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Multiple equilibria and overturning variability of the Aegean-Adriatic Seas

Yael Amitai [a,b], Yosef Ashkenazy [b], Hezi Gildor [a,*]

[a] The Institute of Earth Sciences, The Hebrew University of Jerusalem. Edmond J. Safra campus, Givat Ram, Jerusalem 91904. Israel
[b] Solar Energy and Environmental Physics, BIDR, Ben-Gurion University of the Negev, Sede Boqer campus 84990, Midreshet Ben-Gurion, Israel

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ABSTRACT

The Eastern Mediterranean Transient (EMT) – a transition and amplification of the Eastern Mediterranean Sea deep water source from the Adriatic Sea to the Aegean Sea – was observed in the mid-90′ and stimulated intense research. Here we demonstrate, using an oceanic general circulation model, that the meridional overturning circulation of the Eastern Mediterranean has multiple equilibria states under present-day-like conditions, and that the water exchange between the Aegean and the Adriatic Seas can drastically affect these states. More specifically, we found two stable states and a hysteresis behaviour of deep water formation in the Adriatic Sea when changing the atmospheric (restoring) temperature over the Aegean Sea. In addition, the overturning circulation in both seas exhibits large decadal variability of the deep water formation. The Aegean-Adriatic relationship can be summarized as follows: warm and saline water of the Aegean can either flow in the sub-surface to the Adriatic, switching "on" deep water formation in the Adriatic by increasing its salinity, or the Aegean water can feed the deeper layer of the Ionian and Levantine basins, turning "off" the deep water formation in the Adriatic. The "off" steady state resembles some aspects of the EMT in which the Adriatic source of deep water was weakened when the Aegean source became active.

1. Introduction

The Eastern Mediterranean Transient (EMT) – a transition of the major deep water formation site in the Eastern Mediterranean from the Adriatic Sea to the Aegean Sea – is an intriguing change in Mediterranean circulation that was observed in the instrumental era. For almost a century, the Adriatic Sea was the Eastern Mediterranean (EM) major source of deep water (Nielsen, 1912; Wüst, 1961). The Aegean Sea was considered a potential, but sporadic, source of dense water (Roether and Schlitzer, 1991). Surprisingly, a new and much stronger source of deep water was found in the Aegean during a hydrographic survey in 1995 (Roether et al., 1996), an event that was termed the EMT. The EMT attracted the attention of the scientific community that proposed various explanations for this transition (Lascaratos et al., 1999; Malanotte-Rizzoli et al., 1999; Theocharis et al., 2002; Josey, 2003). Understanding the causes and nature of abrupt changes such as the EMT is important since deep water formation processes allow the exchange of physical and biochemical properties (e.g., oxygen and nutrients) between the surface and the deep layers. It possibly also affects the regional climate by changing the stability and the structure of the water column over a wide area.

The Adriatic and Aegean deep water formation sources are different in their nature. When deep water formed in the Adriatic, before the EMT, the average formation rate was ~0.3 Sv (1 Sv$\equiv 10^6$ m^3 s^{-1}). The Adriatic water sank to the bottom of the Ionian (Roether and Schlitzer, 1991), and from there spread southward and eastward (Wüst, 1961; Malanotte-Rizzoli et al., 1997), filling the abyssal EM basins. The water of the new Aegean source, formed during the EMT, was denser (warmer but saltier) than the Adriatic deep water and formed at a mean rate of ~1 Sv (about three times the Adriatic deep water formation rate). The new Aegean deep water outflowed through the Crete Straits toward the Ionian and Levantine basins, and by the year 1995 replaced almost 20% of the old EM deep water (Roether et al., 1996; Malanotte-Rizzoli et al., 1997). It uplifted the nutrient level into the euphotic zone and enhanced EM biological productivity (Klein et al., 1999; Kress et al., 2014). Apparently, the Aegean deep water outflow started around 1987 (Theocharis et al., 1999) and peaked in 1993 (Roether et al., 2007). The Aegean source weakened after the EMT and the Adriatic source recovered (Manca et al., 2003; Velaoras and Lascaratos, 2005; CIESM, 2012) while exhibiting large variability in its deep water properties (Cardin et al., 2011; Cardin et al., 2014).

