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The Effect of the Source of Deep Water in the Eastern Mediterranean on Western Mediterranean Intermediate and Deep Water

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The deep water in the western Mediterranean Sea was found to be significantly affected by a climatic event that took place in the eastern Mediterranean during the 1990s. Numerical simulations of the entire Mediterranean Sea showed that multiple equilibria states in the eastern Mediterranean can exist under present-day-like conditions. The two stable states that were found are associated with intermediate water exchange between the eastern Mediterranean's Aegean and Adriatic Basins. In the first state, the Adriatic acts as a source of deep water that flows into the deep layers of the eastern Mediterranean; in the second state, there is no source of deep water in the Adriatic and the eastern Mediterranean intermediate water is warmer and saltier. We studied the water pathways, in both stable states, into the western Mediterranean and found that the eastern Mediterranean water's properties signature can be seen as far as the Gulf of Lion, which is an important open-ocean deep water convection site. Meaning that, the eastern Mediterranean water characteristics are manifested in deep and intermediate water properties all over the Mediterranean Sea. The water propagating from the eastern to the western Mediterranean also has different flow regimes, in both states, through the Sicily Strait and in the Tyrrhenian Basin, as seen from a Lagrangian analysis.

Keywords: western Mediterranean, eastern Mediterranean, multiple equilibria states, deep water formation, Adriatic Basin, Aegean Basin, Sicily Strait

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1. INTRODUCTION

The western Mediterranean Sea, from which warm and saline water flows to the Atlantic Ocean, has experienced substantial changes over the last decades. Its deep water has exhibited a moderate increase in temperature and salinity since the 1960s; this increase has been associated with global climate change (Bethoux et al., 1990; Krahmann and Schott, 1998). Deep water of the western Mediterranean Sea origin in open ocean convection events that take place in the Gulf of Lion area (Medoc Group et al., 1970). These were attributed to strong Mistral wind events (Cacho et al., 2000; López-Jurado et al., 2005; Font et al., 2007; Somot et al., 2018), but also to the characteristics of water masses advected from the eastern Mediterranean into the western Mediterranean (Gasparini et al., 2005; Schroeder et al., 2006). More specifically, the western Mediterranean convection events were associated with the warm, saline Levantine Intermediate Water (LIW), which crossed the Sicily

Strait (Schroeder et al., 2017) and reached the Gulf of Lion (GoL) area, enhancing (Lacombe et al., 1985), or depressing (Margirier et al., 2020) the deep convection. Numerous studies demonstrated that the properties of LIW vary over different time scales (Mauri et al., 2019; Ozer et al., 2020). Wu and Haines (1996) modeled the LIW pathways in the Mediterranean and showed that the LIW's salt content dictates the depth of convection in the GoL—namely, the saltier it is, the deeper it gets.

The observed trend of deep water temperature and salinity increase was enhanced by exceptional deep water formation events that took place in the GoL in 2004–2005 (Schroeder et al., 2006; Smith et al., 2008) and in 2012–2013 (Houpert et al., 2016; Waldman et al., 2016; Testor et al., 2018), generating a newly formed deep water mass (Schroeder et al., 2008, 2016). The deep water formed in the 2004–2005 and 2012–2013 events was denser than in other convection events and was characterized by high temperature and salinity. This is manifested in a significant jump in the time series of the western Mediterranean deep water properties (Herrmann et al., 2010). These events were identified as part of the Western Mediterranean Transient (WMT), which followed the Eastern Mediterranean Transient (EMT) that occurred at the beginning of the 1990s (Schroeder et al., 2006). The EMT refers to a change in the deep water source, from the Adriatic Basin to the Aegean Basin, causing warmer, saltier deep and intermediate water masses in the eastern Mediterranean that is also observed in Sicily Strait water properties (Schroeder et al., 2017). This climatic shift induced an increase in the LIW density flowing westward through the bottom layer of Sicily Strait. The following WMT is associated with an exceptional injection of heat and salt into the deep Tyrrhenian Basin (Astraldi et al., 2002; Gasparini et al., 2005) and with unusually deep convection in the GoL (Schroeder et al., 2006) as a consequence of the EMT signal propagating westward into the western Mediterranean. Furthermore, recent observations of warmer and saltier LIW in the GoL area were associated with weak convection between 2014 and 2018 due to strong deep stratification following 2012–2013 deep convection event (Margirier et al., 2020). Namely, the western Mediterranean deep water is under continuously impact of the eastern Mediterranean's LIW.

