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From basin to sub-basin scale assessment and intercomparison of numerical simulations in the Western Mediterranean Sea

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ABSTRACT

This study describes a quantitative evaluation of simulations in the western Mediterranean Sea at basin and sub-basin scales. The Mediterranean Forecasting System and the Mercator-Océan simulations provide operational ocean forecasts and hindcasts in the Mediterranean, and are also used as initial and boundary conditions for regional models. In this context, hindcast simulations from 2009 to 2012 are compared with available multi-platform observations at various spatial and temporal scales to evaluate their performance. Both simulations reproduce well the observed mean conditions and variability over the last years. The sub-basin scale analyses of the three-dimensional ocean structures and water mass properties reveal seasonal and regional temperature and salinity errors at the surface in both simulations, as well as significant biases at intermediate and deep layers in the Mediterranean Forecasting System. The simulated surface geostrophic velocities are weaker than those derived from altimetry, and circulation biases persist in the Balearic Sea. Additionally, the seasonal existence of the Alboran gyres is not well reproduced in either simulation. The identification of regional simulation biases is essential to advance from global to regional and local scale forecasting, in particular, improving the representation of the local physical processes and their interactions with the sub-basin dynamics and the general circulation.

1. Introduction

The Mediterranean Sea is a particularly interesting oceanic basin for climatic, environmental and physical studies since most of the ocean physical processes found throughout the world ocean occur in this basin (Malanotte-Rizzoli et al., 2014). These processes play an important role in governing marine sub-systems dynamics (biology, acoustics, and sedimentology). The Mediterranean Sea circulation is composed of three predominant and interacting spatial scales: basin scale (including the thermohaline circulation), sub-basin scale and mesoscale. Its complexity is now well established because of the wide range of spatio-temporal variability scales and their interaction, forming a highly variable general circulation (Robinson et al., 2001).

Despite the increasing amount of available ocean observations over the last decades, which has greatly enhanced our knowledge about the ocean state, variability and dynamics, these observations remain limited in time and space. The satellite-derived products are restricted to the surface and the coverage of *in situ* observations is generally sparse. In this context, ocean numerical simulations provide a complementary source of information, which is very useful to better understand the complexity of ocean dynamics at various spatial and temporal scales. In the Mediterranean Sea, the internal Rossby radius of deformation is $0(10–15$ km), which is four times smaller than typical values of the world ocean (Robinson et al., 2001). Therefore, the study of the ocean system requires high resolution in both observations and ocean models. The increase of computer power and the progress in numerical techniques over the last decades have led to an increase of the spatial resolution of ocean models, enabling them to represent or resolve the mesoscale dynamics, and thus be potentially more realistic. High resolution modeling representing realistic ocean variability at various spatial and temporal scales is a challenge for both the ocean modeling and the operational oceanography communities in the coming years.

Comparisons of numerical simulations with multi-platform observations are necessary to assess the performance of the simulations and to evaluate their capacity to reproduce observed ocean features at various temporal and spatial scales. These comparisons are also used to quantify the possible simulation biases and attempt to determine their origins. This in turn allows to improve the hindcast and forecast simulations, to study and better understand ocean physical processes in well simulated regions and to better address ocean variability analyses at interannual and longer

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time scales. Several studies have compared simulations in the Mediterranean Sea with observations investigating the mesoscale, the seasonal and interannual variability of the surface circulation using altimetry (Bouffard et al., 2008; Pascual et al., 2014; Vidal-Vijande et al., 2011), the basin scale (the whole Mediterranean, western and eastern parts) interannual variability (Adani et al., 2011; Demirov and Pinardi, 2002; Pinardi et al., 2013; Vidal-Vijande et al., 2011), or major physical processes impacting on the general circulation such as water mass formation and exchanges (Ben Ismail et al., 2012; Herrmann et al., 2010; Juza et al., 2013), and the mesoscale dynamics (Bouffard et al., 2012; Guihou et al., 2013).

In the framework of the European MyOcean project (http://www.myocean.eu), the Mediterranean Forecasting System (MFS) (Tonani et al., 2008, 2014) and Mercator-Océan (Lellouche et al., 2013) are the two current operational systems covering the whole Mediterranean Sea. Both forecast and hindcast numerical simulations of the two systems are available and provide initial and/or lateral boundary conditions for higher resolution regional models which are required to study regional and coastal dynamics and to enhance our understanding of the ocean dynamics. High resolution regional models are also necessary to better represent the wide range of spatio-temporal ocean variability, including the mesoscale which is essential for operational applications (e.g. search and rescue, fishery management, oil spill response). Most of regional operational models in the Mediterranean Sea are nested into MFS such as the Adriatic Forecasting System (Oddo et al., 2005), the Sicily Channel Regional Model (Olita et al., 2012), the Tyrrhenian Sea Forecasting (Vetrano et al., 2010), the Aegean-Levantine Forecast System (Korres and Lascaratos, 2003) or the Western Mediterranean Operational Forecasting System (Juza et al., submitted for publication). Mercator is also used to force regional models at the boundary such as the Iberian Biscay Irish regional system (Cailleau et al., 2012). Both Mercator and MFS have been progressively improved through quantitative comparisons of forecasts and hindcasts with observations and sensitivity tests (Adani et al., 2011; Lellouche et al., 2013; Oddo et al., 2009; Tonani et al., 2009). Nevertheless, most of assessments of simulations in the Mediterranean Sea are based on basin scale features and metrics (Oddo et al., 2009; Tonani et al., 2009; Vidal-Vijande et al., 2011) partially because of the lack of data at sub-basin scale. Regional quantitative assessments are now possible with the substantial increase of observational data, and are needed to detect regional biases and to improve the local physical processes, the sub-basin scale dynamics and the general circulation.

