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Seasonal cycle of the mixed layer, the seasonal thermocline and the upper-ocean heat storage rate in the Mediterranean Sea derived from observations

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ABSTRACT

We present a Mediterranean climatology (1° × 1° × 12 months) of the mixed layer and of the seasonal thermocline, based on a comprehensive collection of temperature profiles spanning 44 years (1969–2012). The database includes more than 190,000 profiles, merging CTD, MBT/XBT, profiling floats, and gliders observations. This data set is first used to describe the seasonal cycle of the mixed layer depth and temperature, together with the seasonal thermocline depth and averaged temperature, on the whole Mediterranean on a monthly climatological basis. Our analysis discriminates several regions with coherent behaviors, in particular the deep water formation sites, characterized by significant differences in the winter mixing intensity. Heat Storage Rate (HSR) is calculated as the time rate of change of the heat content due to variations in the temperature integrated from the surface down to the base of the seasonal thermocline. For the first time the quantification of heat storage rate in the upper-ocean, based only on *in situ* oceanographic data, is made for the whole Mediterranean. The spatial and temporal variability of the HSR in the Mediterranean Sea and its link with dynamic structures like oceanic gyres are also discussed.

Introduction

The Mediterranean Sea is a semi-enclosed basin connected with the Atlantic (the Gibraltar Strait, ~300 m depth) and with the Black Sea (the Dardanelles Strait, ~100 m depth). It is composed of two main basins, the Western and the Eastern Mediterranean (WMED and EMED) separated by the strait of Sicily (~400 m depth), and eight sub-basins. The Alboran Sea (ALB), the Algerian Basin (ALG), the Northwestern Mediterranean (NWM, delimited to the South by the Balearic Islands and the Sardinia) and the Tyrrhenian Sea (TY) compose the WMED, while the Ionian Sea (IO), the Adriatic Sea (AD), the Aegean Sea (AG) and the Levantine Basin (LE) compose the EMED (Fig. 1).

In particular the Mediterranean Sea has different deep convection zones (in the West and in the East) and a well-defined overturning circulation (Wüst, 1961; Robinson et al., 2001) with distinct intermediate and deep water masses. The total Mediterranean heat and freshwater surface budgets over a long multi-year period are negative. These deficits of freshwater and heat are compensated by exchanges through the Strait of Gibraltar (positive net water and heat transports), where the inflow is composed by a relatively warm and fresh (15.4 °C, 36.2 psu) upper water, and the outflow to the Atlantic is relatively cooler and saltier (13 °C, 38.4 psu) (Bryden et al., 1994; Tsimplis and Bryden, 2000; Soto-Navarro et al., 2010; Criado-Aldeanueva et al., 2012).

Several past studies analyzed the climatological structure of the salinity and temperature fields of the Mediterranean Sea from observations, based on a variational inverse model (Brankart and Brasseur, 1998), or on inverse methods (Tziperman and Malanotte-Rizzoli, 1991), and even fewer studies estimated the heat content changes in the Mediterranean Sea (Krahmann et al., 2000; Matsoukas et al., 2005). In this work we estimate the heat content changes only in the upper layer of the Mediterranean, because the number of observational data is very large compared to deeper layers. We define the upper-ocean layer as a combination of an upper mixed layer, where temperature is almost vertically uniform, and a seasonal thermocline. The depth of the seasonal thermocline was determined as the depth of the temperature minimum on temperature profiles, except in cases of no distinguishable seasonal

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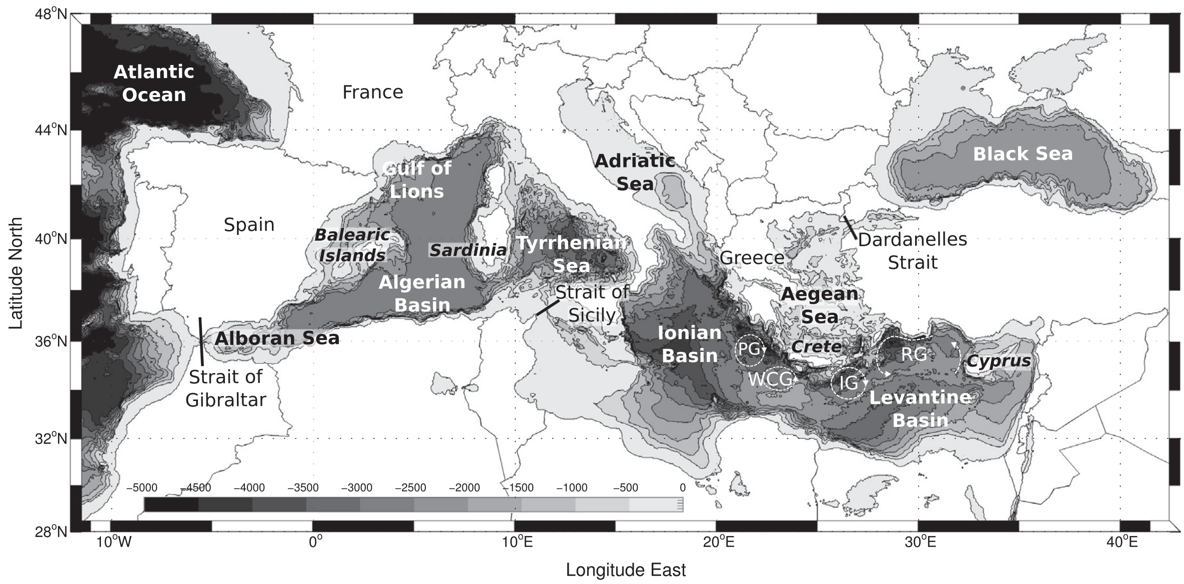