Many studies have investigated the causes and nature of the EMT (Lascaratos et al., 1999; Malanotte-Rizzoli et al., 1999; Theocharis et al., 1999) and whether it was atmospherically driven (Josey, 2003) or the result of an internal oceanic feedback (Gačić et al., 2010, 2011; Theocharis et al., 2014; Velaoras et al., 2014). We previously found, using a general circulation model of the entire Mediterranean, that deep water formation (DWF) in the eastern Mediterranean exhibits a hysteresis behavior and has multiple equilibria states under present-day-like atmospheric conditions (Amitai et al., 2017). The two steady states found are the following: (1) an active Adriatic DWF (dense water outflow from the Otranto Strait to the Ionian Basin) and a smaller Aegean outflow; and (2) a passive Adriatic DWF (the water entering the Adriatic is denser than that leaving it) and a stronger Aegean outflow. Henceforth, we refer to these two states as active and passive Adriatic. The passive Adriatic DWF state is the result of an initialized colder Aegean that is kept forced by a minor atmospheric temperature anomaly of $-0.2^{o}C$. The passive Adriatic state resembles circulation features of the EMT, although the seasonal atmospheric conditions were kept constant.

Here, we examine the manifestation of the two eastern Mediterranean steady states in the western Mediterranean's intermediate and deep water characteristics. The study is based on previous results (Amitai et al., 2017), focusing on the western Mediterranean with an emphasis on Sicily Strait water exchange and deep water formation in the GoL under two distinct eastern Mediterranean steady states. The GoL's deep water formation is substantially different in both spatial pattern and strength under these two steady states.

The paper is organized as follows: in section 2, we describe the main elements of our model and the particle tracking tool we used with the model output analysis. In section 3, we present our results, and we offer our conclusions in section 4.

2. MATERIALS AND METHODS

2.1. Ocean General Circulation Model

We used the Massachusetts Institute of Technology Ocean General Circulation Model (OGCM) (the MITgcm, Marshall et al., 1997a,b) to perform the simulations of the Mediterranean Sea circulation. We used the finite-volume, *z*-coordinate, hydrostatic, free surface, partial cell options of the MITgcm. The simulated domain consists of the entire Mediterranean Sea area, covering the west part of the strait of Gibraltar (**Figure 1**). The water column is resolved by 22 vertical levels with a resolution ranging from 10 m at the top to 500 m at the bottom. The horizontal resolution is $1/8^{\circ} \times 1/8^{\circ}$ on a spherical grid, which is about 9–14 km. The time step for both the tracers and the momentum is 20 min. For a more detailed description of the model and the parametrization of the sub-grid processes we used (see Amitai et al., 2017).

The model was initialized with climatological 3D temperature and salinity from NEMO-MED reanalysis data (obtained by Copernicus Marine Service Products, http://marine.copernicus.eu/). The wind stress was constructed from the monthly climatology of ERA-Interim reanalysis data (Dee et al., 2011). The Atlantic Ocean input was simulated by prescribing the Levitus (1982) monthly climatology of temperature and salinity in the western boundary of the model, outside the Strait of Gibraltar. Sea surface temperature (SST) and sea surface salinity (SSS) were relaxed toward the monthly averaged climatological SST and SSS of the NEMO-MED reanalysis with a relaxation time of 8 and 6 d, respectively. Then, monthly surface salt/freshwater flux was diagnosed, and the simulation continued with mixed surface boundary conditions (of prescribed freshwater flux and relaxation to NEMO-MED SST), to allow the development of natural variability in the simulations.

Our numerical simulations, which resulted in multiple equilibrium states in the Mediterranean, were inspired by studies that investigated the multiple equilibrium states of the Atlantic Ocean Meridional Overturning Circulation (MOC) as a function of freshwater forcing (Marotzke, 2000; Rahmstorf et al., 2005; Stouffer et al., 2006). As in these studies, the MOC hysteresis curves were found when we continually increasing or decreasing a boundary condition parameter between extreme values, as a

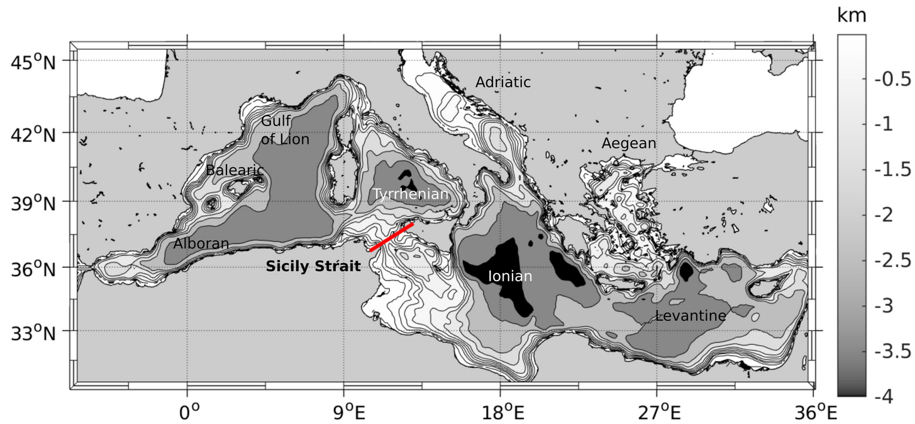

FIGURE 1 | Model's bathymetry of the Mediterranean Sea with the names of the main basins. The Sicily Strait transect used in **Figure 4** is indicated by the bold red line.

