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Decadal thermohaline evolution and water mass variability along the Ligurian and Tyrrhenian shelf under climate forcing (2009–2022)

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Abstract. Understanding the impact of climate change on thermohaline dynamics in the western Mediterranean Sea is essential for assessing shifts in regional circulation and water mass formation. This study analyzes data from twelve summer oceanographic surveys conducted between 2009 and 2022 along the Ligurian and Tyrrhenian continental shelf. Results reveal a decadal-scale warming and salinification of both surface and intermediate layers, leading to enhanced water column stratification. On the northern Sicilian shelf, Atlantic Water exhibited a salinity increase of +0.02 yr^{-1} and a potential temperature rise of +0.40 °C yr^{-1} between 2011 and 2022, driven by sustained surface warming and advection of Ionian Surface Water from the eastern Mediterranean. This warmer and saltier water mass also affected intermediate depths, modifying vertical density gradients. The influence of Ionian Surface Water peaked around 2016, coinciding with the progressive warming of Tyrrhenian Intermediate Water due to the absence of strong winter cooling after 2014. These hydrographic changes are linked to the Adriatic–Ionian Bimodal Oscillating System and the transition of the Northern Ionian Gyre from a cyclonic to an anticyclonic state, which modulates the inflow of intermediate waters through the Sicily and Messina Straits. On the Ligurian shelf, Western Intermediate Water showed moderate warming (+0.06 °C yr^{-1}) until 2017, followed by cooling, and a salinity increase until 2019. These findings underscore the importance of inter-basin connectivity and the need for integrated monitoring and modeling to understand and anticipate climate-driven variability in the Mediterranean Sea.

1 Introduction

The western continental shelf of Italy lies within the Tyrrhenian and Ligurian sub-basins of the Western Mediterranean (WMED), both of which play critical roles in the basin's general circulation and marine biodiversity. Since at least the mid-20th century, significant alterations have occurred in the thermohaline properties of these sub-basins (Schroder et al., 2016; de la Vara et al., 2022) as well as in biota and ecosystem communities (Bianchi et al., 2019; Azzola et al., 2024).

The vertical stratification in the area is structured with an upper layer of Atlantic Water (AW) extending from the surface to

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100-200 m from the Gibraltar Strait, and a core of the Levantine Intermediate Water (LIW) between 700 and 1000 m depth, entering from the eastern basin through the Sicily Channel, as previously described by Millot (2013) and Ribotti et al. (2020b). At greater depth, the Western Mediterranean Deep Water (WMDW) is observed (Fuda et al., 2002; Send and Testor, 2017). Transitional waters, characterized by a relative minimum of potential temperature, have been detected between AW in the surface and the denser LIW and in large parts of the WMED, although their signature significantly changes in latitude, being colder in the Ligurian basin (Gasparini et al., 1999; Sparnocchia et al., 1995) and warmer in the central and southern Tyrrhenian basin (Napolitano et al., 2019).

In the Ligurian sub-basin, the intermediate water mass is identified as Western Intermediate Water (WIW), while in the Tyrrhenian as Tyrrhenian Intermediate Water (TIW). Both water masses are associated to cooling and mixing processes leading to the formation of well-mixed sub-surface waters during the winter months, between the Ligurian-Provençal sub-basin and the Balearic Sea for WIW (Salat and Font, 1987; Sparnocchia et al., 1995; Gasparini et al., 1999; Millot, 1999; Pinot and Ganachaud, 1999; Salat et al., 2010; Juza et al., 2013) and in the Tyrrhenian Sea for TIW (Napolitano et al., 2019). Generally, the WIW forms a portion of the water column positioned between 100-200 m depth, then overlaid by the warmer AW protecting it from any exchange with the atmosphere. After being generated, most of the WIW flows towards the southern part of the WMED through water eddies advected by the Northern Current (Pinot et al., 2002) for months or years progressively mixing with the surrounding water masses (Perkins and Pistek, 1990; Benzohra and Millot, 1995). Due to the discontinuity of the formation processes related to the weather conditions, WIW is not formed every year. It is observed as isolated mesoscale lenses, characterized by a core temperature of approximately 13.2 °C, a salinity between 38.35 - 38.45 and dissolved oxigen (DO) of 5 mL $L^{-}1$ in the Ligurian Sea (Gasparini et al., 1999). The WIW represents a permanent hydrological characteristic of the Ligurian Sea, and intermittent signatures of WIW were also detected at the entrance of Alboran Sea (Vargas-Yáñez et al., 2017), along the northern African coast (Sammari et al., 1999) and till the Sicily Strait, near the coast between 100 – 200 m depth, as documented by Bonanno et al. (2014). The autors measured relative potential temperature minima of 13.95-14.2 °C, salinities of 38-38.5 and densities lower than 28.8 kg m^{-3}, during some surveys between 1999 and 2013. WIW signatures were founded also in the Tyrrhenian basin in the form of small (about 100 km) anti-cyclonic eddies, known as Weddies (Millot, 1999). Moreover Budillon et al. (2009) measured patches of WIW with a potential temperature lower than 13.5 °C, a salinity of 38.25 - 38.35, a density of 28.85 kg m^{-3}, DO about 5.0 mL $L^{-}1$, in the central Tyrrhenian Sea during two surveys carried out in 2005. These values are very similar to those of the water previously observed by Bouzinac et al. (1999) along the western side of the Sardinia Channel between November 1993 and October 1994, identified as WIW by Astraldi et al. (2002). Also, Falco et al. (2016) identified the presence of cold-water patches with density of 28.6 kg m^{-3} at intermediate depth in the middle of the southern-eastern Tyrrhenian Sea during surveys carried out between 2006 and 2010.

The TIW formation region is the northern Tyrrhenian Sea in correspondence of the Bonifacio Cyclonic Gyre (BCG), as described by Napolitano et al. (2019). A homogenization of the water column occurs due to the vertical mixing induced by the cyclonic circulation of BCG, until a depth of about 400 m. The mixing depth depends on the severity of the winter weather conditions (Astraldi et al., 1999; Send et al., 1999; Schröder et al., 2006). The TIW was originally observed in the southern Tyrrhenian basin by Hopkins (1988) and Povero et al. (1990). It shows different physical properties between the northern and

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the southern Tyrrhenian Sea, but it ranges between 13.9 - 14.4 °C (13.6-13.7 °C from Napolitano et al. (2019) and 38.1 - 38.3 from Iacono et al. (2021)). Despite the same formation processes and depths, WIW and TIW are distinguishable by their DO contents, lower for WIW, higher for TIW. The DO content measured in the core of TIW lenses is > 5 mL $L^{-}1$ in the Tyrrhenian basin and close to surface values. This seems at odds with the idea of a structure travelling for a long time and let us exclude a remote contribution of the WIW in the Tyrrhenian basin, as supported by Millot (2013).

In early 21^{st} century, changes in the water masses properties in the Mediterranean Sea have been widely documented, with the production of large amounts of warmer, saltier and denser waters than ever before. These new waters crossed the WMED catching strong changes in its hydrology and circulation (Iacono et al., 2021; García-Monteiro et al., 2022; de la Vara et al., 2022). Recent field measurements have revealed a significant warming trend and an increase in Ocean Heat Content, primarily driven by intensified atmosphere–ocean interactions and the consequent direct impact on surface layers (Ribotti et al., 2016; Kubin et al., 2023). Additionally, the advection of warm water masses from the Levantine Basin has further influenced subsurface thermal structures (Dayan et al., 2023). These dynamics have led to modifications in the thermohaline circulation of the Western Mediterranean Sea, particularly due to a marked increase in stability induced by a stronger stratification of the water column. In the Tyrrhenian Sea, the stability observed between 2014 and 2018 was approximately twice the long-term average estimated from 1970 to 2018 (Ciuffardi et al., 2024).