In this study, a regional and multi-scale assessment approach is proposed. The hindcast MFS and Mercator simulations are evaluated and quantitatively compared at sub-basin scale with available multi-platform observations (*in situ* measurements and satellite products) over the recent 2009–2012 period, during which new observations (such as glider data) and products have been made available. Statistical diagnostics have been developed to assess and inter-compare the simulations at various spatial and temporal scales, in different dynamical regions and in key sections. The assessment focuses on the Western MEDiterranean Sea (WMED) which in this study extends from the Strait of Gibraltar to the Corsica-Sardinia Islands at 9°E (Fig. 1). The assessment will address the ocean surface features and their temporal variability as well as the vertical ocean structure from basin to sub-basin scales. Additionally, as water mass formation and exchanges have a dynamical impact on the ocean stratification and circulation, simulated water mass characteristics are also examined in formation areas and at "choke points" of the WMED.

The paper is organized as follows. An overview of the study area is first given in Section 2. Section 3 introduces the numerical simulations which are assessed in this study. The methodology, based on multi-platform observations and multi-scale assessment, is described in Section 4. In Section 5, the simulations are evaluated in terms of temporal mean conditions, circulation and variability at basin scale. Section 6 extends the assessment to sub-basin and local scales investigating regional variability and ocean processes. Finally, conclusions are given in Section 7.

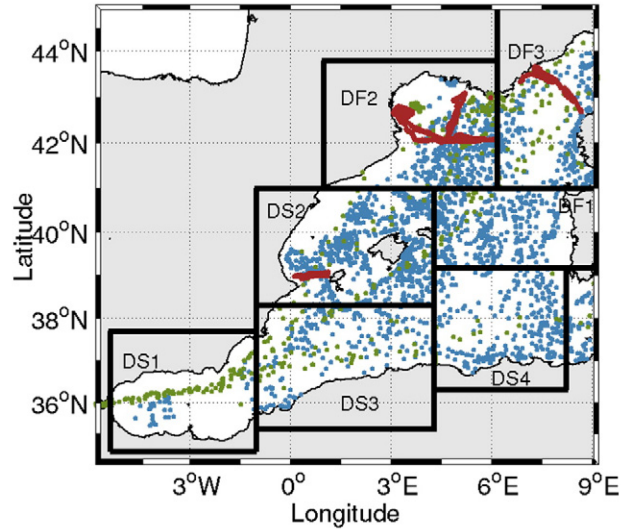

Fig. 1. Domain of study. The colored points indicate the position of *in situ* hydrographic profiles from Argo floats (blue) and XBTs (green) over the period 2009–2012, and glider sections (red) in 2011. The black boxes delimit the regions, as defined in Manca et al. (2004), in the western Mediterranean Sea: Alboran Sea (DS1), Balearic Sea (DS2), western and eastern Algerian (DS3 and DS4), Algero-Provençal (DF1), Liguro-Provençal (DF2) and Gulf of Lion (DF3).

2. Western Mediterranean Sea overview

2.1. General surface circulation

The Atlantic Jet (AJ) enters the Alboran Sea through the Strait of Gibraltar bringing Atlantic Water (AW) into the Mediterranean Sea (Viúdez et al., 1998). The AJ, flowing with a velocity of ~1 m/s, feeds the quasi-permanent Western Alboran Gyre (WAG) and drives the circulation in the Alboran Sea (Baldacci et al., 2001). The AJ meanders eastwards and forms also the intermittent Eastern Alboran Gyre (EAG) in the eastern part of the Alboran basin (Tintoré et al., 1988). The eastern boundary of the EAG is defined by the Almeria-Oran front. Farther east, the AW flows eastwards, forming the Algerian Current, along the North African coast until crossing the Sardinia Channel (8.5°E) (Millot, 1999).

In the northern part of the WMED, the northward currents along each side of Corsica join and form the Northern Current (NC) in the Ligurian Sea (Millot, 1999). This permanent current flows south-westwards along the French and Spanish coast. In the Balearic Sea, the NC flows through the Ibiza Channel or retroflects cyclonically over the northern slopes of the Balearic Islands to form the quasi-permanent Balearic Current (BC) (Pinot et al., 1995). The Catalan and Balearic fronts separate the NC and the BC, respectively, from the old AW in the center of the Balearic Sea (Font et al., 1988). The ocean dynamics in the Balearic Sea is particularly complex and variable. The bathymetry may increase the (sub-)mesoscale activity (e.g. eddies, filaments and shelf-slope flow modifications) affecting the meridional water mass exchanges between the north-western (Gulf of Lion) and the south-western (Algerian Sea) Mediterranean through the Balearic Channels (Astraldi et al., 1999; Pinot et al., 2002).

2.2. Water mass characteristics

The WMED is a four-layer system with water masses originating from the Atlantic Ocean and the eastern Mediterranean Sea or formed in the northern WMED. The AW gets into the Alboran Sea at the surface. Farther east, it is advected eastwards by the Algerian Current along the