function of time. Unlike these studies, we chose the thermal forcing (restoring SST) over the Aegean and Adriatic Seas as the control parameter (see Ashkenazy et al., 2012). This was motivated by the observed severe winter cooling, of almost 3°C, over the Aegean Sea during the EMT (Josey, 2003). Hence, larger forcing boundaries between restored temperatures were chosen to detect the temperature range in which the two DWF states arise.

To obtain the two DWF states discussed in this manuscript, we modified the Aegean temperature boundary condition, i.e., the restoring temperature over the Aegean, but kept the rest of the forcing and boundary conditions as in the control run. We started from the control steady state and restored the Aegean SST to a temperature that is 5°C colder than the control run temperature, until reaching a cold steady state; we then increased the restoring temperature over the Aegean by 10°C at a rate of 0.02°C/yr. This step thus lasted 500 years and reached a restoring temperature of 5°C above the control run restoring temperature and is termed "gradual warming" (GW). Then, we kept the Aegean restoring temperature 5°C warmer than the control run restoring temperature and continued the simulation till reaching a warm steady state. Then, we started from the warm steady state and decreased the restoring temperature of the Aegean at a rate of 0.02°C/yr for 500 years, until it again reached the restoring temperature that is 5°C colder than the control run. This step is termed "gradual cooling" (GC). Finally, we kept the Aegean restoring temperature 5°C colder than the control run restoring temperature and continued the simulation till again reaching the cold steady state. All the above steps are presented in detail in Amitai et al. (2017).

These steps resulted in hysteresis curves of the Adriatic and Aegean deep water formation with respect to the restoring temperature over the Aegean. The existence of two steady states were found when we ran the model with a restoring temperature of the −0.2°C temperature anomaly over the Aegean with different initial conditions. The two runs lasted 1,500 years, starting from the model states achieved in the GW and GC experiments under the −0.2°C temperature anomaly. Thereafter, we obtained two Adriatic DWF steady states under the same Aegean forcing that is similar to present day atmospheric climatology. These two steady states were used to study the western Mediterranean deep water formation.

2.2. PaTATO Toolbox

To understand LIW pathways from the Sicily Strait to the sub-basins of the western Mediterranean, we conducted a Lagrangian transport analysis using the Particle Tracking and Analysis Toolbox (PaTATo) for Matlab (Fredj et al., 2016). From the model velocity fields, using PaTATo, we computed 3D Lagrangian trajectories of 132 water particles released in the Sicily Strait at a depth of 250 m, which is the bottom layer of the strait. We tracked the water particles, released in two successive model years, in monthly changing velocity fields for 3 years for the passive and active Adriatic DWF steady states.

3. RESULTS

Below, we describe and analyze the western Mediterranean intermediate and deep water properties under the active and the passive Adriatic DWF state found in Amitai et al. (2017). The difference between both states at the intermediate depth of 250 m (**Figure 2**) shows that there is a substantial influence of the Adriatic DWF on the Adriatic itself (as expected) and on the western Mediterranean's Tyrrhenian Basin. When the Adriatic is active, its intermediate water has similar characteristics as the surface signal; hence, it is warmer and saltier than when the Adriatic is passive. In the Tyrrhenian Basin, however, the intermediate water is colder and fresher when the Adriatic is active. This can be explained as follows: LIW leaving Sicily Strait typically flow north-eastward into the Tyrrhenian Basin, so when the Adriatic is passive the Tyrrhenian receives warmer (by $\sim 0.6°C$) and saltier (by $\sim 0.2psu$) water than it receives when the Adriatic is active, as was observed during the EMT (Sparnocchia et al., 1999; Astraldi et al., 2001; Gasparini et al., 2005). Another difference between the two states is the appearance of a warm, saline strip in the northwestern Ionian Basin when the Adriatic

