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Key Points:
- This study deals with the longest thermohaline staircases time series ever observed, steps characterization and behavior
- We provide evidence of self-regulating and merging in a thermohaline staircase system
- We evidence the quick mixing due to salt fingers in the Tyrrhenian interior

Supporting Information:
- Supporting Information S1

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Permanent Thermohaline Staircases in the Tyrrhenian Sea

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Abstract The longest historical time series (14 years, from 2003 to 2016) of temperature and salinity of thermohaline staircases with highly homogeneous and reliable data ever observed is here presented and studied. The thermohaline staircase system of the central Tyrrhenian Sea is due to double diffusion in salt finger regime, and our study reveals its conservative behavior, oscillating among slightly different shapes, passing through merging processes, with a systematic upward drift of the interfaces. Data also show enhanced salt finger processes after 2010, near the bottom, promoted by the ingression from the Western Mediterranean of a new denser water mass due to the Western Mediterranean Transition. Our results are relevant for studying the mixing in the intermediate and deep region and open the way for modeling and theoretical follow-up studies aimed to reproduce and explain these observations.

Plain Language Summary This study deals with a microscale mixing process usually denoted as double diffusion. Seawater masses contain different quantities of heat and salt and can be recognized by their resulting density. The molecular diffusion of heat is quicker than that of salt, resulting in a slow but very efficient mixing at the interface between two different water masses. In the Tyrrhenian Sea this peculiar phenomenon is well visible and shows very high persistency and progression: Vertical profiles of temperature and salinity look, in fact, like a staircase; such profiles have been first observed in the 1970s. Tyrrhenian staircases show variability; in particular, they have been used as a proxy to infer general water mass property changes (in turn linked to climate change), confirming the presence of a new, denser water at the bottom of the basin, and its ability to mix very quickly. Moreover, this study shows the longest time series ever observed.

1. Introduction

Due to its geographical location, the Tyrrhenian Sea—bounded by Sicily, Sardinia, and the western coast of the Italian peninsula (Figure 1a)—is the most isolated basin in the Western Mediterranean Sea (Krivosheya & Ovchinnikov, 1973). Its typical water column yields a three-layer system composed of the surface Atlantic Water, the Levantine Intermediate Water (LIW), and the Tyrrhenian Deep Water. The intensity of the cyclonic surface and intermediate circulation decreases from the boundaries to the center of the basin, while the deep circulation is very weak (Astraldi & Gasparini, 1995; Aulicino et al., 2016; Hopkins, 1988; Menna & Poulain, 2010). The Tyrrhenian basin is considered a merging collector of both the Eastern and Western signals (Astraldi & Gasparini, 1995), receiving a considerable amount of eastern waters, mainly the LIW (Sparnocchia et al., 1999) as well as Atlantic Water and Western Mediterranean Deep Water (WMDW) of western origin (Schroeder et al., 2016).

Over a large area of the central Tyrrhenian basin, the transition between LIW and deep water takes place through a succession of homogeneous layers separated by sharp interfaces (Figures 1b and 1c). This staircase structure is due to double diffusion processes, occurring because heat diffuses much more rapidly than salt on the molecular scale. LIW is warmer and saltier than Tyrrhenian Deep Water, and salt and heat exchanges lead to the formation of salt fingers.

A thermohaline staircase due to salt fingers is clearly recognizable from the peculiar step-like shape of both the vertical temperature and salinity profiles. In a few regions of the world oceans these features have been observed, and they all have in common anomalously low values of the stability ratio:

$$R_\rho = \frac{\alpha^\Theta T_z}{\beta^\Theta S_z},$$

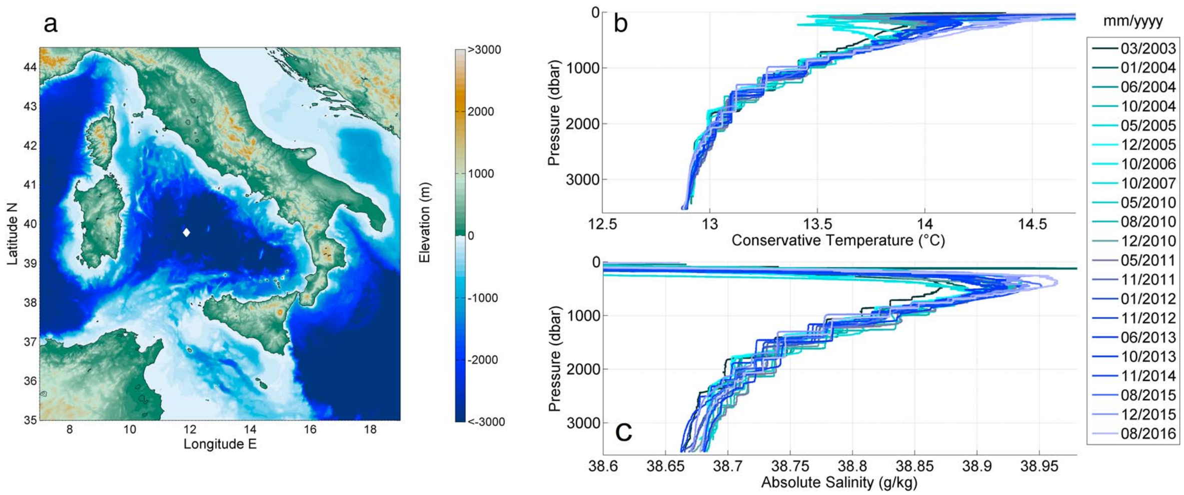

Figure 1. (a) The Tyrrhenian Sea; the blue dot indicates the station where data have been collected. (b, c) Thermohaline staircases envelope from 2003 to 2016, both for conservative temperature (°C) and absolute salinity (g/kg), in the central Tyrrhenian station.

where α^{Θ} is the expansion coefficient of temperature, β^{Θ} is the contraction coefficient of salinity, and T_z and S_z are the vertical temperature and salinity gradients, respectively. A necessary and sufficient condition for staircases formation is $1 < R_\rho < 1.7$ (Radko et al., 2014a).

The Turner angle (Tu) is another common measure of the stratification pattern (Ruddik, 1983). It serves the same purpose as R_ρ, but it is easier to be graphically visualized and offers an easy interpretation of the predisposition of the environment to double diffusion. It is related to R_ρ by the relationship below (Radko, 2013):

$$R_\rho = -\tan\left(Tu + 45^{\circ}\right).$$

Tu variations in the water column define the following classification of the stability of the layers: $-90° < Tu < -45°$ diffusive regime, $|Tu| < 45°$ stable, $45° < Tu < 90°$ finger regime, $|Tu| > 90°$ gravitationally unstable.

Several modeling and theoretical studies deal with the formation mechanisms based on the governing equations for the various parameters (Radko, 2003, 2005, 2007, 2012; Radko et al., 2014a, 2014b; Turner, 1973, 1985). Recent studies underline the importance of the interfaces in the formation process. Laboratory experiments show thin interfaces and allow to derive the corresponding governing equations and parameters. Observations in the field show interfaces that are thicker than those predicted, with consequent differences in the equation systems.

According to Radko (2003, 2005) and Radko et al., (2014a), special attention should be paid to the merging process: The evolutionary staircases pattern is a sequence of merging events between steps, which systematically increase the average layer thickness until a maximum value is reached. Then, the layer stops growing and starts merging with another one (above or below). It is also proved that small inhomogeneity of the convective layers has a stabilizing effect on the staircases system (Radko, 2003, 2005; Radko et al., 2014a), arresting merging and maintaining the thermohaline structure.

In the Mediterranean, the Tyrrhenian Sea is the most susceptible basin to salt finger occurrences (Meccia et al., 2016). Staircases observations in the central part of this basin have been reported since the 1970s (Johannessen & Lee, 1974; Molcard & Tait, 1977; Molcard & Williams, 1975) and have been studied more in detail by Zodiatis and Gasparini (1996) over the period 1991–1992 and Falco et al. (2016) over the period 2007–2009. Both these latter studies show thicknesses of the steps of hundreds of meters, and persistency in space and time, though over a limited time interval. This is a first peculiarity of the staircases of the Tyrrhenian Sea compared with those observed elsewhere. For example, Lambert and Sturges (1977) report layer thicknesses of a few tens of meters, observed over a few days period in the Caribbean Sea; similar observations were made by Hebert (1988) in the Mediterranean outflow and by Schmitt et al. (1987, 2005) in the western tropical Atlantic.

