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ORIGINAL RESEARCH ARTICLE

Modelling the water and heat balances of the Mediterranean Sea using a two-basin model and available meteorological, hydrological, and ocean data☆

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Summary This paper presents a two-basin model of the water and heat balances of the Western and Eastern Mediterranean sub-basins (WMB and EMB, respectively) over the 1958—2010 period using available meteorological and hydrological data. The results indicate that the simulated temperature and salinity in both studied Mediterranean sub-basins closely follow the reanalysed data. In addition, simulated surface water in the EMB had a higher mean temperature (by approximately 1.6°C) and was more saline (by approximately 0.87 g kg^{-1}) than in the WMB over the studied period. The net evaporation over the EMB (1.52 mm day^{-1}) was approximately 1.7 times greater than over the WMB (0.88 mm day^{-1}). The water balance of the Mediterranean Sea was controlled by net inflow through the Gibraltar Strait and Sicily Channel, the net evaporation rate and freshwater input. The heat balance simulations indicated that the heat loss from the water body was nearly balanced by the solar radiation to the water body, resulting in a net export (import) of approximately 13 (11) W m^{-2} of heat from the WMB (to the EMB).

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1. Introduction

The Mediterranean Sea comprises a series of connected sub-basins with connections to the Atlantic Ocean and Black Sea (Shaltout and Omstedt, 2014). Many oceanographers use the box model concept to describe the oceanic characteristics of the Mediterranean Sea. Tziperman and Speer (1994), for example, used a three-box model to study the thermohaline seasonal cycle of the Mediterranean Sea. The three boxes in this model are arranged and connected vertically as surface, middle, and deep boxes. Bethoux and Gentili (1999) used a 20-box model of heat and water fluxes between boxes to capture the increasing temperature and salinity trends in the Mediterranean Sea. This 20-box model treated the Mediterranean Sea as eight main sub-basins, each divided into several boxes according to their maximum depth (e.g., the Ionian sub-basin is divided into surface, intermediate, deep, and very deep boxes). Elbaz-Poulichet et al. (2001) analysed the input and output fluxes of dissolved metals using a one-box model of the Western Mediterranean sub-basin. They describe the water exchange through the Gibraltar Strait and Sicily Channel using two-layer model exchanges. Matthiesen and Haines (2003) defined a hydrostatically controlled box model to study the Mediterranean Sea's response to post-glacial sea-level rise. This hydrostatic model treated the Mediterranean Sea as one basin comprising three boxes (i.e., the water formation, upper-layer, and lower-layer boxes), connected to the Atlantic Ocean through the Gibraltar Strait. Calmanti et al. (2006) improved a simple model to study the spread of the Mediterranean Sea outflow in the North Atlantic Ocean. This simple model treated the Mediterranean Sea as a single basin but with three vertical boxes connected to the North Atlantic Ocean.

We started analysing the Eastern Mediterranean Sea heat and water balances based on a single-basin ocean modelling approach and using available meteorological, hydrological, and ocean data (Shaltout and Omstedt, 2012). The modelling used a vertically resolved grid with 190 grid cells extending from surface to bottom. We estimated various heat and water components and the net import of approximately 9 W m^{-2} of heat to the Eastern Mediterranean sub-basin from the Western sub-basin. The present paper, our second such heat and water balance study, follows the pattern of the first one but now treats the whole Mediterranean Sea and the modelling approach divides the sea into two coupled sub-basins to study the general oceanic features of each sub-basin. To address the local oceanic features of the Mediterranean Sea, the modelling approach should treat the Mediterranean Sea as 15 sub-basins (Shaltout and Omstedt, 2014). Our process-oriented modelling approach is based on the use of time-dependent models of vertically resolved connected basins, which have been extensively used in the Baltic Sea (for a review, see Omstedt et al., 2014). The approach allows long-term runs on time scales of centuries and millennia to be studied and is a complement to fully three-dimensional model studies. The Mediterranean Sea, which extends from 30°N to 46°N and from 6°W to 36.5°E, has a negative water balance. It is connected to the Atlantic Ocean by the Gibraltar Strait (13 km wide), to the Black Sea by the Bosphorus—Marmara—Dardanelles system, and to the Red Sea by the Suez Canal (Fig. 1). In the present work, we treat the Mediterranean Sea as two coupled sub-basins, i.e., the Eastern Mediterranean sub-basin (EMB) and the Western Mediterranean sub-basin (WMB), connected through the Sicily Channel (149 km wide) and the Strait of Messina (4 km wide) as illustrated in Fig. 1.

Atlantic surface water flows into the Mediterranean Sea through the upper layer of the Gibraltar Strait and mixes with WMB surface water. Part of the surface WMB water then flows through the upper layer of the Sicily Channel to the EMB and mixes with EMB surface water. Net precipitation and river discharge influence the water and heat balances in both sub-basins as well as the exchange with the Black Sea. In the winter, convection occurs because of the negative water balance in certain areas of the northern EMB, forming the deep-water outflow through the Sicily Channel to the WMB (Zervakis et al., 2000). This lower flow together with deep-water formation in the Gulf of Lion (in the northern WMB) is responsible for the dense water outflow through the Gibraltar Strait to the Atlantic Ocean. The Mediterranean Sea's large-scale inverse estuarine circulation is driven by the water balance, causing dense bottom-water formation due to strong evaporation and outflowing dense water through the Sicily Channel and Gibraltar Strait into the Atlantic

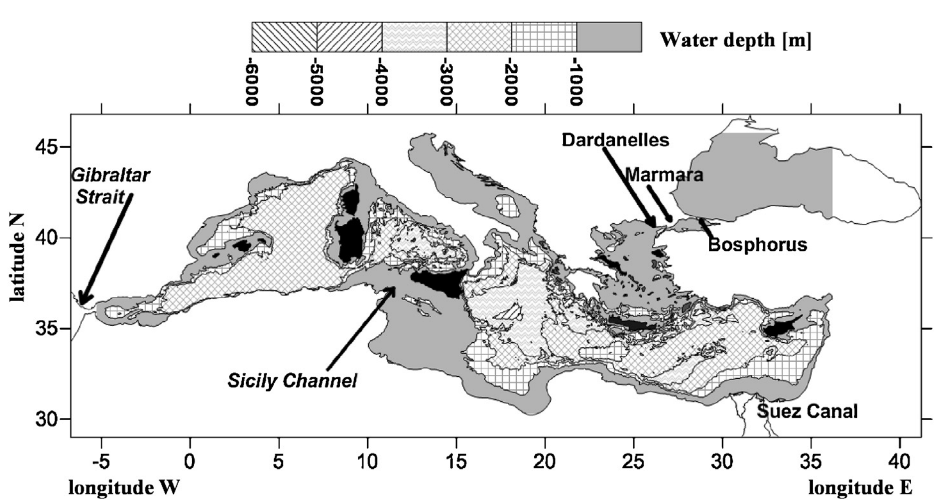

Figure 1 Bathymetric chart of the Mediterranean Sea.