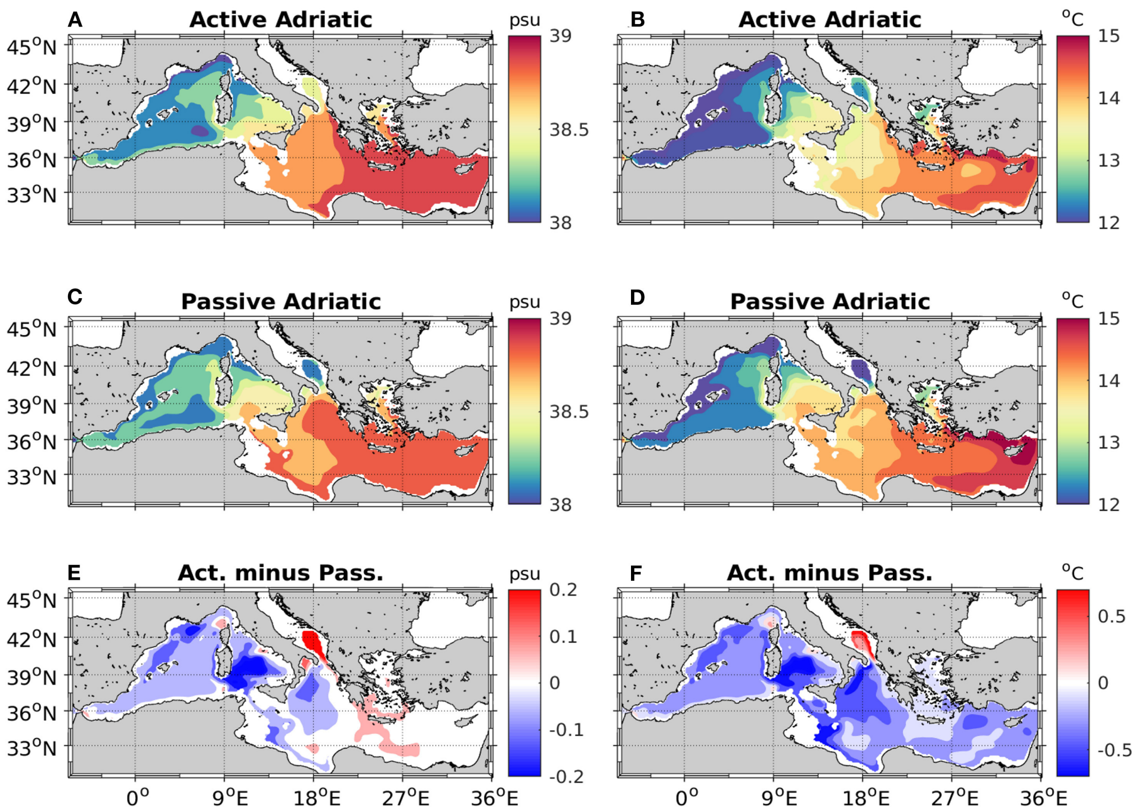

FIGURE 2 | Five-year means of salinity **(A,C)** and temperature **(B,D)** at a depth of 250 m from both steady states of active **(A,B)** and passive **(C,D)** Adriatic DWF and their difference **(E,F)**.

is passive. This water strip may be due to LIW entrainment (Astraldi et al., 2001) or transitional eastern Mediterranean deep water, which is associated with the EMT (Sparnocchia et al., 1999), following the steep topography in that region (**Figure 1**).

To better understand the intermediate anomaly in the Tyrrhenian Basin, we conducted a Lagrangian analysis using the PaTATo toolbox. We released 132 virtual particles in the bottom layer of the Sicily Strait (250 m) in two successive model years; this release was repeated for the two flow patterns created by the two steady states (**Figure 3**). The virtual water particles were released in the beginning of each year and were tracked for 3 years. The colors in **Figure 3** indicate the depth they reached at any time step and f/H contours were plotted in gray, where f is the planetary vorticity (local Coriolis parameter) and H is the bottom depth. This analysis was repeated several times, starting from various months and years, resulting in pattern similar to the one shown in **Figure 3**. When the Adriatic is passive, the water coming from the Sicily Strait widely disperses in the Tyrrhenian, following along Sardinia's eastern coast and recirculate mainly in intermediate levels before reaching the GoL region. However, when the Adriatic is active, the water flowing along the eastern Tyrrhenian, dilute with deep Tyrrhenian's water, hence less trajectories seen reaching the GoL region. In average the particles reach the convection area in the GoL $\sim$ 2 and $\sim$ 3 years after passing through the Sicily Strait under a passive and an active Adriatic states, respectively. It seems that most water particles leaving the Sicily Strait under active Adriatic state tend to follow the deeper barotropic streamlines in the eastern Tyrrhenian but this is not the case under passive Adriatic state. This may explain the presence of warm and saline intermediate water in the central and western Tyrrhenian under passive Adriatic DWF (**Figures 2E,F**). The difference in the observed circulation pattern is related to the density of the water leaving the eastern Mediterranean and may also be related to the differences in the Sicily Strait's flow regime.

