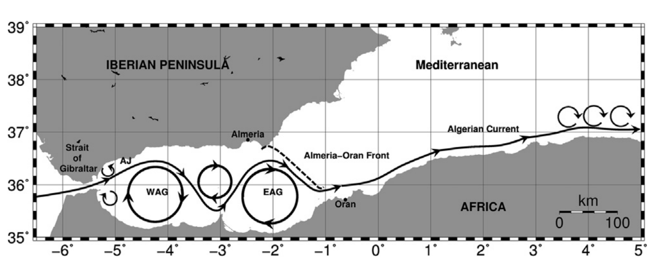

Fig. 1. Scheme of the surface circulation in the Alboran Sea and the Algerian Basin. Features such as the Atlantic Jet (AJ), Western and Eastern Alboran Gyres (WAG and EAG, respectively) and the Almeria-Oran Front together with the Algerian Current are depicted.

Alboran Gyres formation using baroclinic models (Speich et al., 1996), dynamics of the Alboran Gyres together with their variability (Sánchez-Garrido et al., 2013), the volumetric transport through the Strait (Sánchez-Román et al., 2009; Sannino et al., 2002; Aznar, 2014 and Aznar et al., 2016), the thermohaline properties of the outflows (Soto-Navarro et al., 2014) and the impact that an accurate modelling of the Gibraltar Strait have on other regions or circulation features such as the multi-decadal Mediterranean circulation (Sannino et al., 2009). Finally, in recent years there is also a growing interest in modelling the ecohydrodynamics and the biological productivity of the area linked to its physical oceanographic conditions (Skliris and Beckers, 2009 and Sánchez-Garrido et al., 2015).

The increase of the knowledge on the ocean processes in the area and the improvement of the model capabilities have been accompanied by a growing demand for ocean related information arising from a variety of disciplines (e.g. scientific research on marine ecosystems, monitoring of seawater quality, decision-making support for marine safety and coastal management, ship-routing, etc.). Considering the above, it is not surprising that operational oceanography has undergone a rapid maturation process in recent years. This process is observed globally. Thus, at a pan-European level, the Copernicus Marine Environmental Monitoring Service (CMEMS, http://marine.copernicus.eu/), which has been fully operational from May 2015, represents the demonstration of a noticeable advancement in the European operational oceanography capabilities.

This "core" operational oceanographic CMEMS service is based on developments of numerical solutions and improvements of cutting-edge modelling algorithms to simulate ocean circulation using high computational resources as well as an enhanced combined use of observational data sources and modelling solutions, both for data assimilation and for validation purposes. The roadmap to this pan-European operational oceanographic core service was outlined in the framework of the EU GMES initiative (Drinkwater et al., 2005; Ryder, 2007) and it was evolved and matured through the MyOcean projects (Bahurel and Co-Authors, 2010).

The CMEMS forecast service is delivered by different Monitoring and Forecasting Centres (MFC), which cover six areas of the European seas. For the Gibraltar Strait area, two of them: the Mediterranean (MED-MFC) and the Iberia-Biscay-Ireland (IBI-MFC) deliver daily forecast products. More specifically, the IBI-MFC provides a regional 1/36° operational forecast (updated on daily basis since April 2011) and a 1/12° multi-year (2002-2014) reanalysis product (Sotillo et al., 2015). Both products are freely available through the CMEMS website (http://marine.copernicus.eu/) and delivered in accordance with end-user community demands.

Through the delivery of these products, CMEMS plays a "core" service role, focusing on providing reference regional standard products, and not being aimed to generate tailored products for specific end-users. Nevertheless, the availability of these CMEMS core products enables the intermediate users to generate new added-value "downstream" services that meet the needs of specific end-users. In this context, the SAMPA initiative promoted and developed by Puertos del Estado (PdE) and the Port Authority of Algeciras Bay, emerges as one of the most ambitious initiatives to boost operational oceanography in the Gibraltar Strait area. In the framework of this initiative, new monitoring instruments (i.e. met-wave-ocean buoys, meteorological stations and tide gauges) were deployed and new high-resolution forecast model services (simulating waves, wind and 3D ocean circulation) were developed. Through this enhancement of in-situ observational and modelling capabilities, from 2013 the harbours have been relying on tailor-made software application, the SAMPA-CMA, to provide customised access to the met-ocean information available as well as advanced viewing capabilities and services, such as a user alert system (through e-mail and SMS). The PdE SAMPA Ocean Forecast Service (Sánchez-Garrido et al., 2013) is based on a model