Several explanations for the EMT have been proposed and there is an ongoing discussion whether the EMT was a single phenomenon that

* Corresponding author.
E-mail addresses: yael.amitai@mail.huji.ac.il (Y. Amitai), ashkena@bgu.ac.il (Y. Ashkenazy), hezi.gildor@huji.ac.il (H. Gildor).

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was caused by the unique conditions in the EM during 1987–1992 (Theocharis et al., 1999; Zervakis et al., 2000; Krokos et al., 2014), or whether it is a recurrent phenomenon associated with the natural variability of the EM circulation (Borzelli et al., 2009; Gačić et al., 2010; Theocharis et al., 2014; Velaoras et al., 2014).

For instance, it was suggested that the EMT was stimulated by the intense heat loss during the particularly cold winters of 1991–1993 (Lascaratos et al., 1999; Wu et al., 2000; Stratford and Haines, 2002; Josey, 2003; Beuvier et al., 2010), by intensification of the prevailing wind-stress (Samuel et al., 1999), or by altered intermediate water circulation (Wu and Haines, 1996; Malanotte-Rizzoli et al., 1999; Gertman et al., 2006). Malanotte-Rizzoli et al. (1999) observed that during the EMT, an anticyclonic circulation between the Levantine and the Ionian basins was blocking the salty Levantine Intermediate Water (LIW) inflow into the Adriatic Sea. Other studies focused on the increase of salinity (and hence the density) in the Aegean Sea, enabling the EMT. It was associated with a decrease in precipitation over the Aegean (Theocharis et al., 1999); with a reduction in the inflow from the Black Sea (Zervakis et al., 2000); and with the long-term salinity increase in the EM due to the damming of the Nile river (Skliris et al., 2007). Few studies suggested that both an increase in Aegean salinity and extreme cold weather conditions are essential to cause an EMT-like event (Lascaratos et al., 1999; Krokos et al., 2014).

Studies linking the EMT to natural variability of the EM circulation, include, e.g., the Adriatic-Ionian Bimodal Oscillating System (BiOS) mechanism (Gačić et al., 2010). According to this mechanism, a cyclonic circulation in the north Ionian causes an advection of saline LIW into the Adriatic, enhancing deep water formation there. In contrast, anticyclonic circulation in the north Ionian leads to advection of fresher Modified Atlantic Water (MAW) into the Adriatic, weakening the Adriatic deep water formation. This mechanism is associated with a feedback between the LIW, MAW, and the stretching of the water column due to changes in water density. Another mechanism, suggested by Theocharis et al. (2014), is the "pumping mechanism" in which the outflow of dense water through deep layers of either the Otranto Strait or Crete Straits is balanced by the inflow of MAW in the upper layers. The relatively fresh MAW stabilizes the water column of the sea into which it flows, halting (or significantly weakening) its deep water formation. At the same time, the other source is enhanced by receiving LIW inflow instead of MAW, eventually leading to a switch from one source of deep water to the other.

Stommel (1961) raised the possibility of multiple equilibria states of the overturning circulation in the Mediterranean Sea, similar to the ones he predicted using a simple two-box model in the Atlantic Ocean. Recently, Ashkenazy et al. (2012) showed, using a three-box model representing the Adriatic, Aegean, and Ionian Seas, that the meridional overturning circulation of the EM may indeed have a few steady states. Ashkenazy et al. (2012) also associated the EMT with a transition between these states.