Next, we examine the properties of the flow in the Sicily Strait along the transect marked in **Figure 1**. Transect of Sicily Strait water temperature (left column in **Figure 4**) and salinity (right column in **Figure 4**) are examined with contours of density (left column in **Figure 4**) and velocity (right column in **Figure 4**) superimposed above. Since the transect is diagonal, the velocity fields were rotated so that the velocity examined is the component that is perpendicular to the transect. The dashed lines in **Figures 4B,D** indicate southeastward flow, and the solid lines indicate northwestward flow. For both states, the known depiction of low salinity (density) water entering the eastern Mediterranean through the upper layer and high salinity (density) water leaving mostly through the bottom layer is seen. However, in the passive Adriatic state (**Figure 4D**), there is water outflowing from the eastern to the western

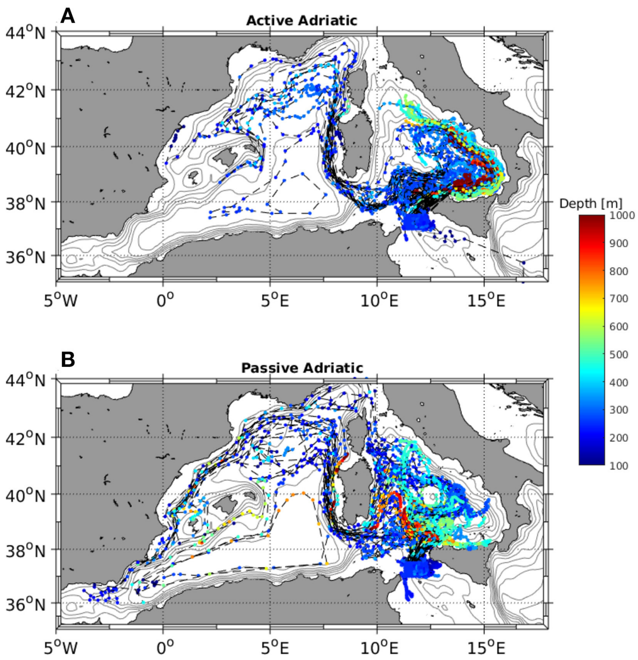

FIGURE 3 | 3D Lagrangian trajectories of 132 water particles released in the Sicily Strait at a depth of 250 m in two successive model years. The water particles were tracked for 3 years in an active Adriatic state **(A)** and a passive Adriatic state **(B)**. The colorbar indicates the depth of the particles at the given time. f/h contours are plotted in gray.

Mediterranean (northwestward velocity) in very shallow depths around longitude $11.2°E$, which is not found in this region in the active Adriatic state (**Figure 4B**). This signal might correspond to the uplift of deep and intermediate water masses reported during the EMT (Roether et al., 1996). When looking at the differences between the active and passive states (**Figures 4E,F**), the most prominent feature is the positive salinity and density anomalies around 150 m in the middle of the strait that emerges together with velocity anomalies along the transect. It appears that when the Adriatic is passive, the flow from the eastern to the western Mediterranean in 150 m depth at the strait southwestern part is stronger but with lighter water (positive anomaly contours in **Figure 4E**). In the bottom layer of the strait, the flow strength is unchanged between states, but the density of the water leaving the eastern Mediterranean is a bit higher (negative anomaly contour beneath 250 m at **Figure 4E**), as was evidenced during the EMT. We also note that the isopycnal contours follow the salinity slopes rather than the temperature slopes along the transect, emphasizing the role of LIW salinity in dictating the Sicily Strait's flow regime.

To summarize, the shallow water in the transect is denser when the Adriatic is active, but the flow regime in the shallow layers when the Adriatic is passive is such that the water exchanges more rapidly (velocity anomalies from both sides of the transect) between eastern and western Mediterranean. The deep water flux (denser than 1029.1 kg m^{-3}) from the eastern to the western Mediterranean is $1 \pm 0.08 Sv$ (mean $\pm$ 1 std) in the active Adriatic case and only $0.7 \pm 0.14 Sv$ in the passive Adriatic case. This verifies that most water that leaves the eastern Mediterranean in a passive Adriatic state (50 vs. 40% in the active Adriatic state) is not dense enough to sink to the bottom layer of the transect and, therefore, mostly fills the shallow and intermediate levels of the Sicily Strait, as seen in the above results.

We next study the temperature and salinity differences between the active and passive Adriatic states at depths of 550 and 1,750 m (**Figure 5**) in comparison to the differences between the states at a depth of 250 m (**Figures 2E,F**). At the 550 m depth, similar to the 250 m depth, the Tyrrhenian is still warmer and saltier when the Adriatic is passive (negative anomaly in both properties). However, the Balearic and Alboran Basins of the western Mediterranean exhibit positive anomalies of temperature and salinity that are absent from the 250 m layer. These anomalies are enhanced and spread eastward to the Tyrrhenian in the 1,750 m layer. This result does not accord with the observations reported by Gasparini et al. (2005) and Schroeder et al. (2006), who showed a dramatic increase in temperature and salinity in the western Mediterranean deep water that was associated with the absence of deep water production in the Adriatic. However, this result is implied by the density transect through the Sicily Strait (**Figure 4**), which indicate a significant density difference that is confined to shallow (above 200 m) depths. This suggests that the positive salinity and temperature anomalies propagating from the eastern Mediterranean are not sufficient to reproduce the observed impact on the western Mediterranean deep water and that dry, cold atmospheric conditions are crucial to understand the deep water formation in the western Mediterranean (López-Jurado et al., 2005; Font et al., 2007; Durrieu de Madron et al., 2013). When comparing the control run (a simulation with climatological atmospheric boundary conditions) properties with both steady state properties, we evidence that the control run is almost identical to the active Adriatic state (not shown), suggesting that it is the "natural" state of the Mediterranean Sea.