Climate change has emerged as a dominant driver of such transformations, acting through multiple atmospheric and oceanic vectors that reshape basin-scale circulation and coastal-shelf exchanges. Increased surface warming has enhanced the permanent and seasonal stratification of the upper ocean, weakening vertical turbulent fluxes, shoaling mixed layers, and reducing the renewal of nutrients and oxygen in intermediate and deeper layers (Holt et al., 2025). These changes also modulate density-driven circulation patterns, affecting the supply of LIW and the structure of transitional intermediate waters such as WIW and TIW. The observed thermohaline trends reflect a broader climate-induced reorganization of the Mediterranean's intermediate circulation, with implications for the biogeochemical balance, ecosystem functioning, and coastal hydrographic stability.

The characteristics of all intermediate waters have changed during the last decades due to multiple factors, including the impact of the climate change (Vargas-Yáñez et al., 2010, 2017; Garcia-Martinez et al., 2018), variations in atmospheric forcing (Margirier et al., 2020), alterations in the water exchanges with the Atlantic Ocean (Rogerson et al., 2010), changes in water mass formation (Ali et al., 2022), and anthropogenic impacts on the shelves (Venegas et al., 2025). Recent measurements have shown a consistent increase in temperature, primarily due to an increase in heat flux from the atmosphere, as well as of the salinity, mainly due to an increased evaporation, reduced precipitation and limited freshwater inputs from the rivers (Schröder et al., 2006; Marty and Chiavérini, 2010; Borghini et al., 2014; Ben Ismail et al., 2014; Houpert et al., 2016; Schroeder et al., 2017). Moreover, LIW is experiencing shifts in regions of water formation and properties, becoming warmer and saltier before it spreads into the WMED through the Sicily Strait (Fuda et al., 2002). Then, WIW core temperature is increased in the range 0.07 - 015 °C yr^{-1}, while for salinity 0.003 - 0.04 yr^{-1} from 2011 to 2015 (Juza et al., 2019), and Soto-Navarro et al. (2020) expect a strong reduction of WIW production between 20 % and 60 % at the end of the twenty-first century. Although a wide bibliography exists on the water masses characteristic evolution and circulation variability into the sub-basins, thanks to a huge amount of data from oceanographic instruments since early '70s (Krivosheya, 1983; Astraldi et al., 1990; Astraldi and

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Gasparini, 1994; Astraldi et al., 1999; Poulain and Zambianchi, 2007; Budillon et al., 2009; Vetrano et al., 2010), studies on the changes on the coastal waters properties in term of interannual variability are missing. Substantial changes in the formation of dense waters, particularly in the Ligurian Sea, were noted by Sparnocchia et al. (1995) comparing temperature profiles measured during the MedOc experiment (in 1969) with others measured within the UNESCO - PRIMO programme in 1991. The authors reported a transition from deep winter convection conditions to those of intermediate depth convection.
The main objective of this study is to investigate the spatial and interannual variability of water mass characteristics and to assess the impact of global change on these properties along the Tyrrhenian and Ligurian continental shelves. This research aims to address a significant gap in oceanographic observations within the study area. The analysis is based on a CTD dataset collected by the National Research Council of Italy (CNR) during twelve cruises called EVATIR conducted in the summer months between 2009 and 2022, supported by satellite and modelling products. These surveys span from the westernmost point of Sicily in the south to the Italian continental border in the north-west (Fig. 1). Section 2 provides a description of the study area, while Section 3 outlines the surveys and data collected, and Section 4 the analysis and interpretation of the results. The paper concludes with a discussion and final remarks.

2 Area of study

The western Italian continental shelf extends along the coasts from Liguria at north, to Sicily at south, characterized by steep slopes, submarine canyons, and tectonic activity. The Ligurian continental shelf is particularly narrow, especially along the north-western Italian coast, where the Alpine and Apennine arcs are close to the coast (Bozzano et al., 2006; Mercier de Lépinay et al., 2010; Wolf et al., 2021; Bo et al., 2023). The steep bathymetry in this region promotes the formations of submarine canyons that cut the shelf, and play a key role in sediment transport, nutrient mixing and deep-water exchanges (Allen and Durrieu de Madron, 2009) . From Tuscany to Sicily is more variable in width, with wider shelf areas due to the presence of big rivers that contribute to the sediment transport on the shelf (Lo Iacono et al., 2014; Cocchi et al., 2015; Casalbore and Chiocci, 2019; Palmiotto and Loreto, 2019; Ciuffardi et al., 2023). This is particularly true in the area highlighted in Fig. 1 where the shelf is particularly wide. This limits the exchange of mainly Tyrrhenian waters northward just across the Corsica Channel, while on the shelf we find resident waters (Manzella, 1985).

3 Observational and numerical modelling products

3.1 Survey products

Table 1 provides an overview of the twelve oceanographic cruises EVATIR carried out along the Tyrrhenian and Ligurian continental shelf during the summer months from 2009 to 2022, excluding the years 2010 and 2012. Their spatial limits are given by the plotted casts. The in-situ sampling design for this study focused on the nearshore and continental shelf areas (Fig.

1). High spatial resolution sampling was conducted in 2019 and 2022, while the surveys in 2013 and 2014 were limited to the middle and southern sections of the Tyrrhenian shelf. The design was the same every year, but the number of casts has been conditioned to the local weather conditions. Transects were oriented perpendicular to the coast, with observations primarily confined to the upper 400 m of the water column, except for the 2016 survey which includes deeper CTD casts in the Ligurian Sea, reaching a maximum depth of approximately 950 m. Each transect was composed by two CTD casts spaced of 10 to 40 km each other.

Totally, in-situ data consist of 2695 vertical profiles of potential temperature, conductivity and pressure between the surface and the bottom (maximum depth of 400 m) by means of a calibrated Sea Bird Electronics multiparametric probe, model SBE 911 plus, deployed from the R/V G. Dallaporta. The CTD was mounted on a General Oceanics Rosette system, equipped with sensors of conductivity, temperature, depth, and dissolved oxygen, used to sample the hydrological parameters along the vertical at 24 Hz and with a lowering speed of 1 m s^{-1}. These data were respectively measured by means of: an SBE 4 water conductivity sensor (resolution of 3×10^{-4} S m^{-1} and an accuracy of ±0.0003 S m^{-1}) and an SBE 3F thermometer (resolution of 0.00015 °C/bit at -1 °C, or 0.00018 °C/bit at 31 °C, and an accuracy of ±0.001 °C), a Paroscientific Digiquartz pressure sensor (with ±0.015 % of full scale range of accuracy) and a SBE 43 polarographic membrane sensor for dissolved oxygen with a range of 120 % of surface saturation and an accuracy of ±2 % for saturation. Pre-cruise calibrations of sensors of temperature, salinity and dissolved oxygen were performed, not in all years, to obtain a slope correction, used in the configuration file of the SBE Seasoft™ suite of programs, improving the data quality. After their acquisition, data were pre- processed by the SBE Data Processing™ software with the updated configuration file, to correct coarse errors (Ribotti et al., 2020a). The pressure sensor is usually stable and so it is not calibrated.

