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Seasonal and interannual variability of dissolved oxygen around the Balearic Islands from hydrographic data

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ABSTRACT

Oceanographic data obtained between 2001 and 2011 by the Spanish Institute of Oceanography (IEO, Spain) have been used to characterise the spatial distribution and the temporal variability of the dissolved oxygen around the Balearic Islands (Mediterranean Sea). The study area includes most of the Western Mediterranean Sea, from the Alboran Sea to Cape Creus, at the border between France and Spain. Dissolved oxygen (DO) at the water surface is found to be in a state of equilibrium exchange with the atmosphere. In the spring and summer a subsurface oxygen supersaturation is observed due to the biological activity, above the subsurface fluorescence maximum. Minimum observed values of dissolved oxygen are related to the Levantine Intermediate Waters (LIW). An unusual minimum of dissolved oxygen concentrations was also recorded in the Alboran Sea Oxygen Minimum Zone. The Western Mediterranean Deep Waters (WMDW) and the Western Intermediate Waters (WIW) show higher values of dissolved oxygen than the Levantine Intermediate Waters due to their more recent formation. Using these dissolved oxygen concentrations it is possible to show that the Western Intermediate Waters move southwards across the Ibiza Channel and the deep water circulates around the Balearic Islands. It has also been possible to characterise the seasonal evolution of the different water masses and their dissolved oxygen content in a station in the Algerian sub-basin.

1. Introduction

The Balearic Islands are the natural limit present between two sub-basins of the Western Mediterranean Sea, viz., the Algerian and Balearic sub-basins (Fig. 1). The Algerian sub-basin receives fresh surface water from the Atlantic Ocean (Atlantic Water, AW), and its circulation is mainly driven by density gradients. The Balearic sub-basin contains the colder and saltier AW that has remained for a longer time in the Mediterranean (resident AW), and its circulation is affected by atmospheric forcing (Hopkins, 1978). The Mallorca and Ibiza channels play an important role in the regional circulation of the water masses in the area. Their topography controls the exchanges between the two sub-basins (Pinot et al., 2002). Consequently, significant differences are visible between the general hydrodynamic conditions that affect the northern and the southern regions of the Balearic Islands. The confluence of the fresher and resident surface AW around the Balearic Islands triggers ocean fronts that affect the dynamics (Balbín et al., 2014–this issue; López-García et al., 1994).

Two intermediate waters are present surrounding the Balearic Islands, viz., the Levantine Intermediate Water (LIW) and the Western Intermediate Water (WIW). The LIW, formed in the Eastern Mediterranean Sea, is characterised by an absolute maximum of salinity, a relative maximum of temperature and an absolute minimum of dissolved oxygen (DO). The WIW, on the other hand, is formed seasonally during the winter convection processes in the Gulf of Lions over the continental shelf extending from the Ligurian Sea to the Ebro Delta (Vargas-Yáñez et al., 2012). The WIW lies above the LIW, and varies in thickness from tens to a few hundred metres. It is characterised by an absolute minimum of temperature and shows relative high values of DO. Just below the WIW and LIW lies the Western Mediterranean Deep Water (WMDW), formed during the deep winter convection events in the Gulf of Lions and the Ligurian Sea (MEDOC-Group, 1970). Table 1 shows the salinity, S and potential temperature, θ, that characterise the different water masses and their values in the area, after López-Jurado et al. (2008); Table 2 shows the spatially averaged water properties in the Gulf of Lions and the Alboran Sea after Manca et al. (2004). The intermediate and deep water masses reach the Balearic channels after circulating along the continental slope of the north western Mediterranean. The WIW is dragged by the Northern Current (NC) into the Gulf of Valencia and the Ibiza channel towards the end of the winter and until the beginning of the spring, although it is not found in the Balearic channels every year (López-Jurado et al., 2008).

The vertical and horizontal distributions of the DO in the oceans reflect a balance between the exchange across the air–sea interface with the atmosphere, its involvement in the biological and chemical processes and its physical transport. Oxygen solubility is strongly temperature dependent and decreases at higher temperatures. Within the mixed layer, the DO very closely approaches the temperature-dependent saturation concentration. The oxygen solubility lowest

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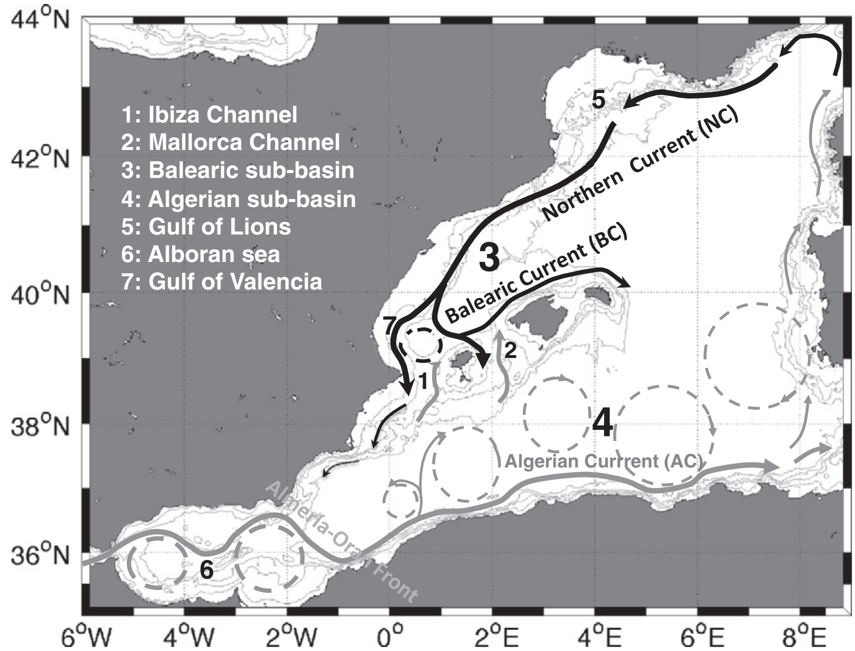