Deep water formation often affects the mixed layer depth (MLD), and we now concentrate on the MLD's characteristics in the GoL region under active and passive Adriatic states. The MLD was calculated from the model results and was chosen to be the depth at which the density is $\Delta\rho = 0.02$ kg/m^3 higher than the surface density. This MLD criteria was chosen since the coupling between temperature and salinity is significant in the presence of the warm and saline LIW in the GoL deep convection process (Houpert et al., 2015; Somot et al., 2018).

When looking at a representative pattern of March MLD in an active Adriatic (**Figure 6A**) vs. a passive Adriatic (**Figure 6B**), we notice a completely different structure and amplitude of MLD in the GoL region. In an active Adriatic, the MLD amplitude is moderate ($\sim$600 m) and spans a widespread area near the northwestern coast of the western Mediterranean. However, under a passive Adriatic state, the MLD is deeper ($\sim$1,200 m) and its maximal values are confined to a small area farther from the coast, which can vary between years. A monthly mean, over 100 model years, of the maximal MLD in the region is shown in **Figures 6A,B** where the maximal MLD in the region $\pm$ the standard deviation is shown in **Figure 6C**. It shows that

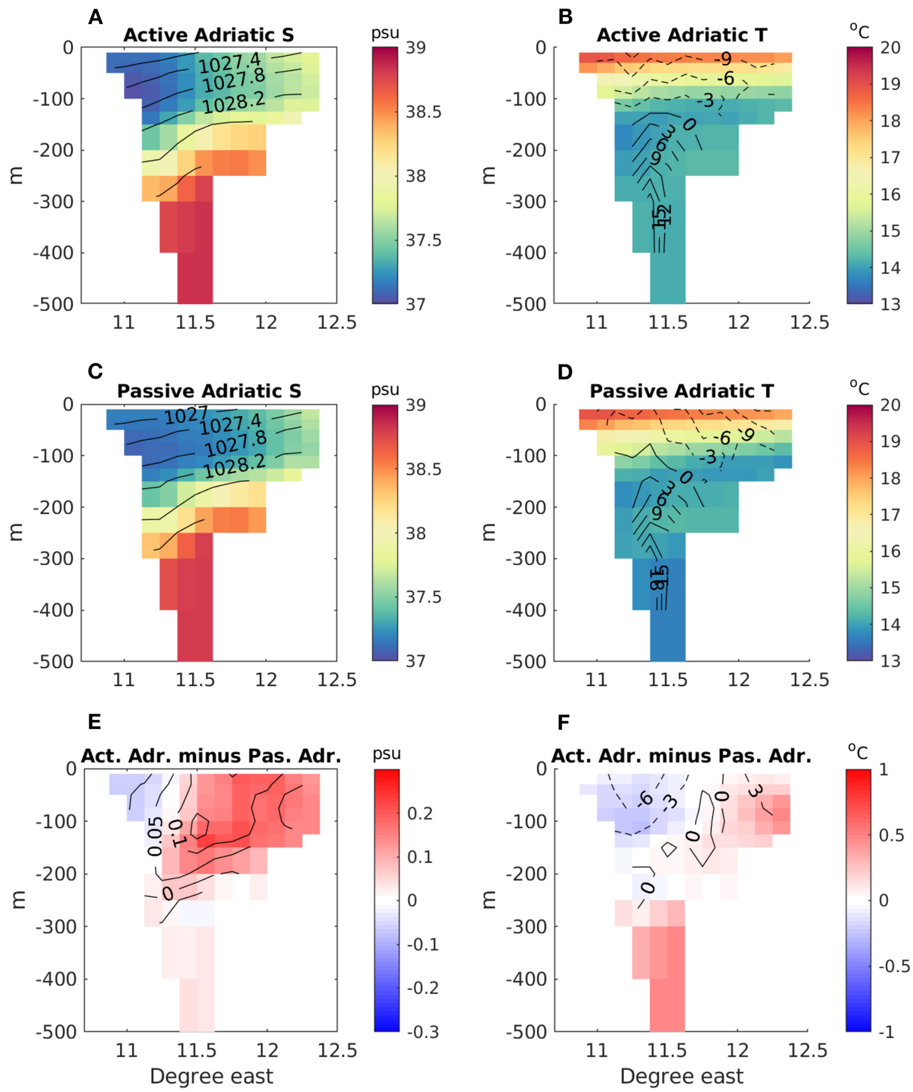

FIGURE 4 | Five-year means of salinity (left) and temperature (right) of water passing through the Sicily Strait along the transect plotted in **Figure 1**. Contours of density (left) and velocity (right) along the transect are superimposed, in an active Adriatic state **(A,B)**, passive Adriatic state **(C,D)**, and their difference **(E,F)**. The dashed (negative) lines indicate southward flow, while the solid (positive) lines indicate northward flow. The density is given in units of kg/m^3 and the velocity in units of cm/s.