All CTD acquired data are available in the SEANOE data repository (Bonanno et al., 2025) where each dataset is identified per cruise and provided as Ocean Data View (Schlitzer, 2025) ASCII file format with missing values set to -1.e^{10}. Methodologies before, during and after any acquisition, instruments and personnel changed a little during the 12 years of CTD acquisitions. This makes the data in the datasets highly coherent and comparable. The identification of water masses was based on the analysis of vertical profiles of potential temperature (θ), salinity (S), and dissolved oxygen (DO), supported by θ–S diagrams and vertical sections. The analysis focused on the upper 250 m of the water column, except the Ligurian continental shelf, enabling the characterization of both the surface layer, dominated AW, and a transition layer beneath it, representing the upper portion of the intermediate layer that preconditions the formation of LIW. AW was identified by the presence of a salinity minimum, typically located between 50 and 150 m depth. For each station and year, core properties of AW were determined by averaging θ and S values from the depth of the salinity minimum down to 10 m below, following the method of Bonanno et al. (2014). Although the dataset does not capture the full LIW core, usually found between 300 and 500 m, a subsurface layer between AW and LIW, defined as transition layer, was identified.

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3.2 Satellite and modelling products

Satellite derived observations consist of Sea Surface Temperature (SST) that, with ocean model products and heat fluxes by the European Centre Medium-range Weather Forecast (ECMWF), are used to support the interpretation of the interannual variability of the water masses. Specifically, SST consists of daily (night-time) fields with a horizontal resolution of 0.05° (about 4 km), optimally interpolated (L4) from the original Pathfinder Advanced Very High-Resolution Radiometer (AVHRR) data (Pisano et al., 2016). Ocean model solutions were used to analyse the large-scale and mesoscale circulation in the Tyrrhenian Sea derived from the Mediterranean Sea Physical Reanalysis, product ID MEDSEA MULTIYEAR_PHY_006_004 (Escudier et al., 2020; Nigam et al., 2020). The ocean model horizontal grid resolution was 1/24° (about 5 km) with 141 unevenly spaced vertical levels (Escudier et al., 2021). These products are available through the Copernicus Marine Environmental Monitoring Service. Moreover, heat fluxes provided by ECMWF, on regular spatial grid of 0.25° x 0.25° and a temporal step of six-hours (00:00, 06:00, 12:00, 18:00 UTC time) were also used. The variables were the surface downwelling shortwave flux corrected with the fraction of cover cloud, the surface net thermal radiation (long wave radiation), the surface net upward sensible heat flux and the surface upward latent heat flux.

4 Results

The θ-S diagram in Fig. 2A shows the physical characteristics of the water column from all casts during the twelve EVATIR surveys (refer to Table 1). The diagram shows a shift over time towards an increase in both temperature and salinity and the presence of two distinct surface water masses: AW characterized by high temperature and low salinity (S<37.6), and Ionian Surface Water (ISW) which originates in the Ionian Sea and is typically characterized by warm and saline properties (S>38.3, θ>20 °C). Another important water mass identified in the θ-S diagram is the Intermediate Water (IW), as represented by distinct signatures in Fig. 2B. The IW is characterized by a local minimum in temperature within the range 12.85 °C and 14°C, and salinities between 37.7 and 38.4. These thermohaline features are typically found in the intermediate layers of the water column, between depths of 100 and 200 m. IW forms a transitional zone between the AW in the upper layers and the deeper LIW. Deeper water masses such as LIW, Tyrrhenian Deep Water (TDW), and Western Mediterranean Deep Water (WMDW) were not detected in most surveys due to the relatively shallow depths of the continental shelf where CTD profiles were collected. However, during the 2016 survey, which included deeper CTD casts in the Ligurian Sea (with a maximum depth of approximately 950 m), signatures of both LIW and WMDW were observed.
The spatial and temporal variability of the water masses detected in the upper and intermediate layers, based on surveys conducted between mid-May and September from 2009 to 2022 (except for 2010 and 2012, Table 1), are discussed in the subsections 4.1 and 4.2, respectively. Following the analysis, the thermohaline properties exhibit distinctive features that warrant a dedicated, separate investigation of the water column. The study area has been divided into three distinct sub-regions based on latitude (ϕ): the southern Tyrrhenian (ϕ<40° N), the middle and northern Tyrrhenian (39° N<ϕ<43.10° N), and the Ligurian

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shelf (ϕ>43.10° N). These sub-regions are graphically represented by dashed red segments in Fig. 1.

4.1 The surface layer

The temporal variability of AW is highlighted by the salinity minimum (S_{min}) for the three sub-regions as reported in Fig. 3 (panels A1, A2 and A3). The lowest S_{min} values were observed on the Tyrrhenian shelf in 2011, with a mean value of Smin = 37.42 in its southern part, and in 2014 with a mean value of S_{min} = 37.45 in both the southern and middle part. These values confirm the presence of a surface current system feeding AW onto the shelf, originating from the Algerian Current entering the Tyrrhenian Sea (Béranger et al., 2004; Pinardi and Zavatarelli, 2006). Although the AW signatures were also detected on the Ligurian shelf, their presence was less pronounced than in the Tyrrhenian area, reflecting the more complex dynamics. The greater impact of AW on the Ligurian shelf was observed in 2011, 2017, and 2020, with an S_{min} of about 37.8. The highest observed mean S_{min} was 38.22 in 2018. At the depth of S_{min}, the potential temperature ranged from 18 °C on the Ligurian shelf (Fig. 3, panel B1) to 23 °C on the central and northern Tyrrhenian shelf (Fig. 3, panels B2 and B3), based on mean values estimated from surveys conducted in 2014 and 2015, respectively. A clear positive trend in the potential temperature at S_{min} is evident across all the three sub-regions, with the greatest increase observed on the southern Tyrrhenian shelf. Here, the mean potential temperature of S_{min} increased from 17.61 °C in 2011 to 22.02 °C in 2022, corresponding to a total rise of approximately +4.41 °C over 11 years, with an average dθ/dt=+0.40 °C yr^{-1}. Differently, the Ligurian shelf exhibited a more moderate warming trend with an average dθ/dt=+0.29 °C yr^{-1}. The vertical position of the salinity minimum (H_{Smin}) also shows regional variability (not visualized). The mean H_{Smin} fluctuates slightly around 19 m depth in the southern and central Tyrrhenian regions while, on the Ligurian shelf, it is generally deeper, averaging around 30 m.

Sparnocchia et al. (1994) published averaged values of the core of AW in different areas of the Western Mediterranean. We have compared the EVATIR datasets shown in Fig. 3 with Sparnocchia's summer data for the Tyrrhenian and the Ligurian areas (Sparnocchia et al., 1994), taking into account the differences between the two datasets: Sparnocchia's data coming from offshore and coastal casts, while EVATIR are only coastal. The bias of the mean values in the AW core, calculated across all EVATIR oceanographic surveys, are similar for salinity in both areas with +0.06±0.18 in the Ligurian Sea and +0.03±0.12 in the Tyrrhenian while EVATIR data are consistently higher for temperature with +1.85±0.56 °C in the Ligurian Sea and 2.61±0.4 °C in the Tyrrhenian.