Fig. 1. The Balearic Islands and the main surface currents that describe the regional circulation. The Mallorca and Ibiza channels are shown. The Northern and Balearic Currents are indicated by dark grey arrows whilst the Algerian gyres are indicated by light grey arrows. The light grey lines denote the isobaths (100 m, 500 m, 1000 m, and 2000 m).

concentrations are reached during late summer, whilst the highest are seen in late winter (Najjar and Keeling, 1997).

At the subsurface level, the atmospheric supply is supplemented by the oxygen released during the photosynthetic processes occurring in the photic zone (Chester, 2000). As photosynthesis can produce a DO supersaturation, a shallow DO maximum has been reported in some oligotrophic marine regions like the Mediterranean Sea (e.g. Deya-Serra, 1978; Manca et al., 2004). On the contrary, the subsurface DO minima are a common feature found in many productive regions, particularly in the non-oligotrophic regions. Below the euphotic depth a decrease in DO is observed due to consumption by the respiration and remineralisation of organic matter.

Oxygen minima are a characteristic feature of many marine areas and are due to an *in situ* consumption of oxygen or to less oxygenated waters advected into the area. One example is the DO minimum zone (OMZ) in the Alboran Sea related to the LIW core (Packard et al., 1988) or the OMZs of the tropical Atlantic and the equatorial Pacific (Stramma et al., 2008). There is a small amount of oxygen consumption in the deep waters. Therefore, the DO distribution has been used as a non-conservative tracer to identify the pathway of water masses around the ocean basins or to qualitatively indicate its age, defined as the time elapsed since the fluid was at the surface (Jenkins, 1987). In practice, a quantitative calculation of the age from the DO concentrations is rarely performed, as it requires assumptions to be made regarding the consumption of oxygen, along with the exact paths of the fluid parcels and interior mixing (Stratford et al., 1998).

The objective of this work is to describe the spatial distribution and seasonal and interannual behaviour of the DO around the Balearic Islands. Keeping this aim in focus, after presenting the available data, we will first describe the spatial distribution of the DO along the Spanish Mediterranean Coast followed by a discussion of the main features of the DO in the different water masses and their seasonal evolution, computing the seasonal mean values at four representative positions around the Balearic Islands. The interannual variability of the DO at the different water masses will be discussed using the data obtained from a deep station at Cape Palos between the summer of 2007 and the autumn of 2011. Finally, the seasonal evolution of dissolved oxygen of biological origin will be considered.

Table 1
Characteristic values of the potential temperature (θ) and salinity (S) of the different water types and local values in the Balearic Sea (López-Jurado et al., 2008).

Water mass	Values at origin	Local values
AW	$15.0 < \theta < 18.0$	$15.0 < \theta < 28.0$
	$36.15 < S < 36.50$	$36.50 < S < 37.50$
Resident AW	$13.0 < \theta < 28.0$	$13.0 < \theta < 28.0$
	$37.50 < S < 38.30$	$37.50 < S < 38.20$
WIW	$12.5 < \theta < 13.0$	$12.5 < \theta < 13.0$
	$37.90 < S < 38.30$	$37.90 < S < 38.30$
LIW	$14.0 < \theta < 15.0$	$13.0 < \theta < 13.4$
	$38.70 < S < 38.80$	$38.45 < S < 38.60$
WMDW	$12.7 < \theta < 12.9$	$12.7 < \theta < 12.9$
	$38.40 < S < 38.48$	$38.40 < S < 38.48$

2. Material and methods

The data used in this study were obtained over the course of several projects developed by the Spanish Institute of Oceanography (IEO) and are compiled under the IBAMar database (Aparicio et al., 2012). The spatial coverage extends from the Alboran Sea to Cape Creus, including the Balearic Islands. The period used in this study extends from 2001 to 2011 and the data correspond to the following projects, viz., TUNIBAL (Alemany et al., 2010), IDEA (López-Jurado et al., 2008), IDEADOS (Massutí et al., 2014–this issue), CIRBAL and RADMED (Amengual et al., 2010), which had been developed within the area using a similar strategy and methodology for the data collection. This spatiotemporal range facilitates the observation of the differences in the spatial and temporal distribution of the DO content in the different water masses.

The dissolved O_2 concentration measured will hereafter be referred to as DO. The hydrographic data were recorded using different CTDs, SBE911 and SBE25, operating at a sampling rate of 24 and 8 Hz, respectively. A SBE43 sensor with a redesign of a Clark polarographic membrane was used to record the DO. The CTDs were lowered at an average speed of less than 1 m s^{-1}. The salinity (S), potential temperature (θ) and the DO were processed using the Sea-Bird Electronics Data Processing routines. The salinity and DO concentration were calibrated