the difference in maximal MLDs between the passive and active Adriatic states can vary between 200 and 700 m, suggesting deeper convection for the passive Adriatic state. All the above indicates that the passive Adriatic MOC results in circulation that enables a deeper convection. This result might be explained by the LIW's pathway in a passive Adriatic state, where the flow is through the Sicily Strait at shallow—intermediate levels (**Figure 4**) and, after recirculating in the Tyrrhenian (**Figure 3B**), reaching rapidly the region of convection in the GoL. There it enhances the production of deep water (Lacombe et al., 1985; Wu and Haines, 1996; Schroeder et al., 2006; Herrmann et al., 2010). In an active Adriatic state it seems that LIW's pathway follow the eastern Tyrrhenian coast while deepening (**Figure 3A**), hence less LIW reach the GoL and act as preconditions to deep convection.

We note that in all the simulations, the atmospheric forcing over the western Mediterranean is monthly climatology, such that the forcing has no interannual variability. Therefore, we cannot relate the role of weather conditions and their extremes to the deep water formation in the GoL (López-Jurado et al., 2005).

To further understand the difference between the two states of the Adriatic we calculated the difference in the stratification index (SI) between the active and passive Adriatic states (**Figure 6D**). The SI was previously used in studies regarding the Mediterranean Sea (Herrmann et al., 2010; Somot et al., 2018) and is defined as follows:

$$SI(H,t) = \int_0^H N^2(z,t) z dz \quad ; \quad N^2(z,t) = -\frac{g}{\rho}\frac{\partial \rho(z,t))}{\partial z} \qquad (1)$$

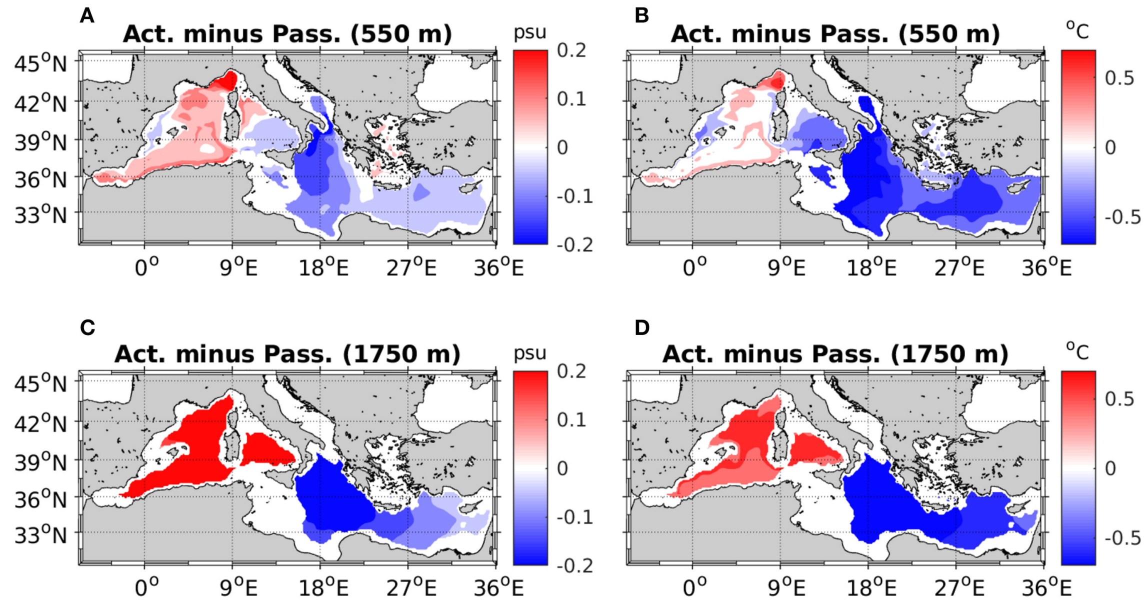

FIGURE 5 | Active and passive Adriatic states' differences in salinity and temperature, at depths of 550 m **(A,B)** and 1,750 m **(C,D)**.