The vertical distribution of the salinity field from the surface to 150 m during the surveys conducted in 2011, 2014, and 2022 is presented in Fig. 4. These distributions highlight the prominent influence of fresher AW in the upper layer, particularly within the top 50 m of the water column. As previously discussed, the strongest AW signature was observed in 2011, marked by a pronounced intrusion along the Sicilian coast, extending from the western tip to the Strait of Messina (Fig. 4A). During this year, a broad surface layer with salinity values below 37.5 extended across much of the upper water column. Similar low salinity conditions were reported by Vetrano et al. (2004) in the eastern segment of the Sicily-Sardinia transect during the May–June 2004 survey, further supporting the presence of currents able to transport AW toward the western Sicilian shelf. This transport is associated with the Bifurcation Tyrrhenian Current (BTC), a branch of the Algerian Current system, which splits upon entering the Tyrrhenian Sea. The BTC, described by Sorgente et al. (2011), is particularly active during winter months and constitutes one of the three primary branches derived from the Algerian Current in this region (Béranger et al., 2004; Pinardi and Zavatarelli, 2006). Salinity generally increases toward the coast (not shown), due to the presence of coastal waters not affected by the fresher AW, as well as with depth, where saltier waters with salinity values exceeding 38.25 are consistently observed below 100 m.

During the 2014 survey, low salinity values were again detected on the southern and middle Tyrrhenian shelf (Fig. 4B), indicative of the continued influence of fresher AW in these regions. These observations support the presence of dynamic mesoscale features associated with the Middle Tyrrhenian Current (MTC), as described by Pinardi et al. (2016), which contributes to the advection of AW toward the middle and northern Tyrrhenian shelf. This process is further modulated by localized mixing and stratification dynamics. The presence and behavior of the MTC align with the broader conceptual model of surface circulation in the Tyrrhenian basin proposed by Vetrano et al. (2010), and more recently refined by Iacono et al. (2021), underscoring the persistent role of regional current systems in shaping the distribution of water masses.

The signature of fresher AW, defined by salinity values below 37.5, is no longer observed in 2022 along the Sicilian shelf (Fig. 4C). Instead, the vertical salinity profile reveals a marked increase throughout the water column, accompanied by a noticeable uplift of the halocline along the Sicilian shelf. This salinity increase is primarily attributed to the advection of ISW into the southern Tyrrhenian basin and along the Sicilian shelf. The influence of ISW is particularly pronounced below 100 m, where its thermohaline signature becomes dominant. ISW is considered a localized feature resulting from the northward tidal inflow through the Strait of Messina, as previously described by Brandt et al. (1999). This flow significantly impacts the water column, rising from depths below 100 m up to approximately 15 m near the Strait, visible on the right side of Fig. 4C. This vertical movement contributes to an overall increase in both mean salinity and potential temperature, when compared with the conditions observed in 2011 (Fig. 4A). A particularly strong ISW signal is detected near the Strait of Messina, characterized by salinity values around 38.59 and potential temperature exceeding 15.74 °C within the 60–75 m.

4.2 The intermediate layer

The θ-S diagram shown in Fig. 2A also reveals the presence of intermediate waters, identified by a relative minimum in potential temperature. This thermal feature is indicative of the advection of intermediate waters, such as WIW and TIW. They are located beneath the AW layer and are typically confined to depths between 100 and 200 m. Both are characterized by potential temperature minima ranging from 13.85 °C to 14.0 °C, and corresponding salinity values between 37.7 and 38.4. The thermohaline characteristics observed in this depth range reflect the transition zone between the overlying AW and the deeper LIW, significantly contributing to the stratification and vertical structure of the water column in the Tyrrhenian and Ligurian sub-basins. The presence of WIW was consistently observed in all surveys conducted over the Ligurian shelf, where it appears as a broad, quasi-isothermal layer spanning depth between 90 and 200 m, in agreement with earlier findings by Millot (1999). The lowest minimum potential temperature was observed during the 2009 survey reaching 13.34 °C at a depth of 140 m (Fig. 5A), accompanied by a dissolved oxygen of 6.93 mL L^-1, salinity of 38.24, and a potential density anomaly of 28.846 kg m^{-3}

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(cast ST219, $\phi = 43.824°$ N, $\lambda = 10.135°$ E). This observation aligns with the values reported by Salat and Font (1987), who identified WIW in the Ligurian Sea with potential temperatures ranging from 12.4 to 13.0 °C and salinities between 38.1 and 38.3, typically forming isolated structures distributed along the coastal margins. The average temperature of the WIW core was 13.61 °C in 2009, reaching a peak of 14.09 °C in 2017, corresponding to a positive warming dθ/dt= +0.06 °C yr^{-1}. Thereafter, the trend reversed, with the core temperature decreasing to 13.75 °C in the most recent survey. Salinity continued to increase until 2019, with a rate of dS/dt=+0.029 yr^{-1}, after which it also reversed, decreasing with a slower dS/dt=-0.008 yr^{-1} up to the last survey. A marked thermal contrast between WIW and the warmer Tyrrhenian waters creates a vertical thermal front near the Corsica Channel ($\phi = 43.1°$ N). This front exhibit strong interannual variability, as depicted in Fig. 5, and serves as a dynamic boundary between the Ligurian and the Tyrrhenian sub-basins.

Monitoring activities during EVATIR also revealed the presence of intermediate cold-water patches located between 70 and 200 m depth along the Tyrrhenian shelf at latitudes 41-42° N (Fig. 5B). One of the most prominent features was observed at cast ST166 (ϕ=41.519° N, λ=12.182° E), where the potential temperature reached a minimum of 13.58 °C at 144 m depth. This water mass was characterized by a dissolved oxygen concentration of 7.18 mL L^{-}1, salinity of 38.205, and a potential density anomaly of 28.760 kg m^{-3}. These thermohaline properties are comparable to those typically associated with the WIW; however, the elevated dissolved oxygen concentration suggests a more recent formation. This supports the identification of this water mass as TIW, likely resulting from winter convection processes driven by the BCG, as previously described by Napolitano et al. (2019). TIW was also detected in 2013 (not shown), characterized by a minimum potential temperature of 13.89 °C at a depth of 130 m, DO of 6.72 mL L^{-}1, salinity of 38.24, and a potential density anomaly of 28.72 kg m^{-3} (cast ST116, at 40.011° N, 15.141° E). However, subsequent surveys did not reveal any further TIW signatures (θ < 14 °C). Differently, WIW was consistently observed on the Ligurian continental shelf. Specifically, in 2015 the minimum potential temperature on the Ligurian shelf was 13.58 °C at a depth of 128 m (Fig. 5C), with DO concentration of 6.54 mL L^{-}1, salinity of 38.19, and a potential density anomaly of 28.75 kg m^{-3} (cast ST226, at 43.467° N, 9.58° E). The potential temperature increases on the northern Tyrrhenian shelf, between depths of 150–230 m, with the isotherms rising toward the sea surface due to local upwelling. In this region, the minimum potential temperature was 14.09 °C at a depth of 147 m, with a DO concentration of 5.81 mL L^{-}1, salinity of 38.56, and a potential density anomaly of 28.929 kg m^{-3} (cast ST203, at 42.125° N, 11.39° E). The observed lower DO concentration within the upwelling region at intermediate depths suggests the presence of resident water masses on the northern Tyrrhenian shelf, as also noted in 2016 (not shown). Furthermore, the intrusion of ISW is clearly evident, affecting the entire water column on the southern Tyrrhenian shelf (south of 39° N). The isotherm of 14.75 °C, which is typically close to the sea surface, extends to a depth of 200 m near the Messina Strait. The maximum impact of ISW was observed in 2017 where the vertical thermal front (θ=14.75 °C) shifted northward, reaching approximately 41° N (Fig. 5D). On the Ligurian shelf, colder water masses with potential temperatures below 14.0 °C were not observed, reinforcing the evidence of a gradual increase in both temperature and salinity in the intermediate water column (100–200 m) from 2009 (S=38.27, θ=13.57 °C) to 2017 (S=38.36, θ=14.05 °C). This change reflects a dθ/dt=+0.06 °C yr^{-1} for potential temperature and dS/dt=+0.011yr^{-1} for salinity.