Hence, thermohaline staircases observations in the central part of the Tyrrhenian Sea show more than 40 year of persistency, even if with irregular frequency of data collection, with vertical, chronological and spatial coherence (Buffett et al., 2017).

In this context, the present study shows the longest data set ever collected in the Tyrrhenian Sea, analyzing a 14-year time series (2003–2016) of temperature and salinity with highly homogeneous and reliable data. To the best of the authors' knowledge, such long time series of salt finger staircases have never been studied both in the Tyrrhenian Sea and in another part in the world ocean. This data set allows us to define the *shape* of the system, its evolution over time, and its changes.

2. Data and Methodology

This study uses a hydrological time series collected by the Italian Consiglio Nazionale delle Ricerche in a station located at about 3,500 dbar depth in the central Tyrrhenian Sea (39° 46.85°N, 011° 53.00°E; see Figure 1a) over the period 2003–2016 (Borghini et al., 2019). The data set contains 21 hydrological profiles performed on average every 6 months, with a lack of data in the 2007–2010 period. The data set is highly homogeneous in technical characteristics and quality, since the instrument used to collect most of the data is the same CTD probe (SBE911plus).

The calibration of the probe was performed at the NATO-CMRE Centre of La Spezia up to 2014, by the manufacturer (SeaBird) or by the Oceanographic Calibration Center of OGS in Trieste thereafter. To verify the post calibration performance of the probe, redundant sensors were often used for both temperature and salinity measurements, and on board salinity analysis of the water samples was performed using a Guideline Autosal or a Portasal salinometer. Raw data are postprocessed and averaged at 1 dbar. For the quality control process a first data checking and flagging with the manufacturer's software was performed, followed by a specific tool developed in Matlab aimed at despiking with GTSPP procedures (UNESCO-IOC, 2010). The Gibbs-SeaWater Oceanographic Toolbox (TEOS-10, 2017) is used to calculate the conservative temperature (CT), the absolute salinity (S_A), the stability ratio (R_ρ), and the density, represented as Sigma-2 (σ_2) (IOC, SCOR, and IAPSO, 2010).

To identify each step, the relative maxima in the vertical gradient of $\mathrm{S_A}$ and CT are used to identify the interfaces (details are given in supporting information S1). Each interface is further studied through an accurate visual inspection, to carefully identify the real boundaries, since every cast is unique. As a general criterion, the boundary between the end of a layer and the beginning of an interface is identified when the difference in the observed parameter varies by an order of magnitude (changing from 10^{-4} in the layers to 10^{-3} in the interfaces).

In this study the word *interface* refers to a sharp gradient between two well-mixed layers, and unless otherwise specified, it is the main parameter of our analysis. A *layer* is defined as a well-mixed part of the water column bounded by two interfaces. A *step* is intended as a layer and its above interface; *staircases* or *staircases system* refer to the totality of the steps up to the last detectable interface. To describe the general shape of each cast, three qualitative flags have been defined: *clean*, *rough*, or *steppy* shapes. Figure 2 shows an example of each shape.

We will refer to a clean profile if it is characterized by a high numbers of steps, including a high number of significant ones, that is, thicker than 90 dbar and very well mixed. The thickness of the larger steps can reach 500 dbar, and the interfaces are very thin (less than 25 dbar) and sharp with very large variations both in CT (the parameter plotted in the figure) and S_A (not shown); secondary smaller steps are often found at the top and the bottom of the staircases zone. A rough profile implies few steps, generally only the main ones, with a high thickness, which can be considered a general feature; in this case the interfaces are very thick, sometimes reaching the same thickness of the layers they are in between. Large jumps in CT (and in S_A) are present as well which are comparable to those of the clean profile. A steppy profile is, instead, characterized by interfaces with a very small number of substeps inside, well distinguished from the secondary steps that can be found in the clean profile. These substeps are present where an interface is expected.