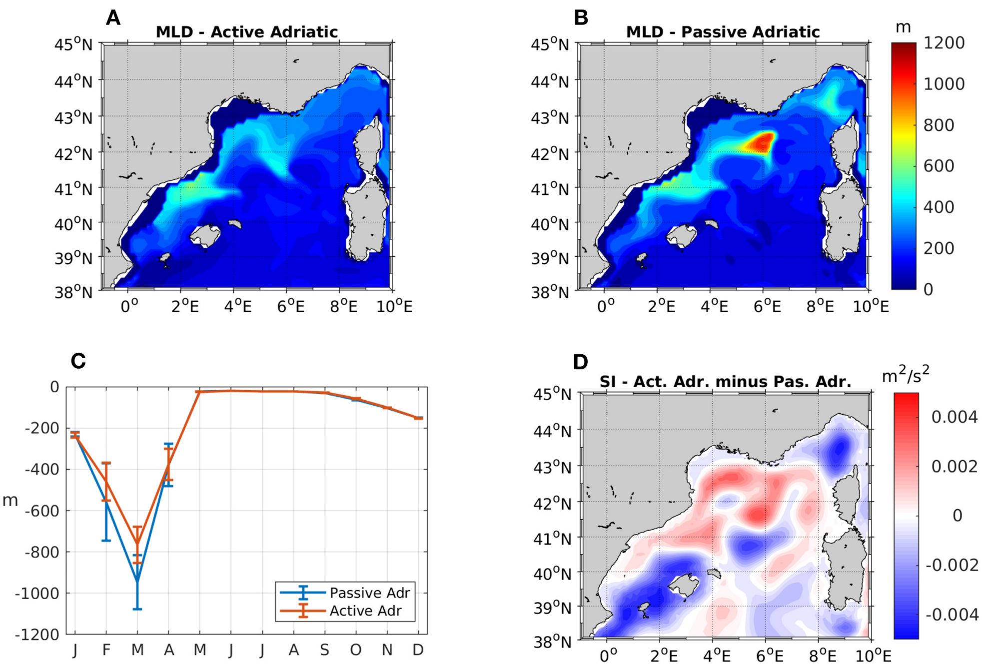

FIGURE 6 | A representative pattern of March MLD in active **(A)** and passive **(B)** Adriatic DWF states over the GoL region. Monthly mean of maximal MLD in the region depicted in the upper panels with standard deviation as error bars in both states **(C)**. Stratification Index difference between states **(D)**.

where N is the Brunt-Väisälä (buoyancy) frequency, t is the time in seconds, z the depth in meters, ρ the potential density, g the gravitational acceleration and H the depth. The larger the SI is, the stronger the vertical stratification is. Positive anomaly in the map of active Adriatic SI minus passive Adriatic SI (**Figure 6D**) emphasizes our former result that under active Adriatic there are less deep convection events in the GoL since it is more stratified than in the passive Adriatic state.

4. DISCUSSION

Our main result, based on our GCM simulations, is that the western Mediterranean is largely influenced by the DWF's location in the eastern Mediterranean. We focus on two cases (under the same forcing): active and passive sources of deep water in the Adriatic Sea. When the Adriatic DWF is active, it produces deep water in the eastern Mediterranean, and the deep layer outflow to the western Mediterranean through the Sicily Strait is larger. However, the exchange of water at depths shallower than 200 m is smaller. This flow regime creates a state where warm, saline eastern Mediterranean water significantly affects the intermediate water of the western Mediterranean under passive Adriatic state. Eventually, these eastern intermediate water reaches the GoL area and modifies the GoL's stratification, hence significantly affects the properties (shape and strength) of the western Mediterranean deep convection.

Another important result of our analysis is that although intense local convection events are simulated in a passive Adriatic DWF, as was observed after the EMT (Gasparini et al., 2005), the weather conditions over the GoL (associated with cold and dry bursts of Mistral winds) are essential for reproducing a new widespread water mass, as was observed after 2004 (Houpert et al., 2016; Schroeder et al., 2016). This result highlights the role of LIW in enabling or disabling the deep convection that appears in the GoL region (Margirier et al., 2020), even if it is spatially sporadic (**Figure 6**).

Furthermore, we found that the Tyrrhenian Basin in the western Mediterranean acts as a buffer zone between the western and the eastern Mediterranean, and dilution of LIW may take place there under an unusual flow regime, as was observed during the EMT (Sparnocchia et al., 1999).

To summarize, although our results were derived from simulations with idealized boundary conditions that only partially resemble the observed climatic transient, they contribute to the understanding of the interaction between the western and eastern Mediterranean and to characterize the propagating signals between them.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

YAm conducted the model simulations and data analysis. All authors contributed to the experimental design, manuscript writing and revision, and read and approved the submitted version.

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