Signatures of WIW and ISW were also observed from 2018 to 2022, although the potential temperature fields showed sig-

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nificant differences, particularly in terms of spatial variability. In 2022, the potential temperature field (Fig. 5E) indicated that WIW affected the intermediate water column of the Ligurian shelf. The minimum potential temperature observed was 13.66 °C at a depth of 151 m, with DO of 4.38 mL L^{-1}, salinity of 38.40, and a potential density anomaly of 28.90 kg m^{-3} (cast ST274, at 43.70° N, 7.88° E). Conversely, ISW was detected on the opposite side, and a tongue of relative colder water extended to 100 m depth along the Tyrrhenian shelf. This water mass, with a potential temperature θ<14.5 °C, affected the water column between 70 and 250 m depth, gradually narrowing southward and forming a weak inverse thermocline around 100 m depth. The mean DO concentration at the depth of minimum potential temperature was 4.5 mL L^{-1}. This low DO suggests that the observed water mass may result from the local mixing of older TIW with the intrusion of underlying ISW, affecting the entire water column downstream.

Monitoring along the northern Sicilian shelf also revealed the presence of cold-water patches on the western side, between 100 and 200 m depth. These patches progressively warmed eastward due to mixing with ISW from the Ionian Basin, which flows through the Messina Strait (Fig. 6A). The minimum potential temperature was 13.81 °C at a depth of 136 m, with a salinity of 38.31 and a potential density anomaly of 28.80 kg m^{-3} on the western side of Sicily (cast ST002, at 38.085° N, 12.399° E) in 2009. A high DO concentration of about 7.06 mL L^{-1} was observed in the core, which is like typical surface values. This finding appears inconsistent with the expectation of a water mass that has travelled for a long time from its formation site. Furthermore, the temperature and salinity values are higher than those associated with the intermediate water identified as WIW by Ben Ismail et al. (2012). The authors observed the water masses between Cape Bone (Tunisia) and Mazara del Vallo (Sicily), where a potential temperature minimum of 13.60 °C was found at a depth of 140 m, approximately corresponding to a density of 28.50 kg m^{-3}. Intermittent signatures of WIW were also reported by Sammari et al. (1999), Lermusiaux and Robinson (2001) and Bonanno et al. (2014), as previously mentioned. Signatures of small patches of colder water were observed in 2011 (not shown) and again in 2013 (Fig. 6B). The minimum potential temperature was 13.89 °C at 75 m depth, with a DO concentration of 6.79 mL L^{-1}, salinity of 38.28, and a potential density anomaly of 28.75 kg m^{-3} (cast ST17, at 38.094° N, 12.82° E). No signatures of colder-water patches were observed on the Sicilian shelf in subsequent years. However, an intermediate inversion of potential temperature was detected between 70–130 m depth (Fig. 6C). This inversion was induced by the presence of a warmer layer (θ>14.5 °C) below it, as well as the substantial presence of ISW coming from the Messina Strait (λ=15.72° E), where ISW occupied almost the entire intermediate water column. Additionally, the 15 °C isotherm from the sub-surface layer descended to 200 m depth, forming a strong vertical density front (not shown). The maximum relative potential temperature observed below the sea surface was 16.97 °C at 50 m depth, with DO of 7.43 mL L^{-1}, salinity of 38.33, and a potential density anomaly of 28.08 kg m^{-3} (cast ST74, at 38.29°N, 15.79°E). Since 2015, the potential temperature in the intermediate layer has progressively increased, with the warmest values observed in 2016 (Fig. 6D). Below the thermocline, the 14.75 °C isotherm lies at around 100 m depth, deepening to 200 m near the Messina Strait, where the potential temperature remains at or above 14.75 °C. The maximum warming and salinization of the intermediate water (100–200 m) occurred in this year (mean values of S=38.65, θ=14.79 °C), with a dθ/dt=+0.088 °C yr^{-1} and +dS/dt=0.04 yr^{-1} for potential temperature and salinity from 2009 (mean values: S = 38.44, θ = 14.17 °C). The observed temperature increase is consistent with that reported by Placenti et al. (2022) for intermediate waters observed in the Strait of Sicily between 2010 and 2017. Between 2016 and the

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most recent observations in 2022, salinity and potential temperature remained relatively stable, showing only slight changes (Fig. 6E).

Vertical profiles further illustrate the progressive warming and salinization of the intermediate water masses observed along the continental shelf (Fig. 7). The figure shows the vertical distribution of potential temperature and salinity at the Corsica Channel, central Tyrrhenian shelf, and western Sicilian shelf for the years 2009, 2016, and 2022. At the Corsica Channel the core of WIW is clearly identifiable (Fig. 7A), except in 2016. The minimum potential temperature was 13.5 °C at a depth of 140 m in 2009, while in 2022, the core appeared weaker and shallower, located around 130 m, with a potential temperature of approximately 14.2 °C, with an increase of +0.7 °C. Salinity also increased slightly, from 38.50 to 38.55, while density remained relatively stable (not shown). A similar trend of warming and salinization is observed at the central Tyrrhenian shelf (Fig. 7B), where the core of TIW was located at depths shallower than 100 m in 2009, with a relative temperature minimum of 14.18 °C. In 2016, the minimum temperature increased to 14.70 °C at approximately 100 m depth, reflecting a warming of +0.52 °C. Salinity concurrently increased from 38.46 to 38.69. At the western Sicilian shelf (Fig. 7C), the TIW core was also observed in 2009, with a potential temperature minimum of 13.81 °C at 130 m depth. In subsequent years, the core was no longer clearly detectable, but at the same depth the potential temperature increased of 1.01 °C in 2016. Salinity also increased, from 38.31 in 2009 to 38.59.

4.3 Discussion

To support water masses variability with described observations, we examine how variability in satellite-derived sea surface temperature (SST) and atmospheric forcing drive changes in water masses properties across the Tyrrhenian sub-basin. The variability of SST in February, the coldest month of the winter season, from 2009 through 2024 is shown in Fig. 8. The coldest fields occurred between 2009 and 2012, with notable interannual variability. The minimum temperatures were always found in the BCG region, where strong cyclonic circulation dominates. Surface temperatures below 14 °C once covered much of the Tyrrhenian sub-basin, reaching a minimum of 13.2 °C in 2012 between Corsica and Sardinia. Since 2013, except for 2015, the area with SST<14 °C has steadily contracted and is confined to the BCG region. The 14 °C surface isotherm was absent in both 2016 and 2024. In 2024, the mean SST was 15.13 °C, +1.54 °C higher than the coldest annual mean recorded in 2010.

