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Box modeling of the Eastern Mediterranean sea

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ABSTRACT

In ∼1990 a new source of deep water formation in the Eastern Mediterranean was found in the southern part of the Aegean sea. Till then, the only source of deep water formation in the Eastern Mediterranean was in the Adriatic sea; the rate of the deep water formation of the new Aegean source is 1 Sv, three times larger than the Adriatic source. We develop a simple three-box model to study the stability of the thermohaline circulation of the Eastern Mediterranean sea. The three boxes represent the Adriatic sea, Aegean sea, and the Ionian seas. The boxes exchange heat and salinity and may be described by a set of nonlinear differential equations. We analyze these equations and find that the system may have one, two, or four stable flux states. We conjecture that the change in the deep water formation in the Eastern Mediterranean sea is attributed to a switch between the different states on the thermohaline circulation; this switch may result from decreased temperature and/or increased salinity over the Aegean sea.

1. Introduction

Observations of a major increase in the amount of bottom water formation and discharge from the Aegean sea [1–4] raise the possibility that the circulations in the Eastern Mediterranean are unstable and subject to sudden changes. A major change in the deep water formation in the Eastern Mediterranean sea occurred in ∼1990, basically, in the vicinity of the Adriatic–Aegean–Ionian seas [2,5,6,3,1,4]. Hydrographic surveys since early last century [7] indicated that the dominant source region for deep water over the entire Eastern Mediterranean, was the Adriatic sea; see Fig. 1. Waters outflowing from the Adriatic were deposited in the bottom of the Ionian sea [8]; then they spread southward and eastward [9,10]. The deep water overturning time was approximately 100 years with an average formation rate of 0.3 Sv $= 0.3 \times 10^6 \mathrm{m}^3\,\mathrm{s}^{-1}$ [11]. An additional, much more dominant, source of deep water was found in a hydrographic survey during 1995 [1]. The new source was found in the southern part of the Aegean sea and has an average outflow rate of about 1 Sv. A recent study suggested that the change in the thermohaline circulations of the Eastern Mediterranean sea actually started before October 1991 [3]. The characteristics of the thermohaline circulation of the Eastern Mediterranean sea continued to change after 1995—Manca et al. [12] and Theocharis et al. [13] reported the weakening of the Aegean source of deep water and the strengthening of the Adriatic source during 1997–1999. These changes may be attributed to changes in the surface fluxes and inflows to the Adriatic, Ionian and Aegean basins.

Several explanations have been suggested for the change in the deep water formation of the Eastern Mediterranean sea. One study suggested that enhanced net evaporation led to the formation of the new Aegean source [14]. In addition, the north Eastern Mediterranean experienced some cold winters during the 1987–1995 period and these have been associated with

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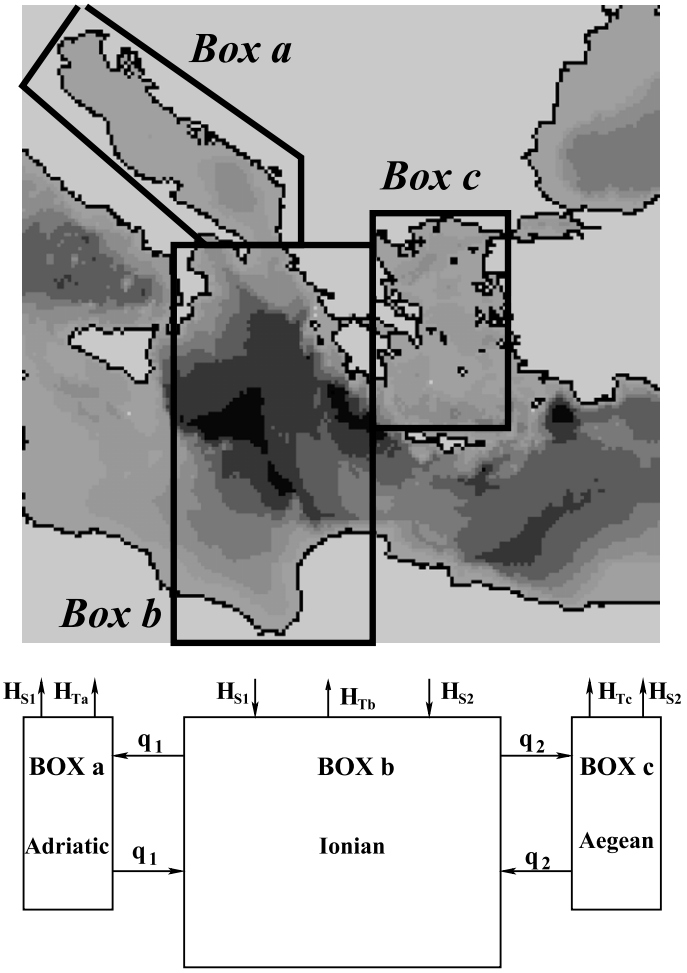

Fig. 1. Upper panel: The bathymetry map of the Eastern Mediterranean sea. The solid lines indicate the choice of the different boxes: Box *a* represents the Adriatic sea, Box *b* represents the Ionian sea, and Box *c* represents the Aegean sea. Lower panel: Illustration of the 3-box model of the Eastern Mediterranean sea. Note that positive fluxes ($q_{1,2} > 0$) are associated with sinking in the Adriatic/Aegean boxes while negative fluxes ($q_{1,2} < 0$) are associated with sinking in the Ionian.

changes in the thermohaline circulation throughout the region [15–17]. However, the lack of oceanic data during 1987–1995 makes it difficult to uncover the exact cause for the formation of the new Aegean source. Ocean General Circulation Models (OGCMs) have been used to better understand the possibilities which led to the formation of the new Aegean source. For example, changes in the wind stress over the Aegean basin were related, using an OGCM, to the formation of the new Aegean source [18]. Dry and cold winters of 1987, 1992–93, were also related, using an OGCM, to the formation of the new Aegean source [5]. These studies based their numerical simulations on re-analysis data and did not fully reproduce the entire Aegean source pattern. Wu et al. [19], on the other hand, forced an OGCM by eight consecutive cold winters (from 1987 to 1995) over the Aegean basin. They showed that a decrease of the atmospheric temperature by 2 °C leads to strong deep water formation over the Aegean; winter sea surface temperature over the Aegean sea was observed to be up to 3 °C colder than the climatological average [20,17]; the box model described below is also based on this work, where we assign the Aegean box with colder temperatures to explain the Eastern Mediterranean Transient (EMT). Stratford and Haines [21] also performed OGCM simulations and suggested that a combination of a few cold winters together with changes in the wind stress over the Eastern Mediterranean underlies the formation of the Aegean source.

The idea that density-driven circulations in the ocean could, under a given set of boundary conditions, display more than one equilibrium state, and therefore may have a behavior like that recently observed in the Aegean sea, was first put forth by Stommel [22]. He illustrated the behavior with a very simple two-box model of the thermohaline circulation. The two equilibrium states that he found in his simple box model have since been found in simulations of the North Atlantic thermohaline circulation with the most sophisticated coupled atmosphere-ocean general circulation models (e.g., Refs. [23,24]). These results lend considerable credibility to Stommel's box model. However, there is nothing in his model that limits its applicability to large-scale circulations in the North Atlantic—indeed in his paper he even suggested that it might be relevant to the Mediterranean sea. Here we apply the same basic ideas as Stommel's to develop a box model of the Eastern