Fig. 1. Bathymetry of the Mediterranean Sea with the main sub-basins. Positions of the Pelops Gyre (PG), the Western Cretan Gyre (WCG), the Ierapetra Gyre (IG) and the Rhodes Gyres (RG) according to Poulain et al. (2012), are also shown.

thermocline (in winter) where we used the mixed layer depth. The temperature minimum associated to the seasonal thermocline can be viewed as the mixed layer temperature (the vertically averaged temperature of the mixed layer) during deep winter ventilation of the water column. We have chosen to calculate heat storage rates down to the seasonal thermocline in order to not omit the heat stored below the mixed layer depth. We choose to work with the thermocline, rather than the pycnocline, because of the larger number of temperature profiles with respect to salinity profiles.

For the first time, climatologies of the seasonal thermocline depth and averaged temperature, together with climatology of the upper-ocean heat storage rate, will be provided for the Mediterranean Sea. In addition, 8 supplementary years of data (corresponding to more than 60,000 profiles, thanks to massive Argo profiling floats and gliders deployments) are available since the computation of the last MLD climatology for the Mediterranean by D'Ortenzio et al. (2005), thus this work will provide also an updated version of the seasonal cycle of the mixed layer depth and temperature for the 1969–2012 period. As in D'Ortenzio et al. (2005), we have chosen to use simple averaging method to stay close to the raw dataset, in order to compare to previous studies and to identify basics statistics. It represents an intermediate step between the raw dataset of individual profiles, and a final analysis using advanced statistics methods like objective analysis or variational analysis (Troupin et al., 2012).

The paper is organize as follows: First we describe the data sets and the method in the second section. Then we present our results in the third section, such as climatologies of the mixed layer depth and temperature, together with climatologies of the seasonal thermocline depth and averaged temperature, on the whole Mediterranean on a monthly climatological basis. Finally we discuss the spatial and temporal variability of the heat storage rate (HSR) in the Mediterranean Sea. Conclusions and perspectives are given in the fourth section.

Data sets and methods

Profile database

The primary source of data for this study is the *Medar-MEDATLAS* project (MEDAR Group, 2002). We also use data from the World Ocean Database (Conkright et al., 2002), from additional Italian (D'Ortenzio et al., 2005, http://www.mediterranean-marinedata.eu/moong/home.htm) and Spanish cruises (Puig et al., 2012), from the CORIOLIS data center (see Coriolis, http://www.coriolis.eu.org) and from deployments of gliders which are relatively new oceanographic platforms (Testor et al., 2010) carried out in the framework of several European and national projects (see EGO, http://www.ego-network.org). Gliders profiles are considered as vertical and are checked with the same quality control than Argo data.

After removal of duplicates and application of quality control procedures (elimination of profiles without data above 10 m below the surface, with constant temperature values, or with excessive temperature gradients; see details in De Boyer Montégut et al. (2004, Appendix A)), 140,083 profiles from 1969 to 2012 are kept for the analysis out of the initial 190,000. This database is composed by 45.8% of mechanical bathythermograph (MBT) and expandable bathythermograph (XBT/XCTD), 25.8% of conductivity–temperature–depth data (CTD from Research vessels cruises), 4.8% of Argo profiling floats data and 23.6% of EGO gliders data. This database is also composed of 74,934 salinity profiles (0.5% of XCTD, 47.2% of CTD, 8.9% of Argo profiling floats data and 43.4% of EGO gliders data). This represents more than 50,000 additional salinity profiles compared to the mixed layer climatology made by D'Ortenzio et al. (2005). This is mainly due to the increasing number of glider deployments (43 since 2006). However, the spatial distribution of these salinity profiles (often distributed along repeat-sections) is still not yet sufficient to have a horizontal description of a pycnocline climatology. The 110,000 supplementary temperature profiles, compared to the salinity profiles, is one of the main reason why we chose to work on the thermocline base, rather than on the pycnocline base.

Because XBT and MBT data compose almost 50% of our database and are known to be biased in temperature, we have paid a special attention in the correction of these data. The manufacturer's product catalogues specify a depth accuracy of >1% of sample depth and a temperature accuracy of 0.1 °C for MBT, and a depth accuracy of 5 m (0–250 m) or 2% below 250 m and a temperature accuracy of 0.2 °C for XBT. The MBT are characterized by smaller and less time-variable biases compared to the XBT. Recently Gouretski and Koltermann (2007) discovered the existence of a globally time-dependent and systemic warm bias in XBT profiles, caused