The increasing of SST and the gradual reduction of the formation site of TIW are driven by changes in atmospheric weather parameters. Figure 9A shows the monthly mean air temperature time series for the BCG region where the monthly mean air temperature increased from about 7 °C in 2012 (blue circle, Fig. 9A) to roughly 12 °C in 2020 (red circle), with a rise of 5 °C over eight years. A similar pattern emerged at the WIW formation site, though mean values were lower, rising from +3 °C in 2011 to +9 °C in 2020. Since 2021, mean air temperature dropped to roughly 10 °C in 2023, then increased slightly to approximately 12.1 °C in 2024. The spatial pattern of 2012's monthly mean air temperature is displayed in Fig. 9B. Minimum monthly means (~ 4 °C) occur along the coast in the Gulf of Lions, with a south-eastward temperature rise that peaks at 9 °C in the Tyrrhenian basin but thermal conditions in 2020 are markedly different (Fig. 9C). The comparison reveals a significant increase in air temperature and a near-isothermal distribution across the basin, ranging from approximately 11 °C in the north to 13 °C in the south. Overall, the sub-basin experienced an average air temperature rise of about +5 °C, with coastal areas showing the highest increase, up to +6 °C. The smallest increase, around +3 °C, was observed in the southeastern Tyrrhenian basin between 2012 and 2020 (Fig. 9B and C). To substantiate the observed increases in air and sea surface temperatures, a time series analysis of the meridional component of surface wind velocity was conducted in the BCG region, given its critical role in ocean-atmosphere interactions and heat transport mechanisms. The maximum intensity of the meridional wind component was recorded in February 2012, reaching approximately 6 m s^{-1}. In contrast, meridional wind speeds did not exceed 3.8 m s^{-1} in 2019 and exhibited a continued decline in subsequent years (Fig. 10). In February 2020, the mean value of the meridional wind component was approximately 1.2 m s^{-1}.

Heat loss derived from ECMWF data model and presented as monthly mean for 2019 and 2020 (Fig. 11) reveals that peaks north-south wind speeds is associated to maximum oceanic heat loss of around -320 W m^{-2} (Fig. 11A). In contrast, during 2020 the heat loss markedly decreased with minima around -200 W m^{-2} (Fig. 11B).

While surface temperature offers an almost instantaneous indication of air–sea interactions, characterized by inherently high variability, the analysis of heat and salt content variability in deeper and intermediate water masses serves as a more reliable climate index for detecting long-term changes. The impact of changing atmospheric conditions on the vertical structure of the water column in the BCG region is illustrated in Fig. 12, which shows monthly mean potential temperature fields simulated by the ocean model (section 3.2) for February 2012 and 2020. In February 2012, the mixed layer extended down to approximately 200 m along the Sardinia/Corsica coast (Fig. 12A), with temperatures west of 11° E consistently below 14 °C. By February 2020, the mixed layer has become significantly shallower, reaching only about 100 m in depth (Fig. 12B), and an overall increase in temperature, particularly noticeable along the eastern coast, extending towards the Tyrrhenian continental shelf. These structural changes in the water column have significant implications. A shallower mixed layer, as observed in 2020, implies reduced vertical mixing and enhanced stratification. This inhibits the exchange of heat and nutrients between the surface and deeper layers, with potential consequences for primary productivity and marine ecosystems dynamics. In particular, the shallower mixed layer could suppress nutrient upwelling, which is crucial for sustaining phytoplankton blooms in coastal and shelf regions. Furthermore, the warming of the surface layer, especially along the eastern coast and near the Tyrrhenian continental shelf, could enhance the stability of the water column, decreasing the efficiency of heat and nutrient transport into deeper waters. This could have cascading effects on the marine food web, altering species distribution and ecosystem dynamics. Additionally, the reduced mixing may also influence local circulation patterns, potentially affecting the dynamics of coastal currents. Temperature changes are also evident at the depth of TIW (150 m), as shown in Fig. 13. In February 2012 (Fig. 13A), temperatures below 13 °C were observed across the BCG region, while temperature ranging between 13 and 14 °C occurred west of the 13° E meridian. In contrast, February 2020 (Fig. 13B) reveals a clear signature of ISW from the Messina strait and also from the Sicily Channel, influencing the hydrology along the Sicilian coast and throughout the southern and central Tyrrhenian shelf.

The observed trend in temperature and salinity in the southern Tyrrhenian Sea could be associated with the circulation regime of the Northern Ionian Gyre (NIG), which alternates between cyclonic and anticyclonic phases under the control of the Adriatic–Ionian Bimodal Oscillating System (BiOS, Civitarese et al. (2010); Gačić et al. (2010)). BiOS is a key driver of decadal-

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scale variability in the Eastern Mediterranean Sea, primarily through its modulation of the surface circulation in the northern Ionian Sea. BIOS dynamics are expressed through the alternating vorticity of NIG, which oscillates between cyclonic and anticyclonic phases, driven by internal feedback involving the dense water formation in the southern Adriatic Sea (Gačić et al., 2011). These shifts in circulation significantly affect not only the surface transport of AW, but also the advection of IW, particularly LIW and Cretan Intermediate Water (CIW), from the Eastern Mediterranean basin. Specifically, during the anticyclonic phase of the NIG, the circulation enhances the westward transport of warmer and saltier toward the WMED (Gačić et al., 2014; Rubino et al., 2020). These dynamics led to a progressive increase in salinity and enhanced vertical stratification in the southern Tyrrhenian Sea, as observed by Figs. 5A-D. Following 2016, NIG shifted into an anticyclonic regime, thereby reducing the westward advection of IW toward the Tyrrhenian basin. However, due to the inertia of the water column and the residual influence of ISW, elevated salinity levels persisted during the initial years of the anticyclonic phase (Fig. 5E and 6).

These processes contribute to the long-term thermohaline transformation of intermediate layers and underscore the significance of BiOS-driven NIG variability in regulating inter-basin exchanges. This interconnected dynamic highlights the importance of coordinated basin-wide observations to fully understand the propagation of climate-driven hydrographic changes from the Ionian to the Tyrrhenian Sea and their broader implications for the central Mediterranean.

5 Summary and Conclusions

This study provides a comprehensive analysis of the thermohaline evolution and spatial distribution of the surface and intermediate water masses along the Ligurian and Tyrrhenian continental shelf, based on twelve summer CTD surveys conducted between 2009 and 2022. The investigation focused on the upper 250 m of the water column, revealing the presence and temporal evolution of distinct water masses: AW origin, WIW, TIW, and ISW.

Atlantic Water displayed pronounced spatio-temporal variability, with the lowest salinity minimum observed in 2011 and 2014. The potential temperature core has shown a clear upward trend, especially in the southern Tyrrhenian, increasing by approximately +0.40 °C yr^{-1}. Vertical salinity distributions highlight strong AW intrusions in earlier years (notably 2011), followed by a decline in AW signatures. By 2016, these had been largely replaced by ISW, whose influence became more evident, particularly along the southern and central Tyrrhenian shelf, where its thermohaline characteristics dominated the subsurface layer.

Western Intermediate Water was consistently observed on the Ligurian shelf. The coldest WIW core occurred in 2009, with a warming trend peaking in 2017, followed by a cooling phase. Salinity exhibited a parallel increase until 2019, then declined at a slower rate. TIW, in contrast, was observed intermittently on the Tyrrhenian shelf, with the most significant occurrence observed in 2009, attributed to winter convection associated with the Bonifacio Cyclonic Gyre. Subsequent observations confirmed sporadic appearances, with no further signatures of TIW (θ<14 °C) detected after 2013. In the southern Tyrrhenian Sea, near the Strait of Messina, the influence of ISW became increasingly evident.