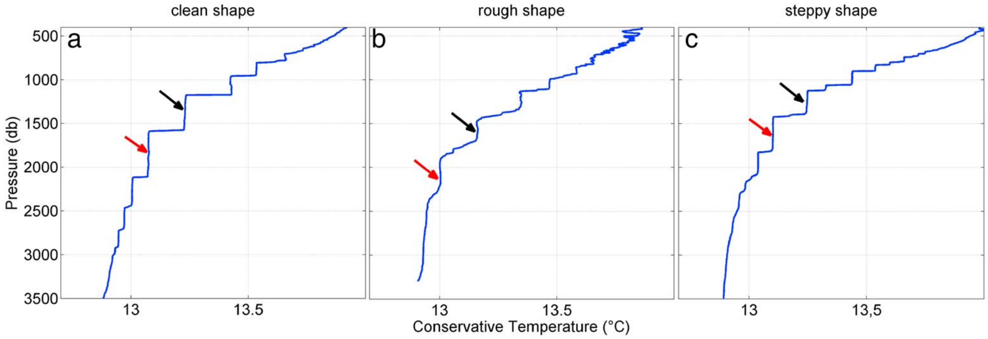

Figure 2. (a) A *clean* profile characterized by a high number of recognizable steps, with high thicknesses and very well-mixed layers; very thin interfaces; and also smaller, secondary steps at the top and at the bottom of the staircase zone. (b) A *rough* profile characterized by few thick steps alternated by sloped and rough interfaces. (c) A *steppy* profile characterized by thin interfaces embedding substeps. Red arrows indicate the *main* step, and black arrows the *middle* step.

Two relevant thermohaline steps are selected for each cast, and their coupled variability is analyzed. We have chosen the largest *main step* (about 2,000 dbar deep) in the first available profile (March 2003), and the one above (at about 1,500 dbar), hence renamed *middle step* because of its position in the middle of the water column. The criterion for the identification of the main-middle couple in every following cast is the thickness: The main step (red arrows in Figure 2) is always the thickest, and the middle step (black arrow in Figure 2) is always the one above.

3. Results

Figure 3a shows the staircases system evolution over time in terms of CT and σ_2. To remove the overlap and obtain a more readable figure, the profiles have been stacked by 0.15 °C for CT and 0.01 kg/m^3 for σ_2. Each profile shows thick and well-mixed steps, both in CT and σ_2. Focusing on the set of thick and well-mixed steps of each cast, one can appreciate an upward lift of several hundred meters starting from 2010. In addition, thermohaline properties change over time along the water column. In particular, the LIW—the heat and salt source for the double diffusion occurring below—shows a general trend of increasing background S_A and CT (0.05 g/kg in S_A, 0.02 °C in CT; see supporting information S2). A further interesting observation is the presence of smaller steps below the deepest thick step, whose number also varies with time, starting from the profile recorded in May 2010. This suggests the intervention of some process that favors the regeneration of the steps starting from their base, pushing at the same time the whole system upward. Looking at the σ_2 profiles, we can see an anomaly just above the bottom from that date, very well visible also in the CT-S_A diagram (see supporting information S3): An appreciably denser water mass slipped into the base of the staircase system. It is colder and fresher than the one above, a situation prone to the salt finger regime (Schroeder et al., 2016). Thus, this new water mass may have generated the secondary step system, operating as a new bottom source. To demonstrate the role of the new water mass, *Tu* profiles were calculated from the CT and S_A at each station after the original profiles were smoothed with a 20-point moving average in the vertical (20-dbar window), to reduce noise. Figure 3b shows *Tu* scatter plot and related fitting curves for casts before 2010 (red curve) and after 2010 (blue curve). The vertical stability is such that a finger regime is well identified below the LIW in all CTDs at any time. Moreover, R_ρ grows approaching the bottom in casts collected after 2010, with value of about 1.14 at 3,390 dbar in the red series (before 2010) and 1.85 in the blue series (after 2010). Closer to the bottom, at about 3,450 dbar, values are about 1.01 for the red series and 1.71 for the blue series. R_ρ is thus closer to 2 in cast after 2010 near the bottom, confirming enhanced salt finger processes (Radko et al., 2014a).

The principal staircases characteristics for each profile are listed in Table 1. The background R_ρ value ranges from 1.12 to 1.66, with a mean value of 1.25 in the period 2003–2016. These values agree with the theoretical layering interval ($1 < R_\rho < 1.7$) and also with previous Tyrrhenian observations: Zodiatis and Gasparini (1996) found values from 1.19 to 1.5, and Falco et al. (2016) from 1.08 to 1.36.

