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Updating temperature and salinity mean values and trends in the Western Mediterranean: The RADMED project

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ABSTRACT

The RADMED project is devoted to the implementation and maintenance of a multidisciplinary monitoring system around the Spanish Mediterranean waters. This observing system is based on periodic multidisciplinary cruises covering the coastal waters, continental shelf and slope waters and some deep stations (> 2000 m) from the Westernmost Alboran Sea to Barcelona in the Catalan Sea, including the Balearic Islands. This project was launched in 2007 unifying and extending some previous monitoring projects which had a more reduced geographical coverage. Some of the time series currently available extend from 1992, while the more recent ones were initiated in 2007. The present work updates the available time series up to 2015 (included) and shows the capability of these time series for two main purposes: the calculation of mean values for the properties of main water masses around the Spanish Mediterranean, and the study of the interannual and decadal variability of such properties. The data set provided by the RADMED project has been merged with historical data from the MEDAR/MEDATLAS data base for the calculation of temperature and salinity trends from 1900 to 2015. The analysis of these time series shows that the intermediate and deep layers of the Western Mediterranean have increased their temperature and salinity with an acceleration of the warming and salting trends from 1943. Trends for the heat absorbed by the water column for the 1943–2015 period, range between 0.2 and 0.6 W/m^2 depending on the used methodology. The temperature and salinity trends for the same period and for the intermediate layer are 0.002 °C/yr and 0.001 yr^{-1} respectively. Deep layers warmed and increased their salinity at a rate of 0.004 °C/yr and 0.001 yr^{-1}.

1. Introduction

The oceans play a key role in the climate change process as it is very likely that their upper 700 m have warmed from 1971 to 2010 and it is probable that this warming process extends from 1871 to 2010 (Rhein et al., 2013). This warming corresponds to a heat absorption of 0.55 W/m^2 through the ocean surface and represents the 93% of the net heat absorbed by the Earth due to the present radiative imbalance (Levitus et al., 2012). In this context, the Mediterranean Sea has received an increasing attention since the early 1990s. Due to the reduced dimensions of the Mediterranean (if compared with the world oceans) the effects of climate change on the temperature and salinity of its water masses could be more easily detected. Furthermore, the Mediterranean has its own thermohaline circulation. Changes in deep water formation and the thermohaline circulation can be studied in the Mediterranean Sea more easily than in the world oceans as deep water formation areas in the Mediterranean are more accessible than other regions of the world. Finally, water masses and circulation in the Mediterranean are affected by other anthropogenic factors different from climate change such as the damming of the main rivers draining into the Mediterranean Sea (Rohling and Bryden, 1992; Krahmann and Schott, 1998). All these factors have led to consider the Mediterranean Sea as a natural laboratory for climate change studies (Bethoux et al., 1999).

Lacombe et al. (1985) reported a temperature and salinity increase of the deep waters in the Western Mediterranean. These results were based on the comparison of temperature and salinity data provided in previous works (Nielsen, 1912; Sverdrup et al., 1942) with those data collected along several cruises carried out from the early 1950s to the

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1970s. Later works analyzed the long term evolution of the upper, intermediate and deep layers both in the Western and Eastern Mediterranean. The upper layer corresponds to the AW and is usually considered as that extending from the surface to 150 or 200 m depth. The intermediate layer is mainly occupied by LIW and is usually considered as extending from 150 or 200 m to 600 m. Finally, the deep layer is below the intermediate layer and extends to the sea bottom. These works revealed the warming and salting of the deep waters (Béthoux et al., 1998; Leaman and Schott, 1991; Rohling and Bryden, 1992; Krahmann and Schott, 1998; Rixen et al., 2005; Vargas-Yáñez et al., 2010a, 2010b). The existence of long term trends in the thermohaline properties of the intermediate and upper layers was not so clear. Some of these works reported changes in the salinity and temperature of the Levantine Intermediate Waters (LIW, Leaman and Schott, 1991; Rohling and Bryden, 1992; Béthoux et al., 1998; Rixen et al., 2005). On the contrary, other works found no significant trends for this water mass (Krahmann and Schott, 1998; Painter and Tsimplis, 2003). Concerning the upper layer, occupied by Atlantic Waters (AW), several studies have used Sea Surface Temperature data from radiometers operated from satellite from the mid 1980s to show a clear warming of the Mediterranean surface waters. These results are confirmed by Skliris et al. (2012) who used in situ measurements from NOCs (National Oceanographic Center Southampton) to extend the analyses to the period 1973–2008. Nevertheless, when in situ data are used to study the upper part of the water column, some discrepancies appear. Once again, some works show no warming trends (Krahmann and Schott, 1998; Sparnocchia et al., 1994), while others present positive trends for the AW temperature (Pascual et al., 1995; Salat and Pascual, 2006).