The progressive intrusion of Ionian Surface Water into the southern Tyrrhenian Sea likely reflects the influence of decadal-

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scale variability in Ionian circulation, particularly the vorticity and intensity of the Northern Ionian Gyre, modulated by the Adriatic–Ionian Bimodal Oscillating System. During the twelve oceanographic surveys, the circulation was predominantly in a cyclonic phase, which enhanced ISW advection and contributed to salinification. Following the transition to an anticyclonic regime after 2018, the inflow of ISW weakened, although the residual effects of earlier ISW accumulation persisted. These findings underscore the crucial role of inter-basin connectivity and climate-driven circulation dynamics in shaping the hydrography of the western Mediterranean, emphasizing the need for sustained, high-resolution observational strategies.

Data availability. The dataset used in this study are avalilable in the online SEANOE repositories. https://doi.org/10.17882/107305 (Bonanno et al., 2025). The dataset includes also Chl-a, turbidity and ph parameters not considered in the present study.

Author contributions. RS: Conceptualization, Formal Analysis, Methodology, Writing – original draft, Writing – review & editing; ADM: Conceptualization, Formal Analysis, Review & editing; AR: Data curation, Formal Analysis, Methodology and review; AC: Review & editing; GQ: Review & editing; SG, IF, GG, GB, SA, MB, PR, AB, RF: data acquisition; AB: Data curation, Investigation, Project administration

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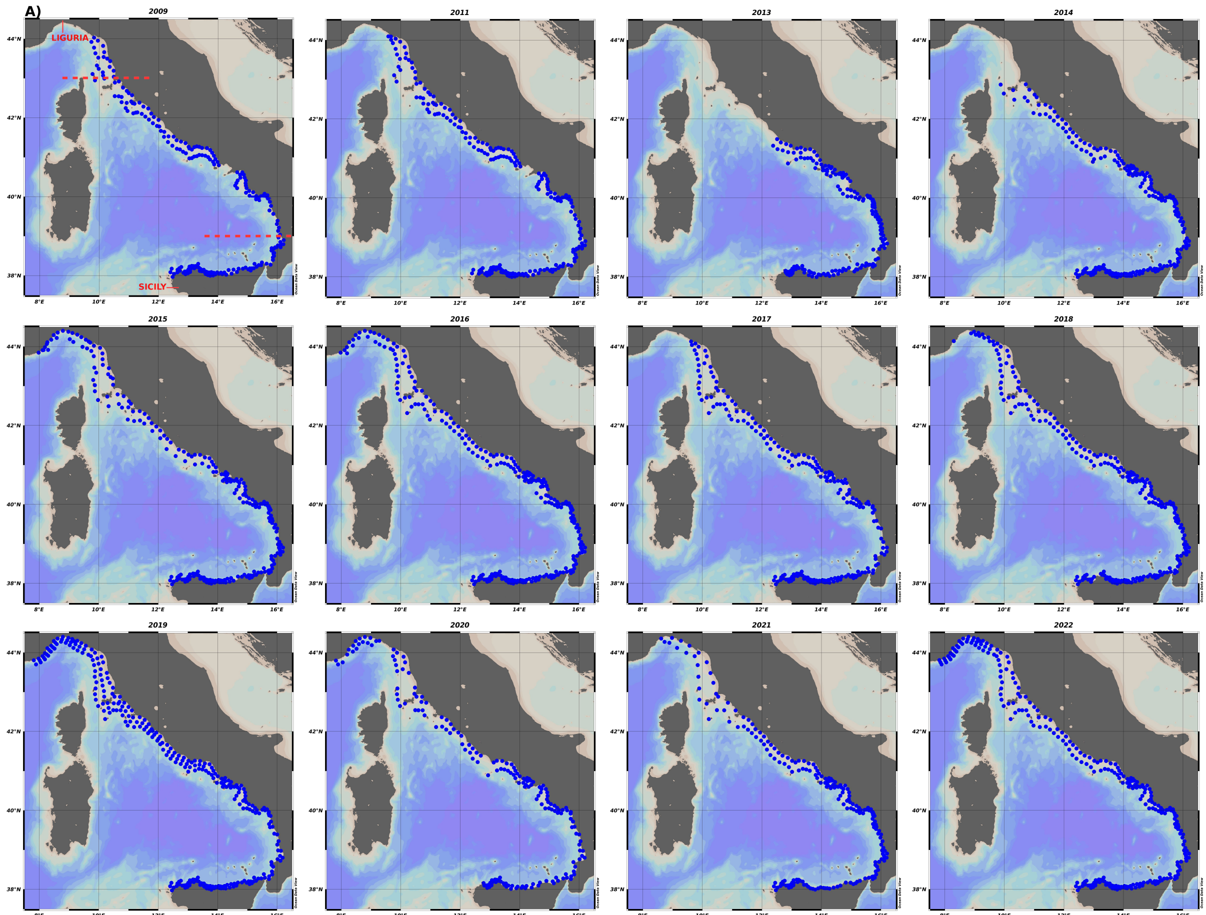

Figure 1. Spatial distribution of hydrological casts carried out during the surveys EVATIR from 2009 to 2022. For each survey its limits north and south are given by the plotted casts. The shaded colour shows the bathymetry (m). Panel A also shows the three sub-domains as the Ligurian (ϕ>43.1° N), northern and central Tyrrhenian continental shelf (39° N<ϕ<43.1° N) and southern (ϕ<39° N). The red box delimits the area with the widest shelf between the Tyrrhenian Sea at south and the Ligurian Sea at north.

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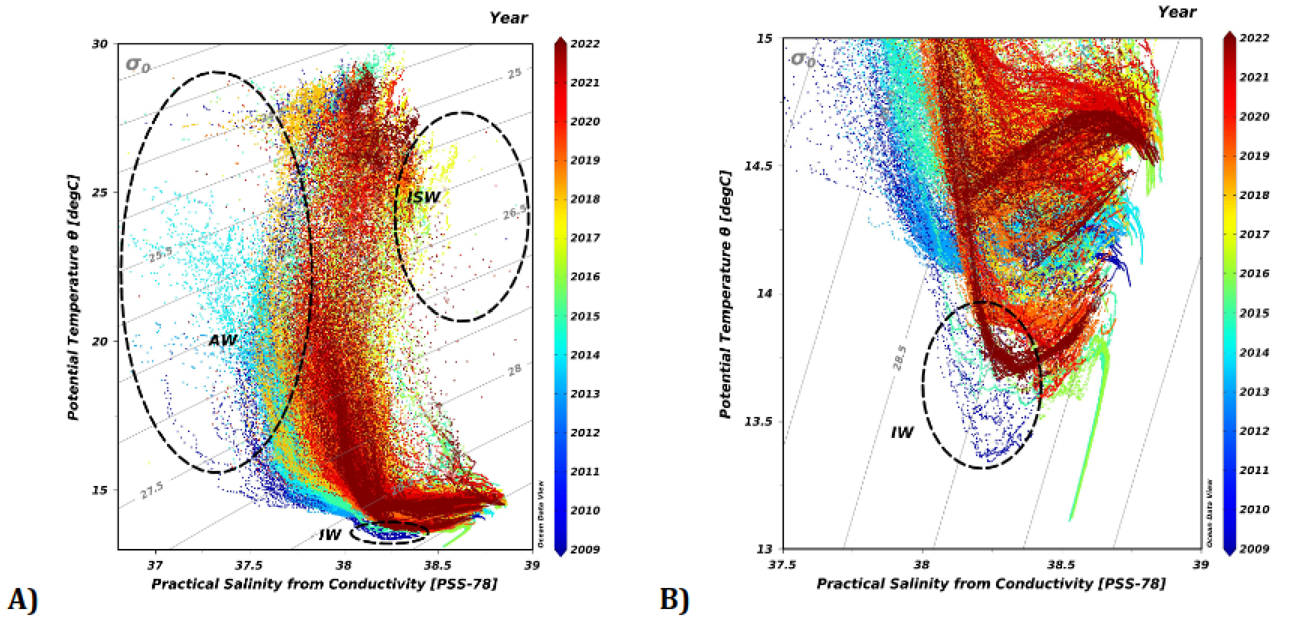