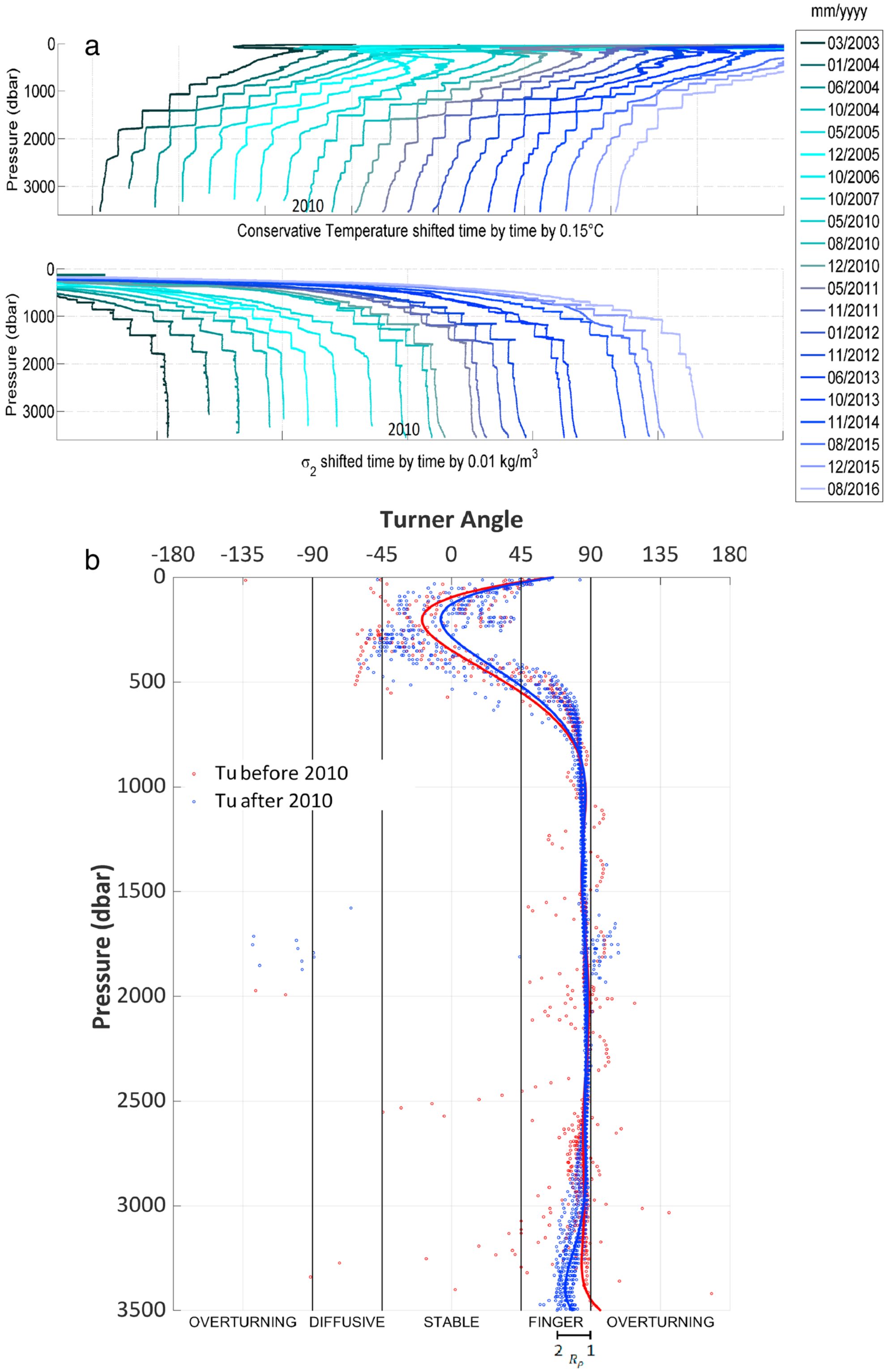

Figure 3. (a) CT and σ_2 profiles shifted in time for a better visualization. The slight density inversions in the first three profiles are due to hydrological cable issue. After 2010 it becomes visible the presence of a denser water at the bottom of the σ_2 profiles. (b) Scatter plot of the Tu along the water column before (red dots) and after (blue dots) 2010. Best fit curves of Tu versus pressure, shown in the same colors, are calculated with an eighth-order polynomial using the Matlab curve fitting toolbox.