Other changes detected in the Mediterranean Sea are related to the abrupt shift of the deep water formation sites and rates in the Eastern Mediterranean. This event, commonly known as the Eastern Mediterranean Transient (EMT), occurred at some moment between 1987 and 1995 and led to a dramatic increase of the temperature and salinity of the new Eastern Mediterranean Deep Waters (EMDW) which replaced and uplifted the old EMDW (Roether et al., 1996, 2007). The changes observed in the Eastern Mediterranean have been transmitted to the Western Mediterranean as saltier and warmer intermediate waters would flow through the Sicily channel after the EMT (Gasparini et al., 2005). The arrival of these saltier intermediate waters and some exceptional atmospheric conditions during winters 2005 and 2006 in the Western Mediterranean would have been responsible for the appearance of a new and anomalous Western Mediterranean Deep Water (WMDW). This water mass is warmer, saltier and denser than the previous or old WMDW and has occupied the bottom layer of this basin. These events are known as the Western Mediterranean Transition (WMT, Schroeder et al., 2010, 2016; Zunino et al., 2012; López-Jurado et al., 2005).

Most of the results outlined above have been derived from the comparison of data obtained in different oceanographic cruises. In most of the cases such cruises had no common purpose nor belonged to any monitoring program. As a consequence of the lack of long term monitoring programs in the Mediterranean Sea during the last century, oceanographic data are scarce and unevenly distributed. Vargas-Yáñez et al. (2009, 2012a) have shown that this could be the cause for some of the discrepancies between different works. These authors concluded that the data scarcity and their irregular distribution could make the results very sensitive to the data analysis methodology. More recently, Llasses et al. (2015) and Jordá and Gomis (2013) have evidenced differences between the results obtained when analyzing temperature and salinity time series from different data bases and monitoring programs. Once again such discrepancies are attributed to the data scarcity, the interpolation method or even the data quality control.

During the late 1990s and the beginning of the twenty first century, several monitoring programs have been implemented in the Mediterranean Sea. Each of these programs is based on a different strategy and methodology, but all of them will contribute to a better understanding of the changes currently affecting the Mediterranean Sea. The Hydrochanges network is based on the mooring of CTDs at key places for the monitoring of the temperature and salinity variability of the water masses within the Mediterranean Sea (Schroeder et al., 2013). Time series collected under Hydrochanges umbrella have already revealed changes in the composition of the Mediterranean outflow through the Strait of Gibraltar (Millot, 2009). The MEDARGO program maintains an array of profiling floats in the Mediterranean Sea (Poulain et al., 2007). As an example, these data have been useful in the description of the deep water formation (Smith and Bryden, 2007) or the study of the Mediterranean mesoscale circulation (Sánchez-Román et al., 2016). The Lion Mooring Line monitors in a continuous way the deep water formation in the MEDOC (MEDOC Group, 1970) area since 2007 (Houpert et al., 2016). This mooring line, equipped with instruments along the water column, is part of the Mediterranean Ocean Observing System.

The RADMED program is devoted to the implementation and maintenance of a monitoring system around the continental shelf and slope, including some deep stations (> 2000 m) around the Spanish Mediterranean (López-Jurado et al., 2015; Tel et al., 2016). This monitoring program is aimed at the study of the seasonal and long term variability of the Westernmost Mediterranean waters from a multidisciplinary point of view. Oceanographic stations are visited on a seasonal basis since 1992 in some cases and since 2007 in the case of the stations most recently included in the RADMED project. Vargas-Yáñez et al. (2010b) have shown that temperature and salinity data from the RADMED project can be merged with historical data in order to construct long time series, providing valuable information about long term changes in the Western Mediterranean. As previous analyses considered TS data up to 2008, they did not include the new stations operated since 2007. The goal of the present work is to update temperature and salinity time series by extending the previous ones to 2015 (inclusive). The new available information will allow us to obtain mean values for the properties of the Atlantic and Mediterranean waters around the Spanish Mediterranean. At the same time, linear trends will be computed in order to check the behavior of these variables along the twenty first century. The analysis of updated time series, including for the first time those stations initiated in 2007, and the use of historical data, will allow us to evaluate new long-term trends. The data set is described in Section 2, results are presented in Section 3, and finally, discussion and conclusions are in Sections 4 and 5.

2. Data and methods

A network of oceanographic stations are periodically visited in the frame of the RADMED project, funded by the Instituto Español de Oceanografía. The stations are distributed in transects perpendicular to the coast. Stations are named by a letter corresponding to each transect and a number increasing from the coast to the open sea. In the Alboran Sea, the westernmost transects are Cape Pino (P in Fig. 1), Málaga (M) and Vélez (V). For instance, the closest station to the coast in Cape Pino transect is named as P1, and the most offshore station is P4. Sacratif transect extends from Cape Sacratif in the central part of the Alborán Sea, and Cape Gata transect (CG) is on its eastern limit. Those transects extending from the eastern Spanish coast are Cape Palos (CP), Tarragona (T) and Barcelona (BNA). Two more transects are located in the Balearic islands, one of them to the south of Mallorca Island (B) and another one extending in a northeast direction from Menorca Island (MH). 37 oceanographic stations forming two triangles cover the Balearic channels: The Ibiza channel between the peninsula and Ibiza Island and the Mallorca channel between Ibiza and Mallorca. These stations are labeled as C. Finally a deep station (> 2200 m) is located to the south of Cabrera Island (EPC). All the stations are visited three-monthly, that is, once per season of the year and the samplings are multidisciplinary including temperature and conductivity profiles by means of a CTD periodically calibrated. Water samples are taken at