Previous studied examined the EM nonlinear response to linear changes in external (atmospheric) forcing using Ocean General Circulation Models (OGCMs) with different levels of complexity. For example, Myers and Haines (2002) forced a coarse resolution OGCM with realistic atmospheric conditions and found that the Mediterranean zonal overturning circulation collapses when increasing (+25%) or decreasing (−20%) the evaporation over the entire Mediterranean. Meijer and Dijkstra (2009) used an OGCM forced by paleo-atmospheric conditions to study the ventilation of the EM sediments in periods equivalent to sapropel episodes (Rohling, 1994; Almogi-Labin et al., 2009; Rohling et al., 2015). They found an abrupt, transient halt of the Mediterranean deep zonal overturning circulation under a decreased meridional temperature gradient. Pisacane et al. (2006) used mixed boundary conditions (i.e., specified freshwater flux and temperature restoring), and found that the EM exhibits large self-sustained variability on a decadal time scale. In their model, the EM undergoes internal oscillations of weakening and strengthening of the zonal overturning circulation cell as a result of alternation between the Adriatic and the Aegean sources. Pisacane et al. (2006) related the EMT to an advection-convection feedback mechanism, similar to the later work of Theocharis et al. (2014), rather than to an atmospheric cause.

Here we performed a set of experiments using an OGCM to demonstrate that the overturning circulation in the Adriatic Sea has multiple steady (or quasi steady) states **under the same atmospheric conditions**. Moreover, the overturning circulation in the Adriatic exhibits a hysteresis behaviour with respect to the atmospheric (restoring) temperature over the Aegean Sea, i.e., it responds to distant atmospheric variations. Essentially, we found in the Adriatic two steady states of overturning circulation with and without an active source of deep water. The two steady states exist under minor atmospheric temperature anomalies (relative to present-day conditions) over the Aegean. Different quasi steady states were found also in the Aegean under the same atmospheric conditions, however not as distinct as in the Adriatic. We also found that the meridional overturning circulation in both the Adriatic and Aegean Seas experience decadal variability that resembles the deep decoupling oscillations of Winton and Sarachik (1993). Given the above we thus conjecture that EMT-like event may occur spontaneously without a major change in atmospheric or other forcing.

The paper is organized as follows: in Section 2 we describe the main elements of our model and the experimental steps. In Section 3 we present our results and we conclude in Section 4.

2. Model and experimental design

2.1. Model setup

We use the Massachusetts Institute of Technology OGCM (the MITgcm, Marshall et al., 1997a; Marshall et al., 1997b) to perform the simulations. The MITgcm supports a wide range of parameterizations and boundary layer options. We use the finite-volume, z-coordinate, hydrostatic, free surface, partial cell options of MITgcm. The simulated domain consists of the entire Mediterranean Sea area, covering the Strait of Gibraltar from the west (Fig. 1).

Model bathymetry is based on ETOPO2 (Smith and Sandwell, 1997). The bathymetry at the Strait of Gibraltar was widen and deepen since the resolution of the model is not fine enough to reproduce the observed water flux through the strait. The water column is resolved by 22 vertical levels centered at: 10, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, 500, 600, 800, 1000, 1200, 1500, 2000, 2500, 3000, 3500 and 4000 m. The horizontal resolution is $1/8^{\circ} \times 1/8^{\circ}$ on a spherical grid, which is equivalent to 14 km in the meridional direction and to 9–12 km in the zonal direction. Since the first internal Rossby radius of deformation is 12–15 km for most of the Mediterranean Sea (Robinson et al., 1992), our simulations can be considered as an eddy-permitting simulations. The time step for both the tracers and the momentum is 1200 s.

Ocean convection was simulated using the implicit vertical diffusion coefficient scheme of MITgcm, i.e., enhancement of the vertical diffusivity to 1 m^2s^{-1} in regions where the water column becomes unstable. The background vertical eddy diffusivity was simulated through a Laplacian formulation with diffusivity coefficient ranging from $3 \times 10^{-4} m^2 s^{-1}$ at the surface to $1 \times 10^{-6} m^2 s^{-1}$ at the bottom. The vertical viscosity coefficient is $1.5 \times 10^{-4} m^2 s^{-1}$ over the entire water column. Horizontal salinity and temperature diffusive terms were modelled using the bi-harmonic formulation of MITgcm, with diffusion coefficients equal to $1.5 \times 10^{10} m^4 s^{-1}$. Smagorinsky harmonic viscosity coefficient equal to 3 was set to formulate the horizontal viscosity according to Griffies and Hallberg (2000).

2.2. Model spin-up

The model was initialized with climatological 3D temperature and salinity from NEMO-MED reanalysis (obtained by Copernicus Marine