Table 1
General Description of the Central Tyrrhenian Staircases Data Set, Thickness Are Expressed in dbar

Cruise	Date	Number of layers	Number of principal layers	Main layer thickness (dbar)	Layer type	Thinnest interface (dbar)	Interface type	Cast type	R_ρ
Medgoos6	29/03/2003	7	5	523	well-mixed	6	sharp	clean	1.66
Medgoos7	08/01/2004	5	5	452	mixed	17	sharp	clean	1.12
Trend04	04/06/2004	7	5	381	mixed	7	slope	clean	1.29
Medgoos9	20/10/2004	8	5	463	well-mixed	9	steppy	clean	1.33
Medgoos10	30/05/2005	4	4	250	mixed	94	slope/steppy	rough	1.14
Medgoos11	01/12/2005	6	4	364	well-mixed	22	steppy	clean	1.22
Medbio06	30/10/2006	4	3	231	mixed	147	slope/steppy	rough	1.19
Medocc7	27/10/2007	5	4	217	very rough	33	very rough	rough	1.19
Biofun10	14/05/2010	8	5	526	well-mixed	4	sharp	clean	1.16
Venus1	22/08/2010	10	6	331	well-mixed	4	sharp	clean	1.28
Bonifacio2010	07/12/2010	10	6	514	well-mixed	8	sharp	clean	1.18
Eurofleets11	04/05/2011	7	4	494	mixed	35	steppy	steppy	1.14
Bonifacio2011	12/11/2011	16	5	444	well-mixed	5	sharp	clean	1.28
Ichnussa2012	14/01/2012	9	5	314	well-mixed	24	steppy	steppy	1.17
Eurofleet12	18/11/2012	11	5	475	well-mixed	9	sharp	clean	1.21
Venus2	15/06/2013	7	3	423	well-mixed	21	slope	steppy	1.13
Ichnussa13	20/10/2013	10	4	421	well-mixed	6	steppy	steppy	1.22
Ichnussa14	23/11/2014	8	4	383	well-mixed	7	very steppy	steppy	1.53
Venus3_OC15	29/08/2015	5	3	311	well-mixed	2	steppy/rough	steppy	1.24
Ichnussa15	06/12/2015	10	4	376	well-mixed	7	sharp	clean	1.28
Talpro2016	20/08/2016	12	4	382	well-mixed	6	very steppy	steppy	1.20

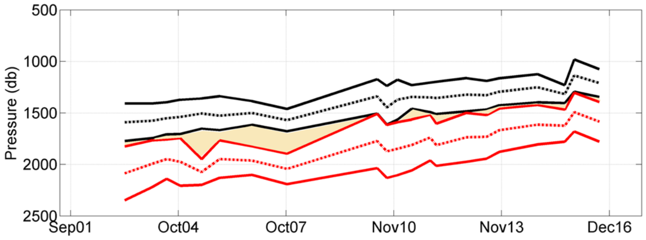

Figure 4. Vertical displacement of the main-middle couple. The dashed lines represent the midpressure; the full lines represent the boundaries of the layer. The interface thickness is highlighted in yellow.

Other characteristics listed in the table classify each profile in terms of the number of all the visible layers (secondary layers included), the number of principal layers (thicker than 90 dbar), the thickest layer size and the size of the sharper interface, and a qualitative description of the layer and interface type.

Each cast can include from three to six principal steps. Starting from 2010, the number of layers (steps) generally increases because of the development of secondary layers, and the shape of the profiles is more frequently steppy (i.e., also the interfaces are stepped). The steppy shape is the alternative of a clean shape after 2010, while it was never observed before. In particular, before 2010 the alternative of a clean shape was the rough one.

Weak-declining trends of the thicknesses of the main layer and the thinnest interface appear evident in the data, but they cannot be identified with confidence due to the irregular temporal sample rate of this data set.

Figure 4 shows the vertical displacements of the couple middle-main steps as a function of time. The graph shows a clear uplifting of both steps. Information on the interfaces can be inferred too, since their thickness is represented by the space between the bottom of the middle layer and the top of the main one (area colored in yellow). In particular, after 2010, the two-step system seems better developed and stable, with thinner interfaces and a more regular trend. Thicker interfaces can be observed over the 2005–2010 period, when rougher profiles are found. It is also possible to notice the thickness evolution of both the main and the middle steps: After 2010 a general decrease of the middle step thickness is detectable compared with the main one. The maximum thickness of the main step is observed in March 2003 (523 dbar) and the lowest in October 2007 (217 dbar). The middle step thickness oscillates between 130 dbar (June 2013) and 417 dbar (October 2004). In this temporal window no regular frequency can be detected, given the sampling frequency of the data set.

4. Discussion

The same thermohaline jumps can be observed in all staircase shapes (clean, rough, and steppy), suggesting that heat and salt transfer mechanisms are not compromised as long as the layers-interfaces system is maintained, even if it is not well developed. Moreover, after one (or some) rough or steppy shape, there is one (or some) clean one; thus, very well developed shapes alternate with shapes with instabilities and so on. According to Radko (2003, 2005) and Radko et al. (2014a) in laboratory experiments, inhomogeneity of the convective layers has a stabilizing effect on the staircases system. Observing the two shapes, the rough shape basically represents instabilities in the convective layer, and the steppy shape shows secondary instabilities at the interface in the form of the substeps within the interfaces. Since these are two characteristics of the merging process, we believe that some merging processes are happening, among the three shapes (more details in supporting information S4). Merging phenomena are rarely observed in the ocean—They are difficult to individuate. In the Tyrrhenian staircases we observe different shapes with characteristics prone to merging and different positions and thickness of the layers: This leads to the suggestion that a merging process occurred (see Figures S4-1).

5. Conclusion

Tyrrhenian thermohaline staircases show a very high stability in space and time since 1970, with the highest sampling frequency over the last 14 years. This can be probably due to the weak deep circulation (Tait & Howe, 1971).

Despite this apparent stability, changes in depth of the location of the steps and of their thermohaline properties can be observed in time. The thickest step uplifts from below 2,000 dbar to about 1,600 dbar in 14 years, replacing the step above it, which, in turn, uplifts from about 1,600 dbar to about 1,400 dbar. Thus, a general uplifting of about 400 dbar of the entire staircase system is observed (with a decrease in size of the middle layer above), preserving the peculiar step-like shape. Thus, the Tyrrhenian staircases system shows a conservative behavior, maintaining its general feature in time and evidencing a selfcapability to limit the expansion of the thickness of each individual step (i.e., a step cannot grow beyond a certain thickness threshold because of the merging process). Therefore, the staircase system acts like a "buffer system," with its small oscillation probably due to intrinsic cause (such for example internal waves).

Moreover, secondary layers are visible after 2010 at the same time of the signal of a new denser water at the bottom. Schroeder et al. (2008, 2016) observed and identified this new water as the new WMDW, due to the Western Mediterranean Transition, and determined its entrance in the Tyrrhenian Sea in 2010. Schroeder et al. (2016) suggested also that due to its thermohaline characteristics, the new WMDW in the Tyrrhenian interior is prone to develop salt fingers, and given that this mixing regime is quite efficient, the interface with the resident water mass above is not always perfectly detectable. Secondary layers at the bottom of the principal staircases system can be the result of quick and strong salt finger processes, mixing the new denser water with the resident one. Furthermore, R_ρ gets closer to 2, demonstrating enhanced salt finger process at the bottom after 2010 (Radko et al., 2014a).

In conclusion, these observations have improved the knowledge of the evolution behavior of the staircases and can be a useful starting point to stimulate modeling and theoretical follow-up studies, aimed to reproduce and explain these observations. Moreover, Tyrrhenian thermohaline staircases show a kind of resilience and self-regeneration capacity that suggests that they constitute a unique, conservative system and not just a sum of mixed layers and sharp interfaces.

After being considered only a mere oceanographic curiosity in the past, today the thermohaline staircases are recognized to be strong mixing hot spots in the main thermocline (Radko et al., 2014a). Given their persistency in the Tyrrhenian Sea, they can be considered as a strong and constant diapycnal mixing engine, especially in the deep layers, and studies about their characterization and evolution become crucial to understand the heat and salt diapycnal vertical transport and water mass transformation. In particular, a specific study—by these authors—on heat and salt fluxes is ongoing in this moment, to shed light on the intrinsic mechanism of the process.

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