Figure 2. θ-S diagram of the data collected during the surveys EVATIR carried out over the Tyrrhenian and Ligurian continental shelf from 2009 to 2022 (panel A, contour interval for σ_θ=0.5 kg m^{-3}). In panel B is visualized the θ-S diagram excluding the surface layer (σ_θ<27.5 kg m^{-3}, contour interval for σ_θ=0.25 kg m^{-3}). Colours show the temporal distribution of the casts. The years 2010 and 2012 don't include data even if they are necessarely indicated in the colours scale.

Table 1. Sampling period, name of survey and numbers of CTD casts carried out between 2009 and 2022.

Date day/month/year	Name of the survey	Number of CTD Stations
17/08/2009-02/09/2009	EVATIR 2009	211
14/05/2011-06/06/2011	EVATIR 2011	212
20/05/2013-09/06/2013	EVATIR 2013	163
08/06/2014-19/06/2014	EVATIR 2014	208
31/07/2015-27/08/2015	EVATIR 2015	241
27/07/2016-18/08/2016	EVATIR 2016	267
07/08/2017-28/08/2017	EVATIR 2017	205
07/08/2017-28/08/2017	EVATIR 2018	237
13/08/2018-03/09/2018	EVATIR 2019	291
12/08/2019-01/09/2019	EVATIR 2020	182
04/09/2020-12/09/2020	EVATIR 2021	204
30/07/2021-24/08/2021	EVATIR 2022	274

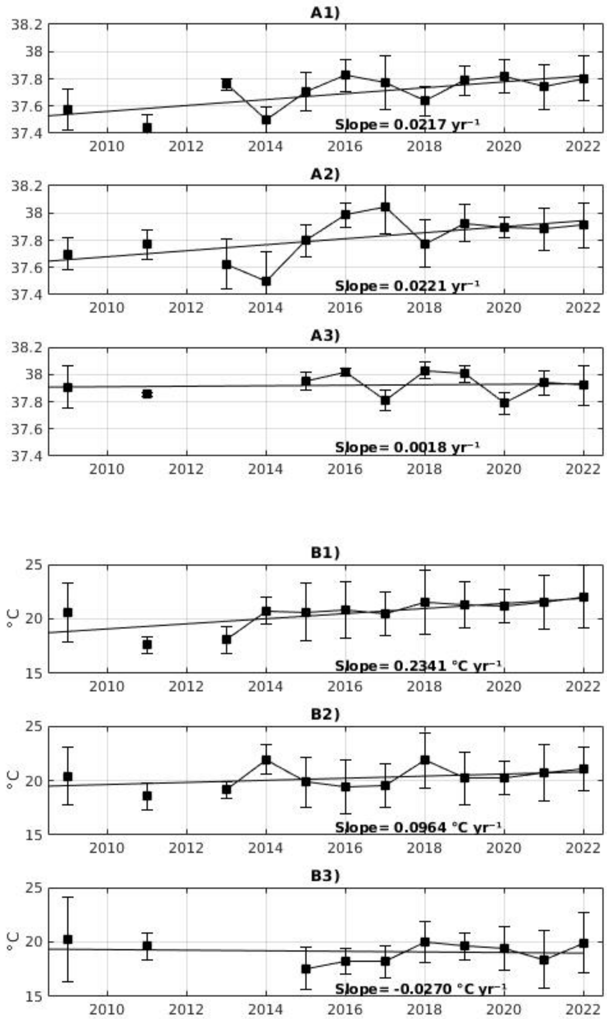

Figure 3. Interannual variability of the mean values of salinity minimum (panels A1, A2 A3) and mean potential temperature (panels B1, B2 B3) for north, middle and south region, respectively. The squares indicate the mean value and the bars the standard deviation (σ) detected from 2009 to 2022. In 2010 and 2012 the CTD data casts are missing.

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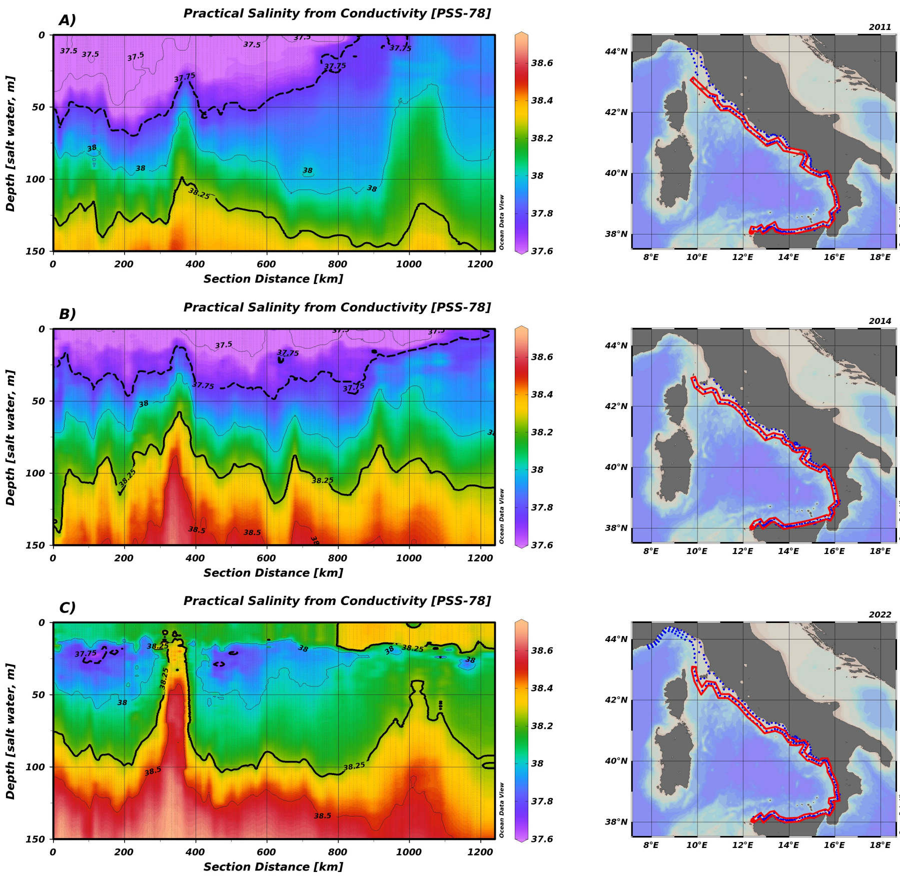

Figure 4. Vertical distribution of salinity along-track over the Tyrrhenian shelf observed at the surface layer (0-150 m) during the surveys in 2011 (panel A), 2014 (panel B) and 2022 (panel C). The section is distance based for a better readability. The start point is the westernmost one on the Sicily shelf.

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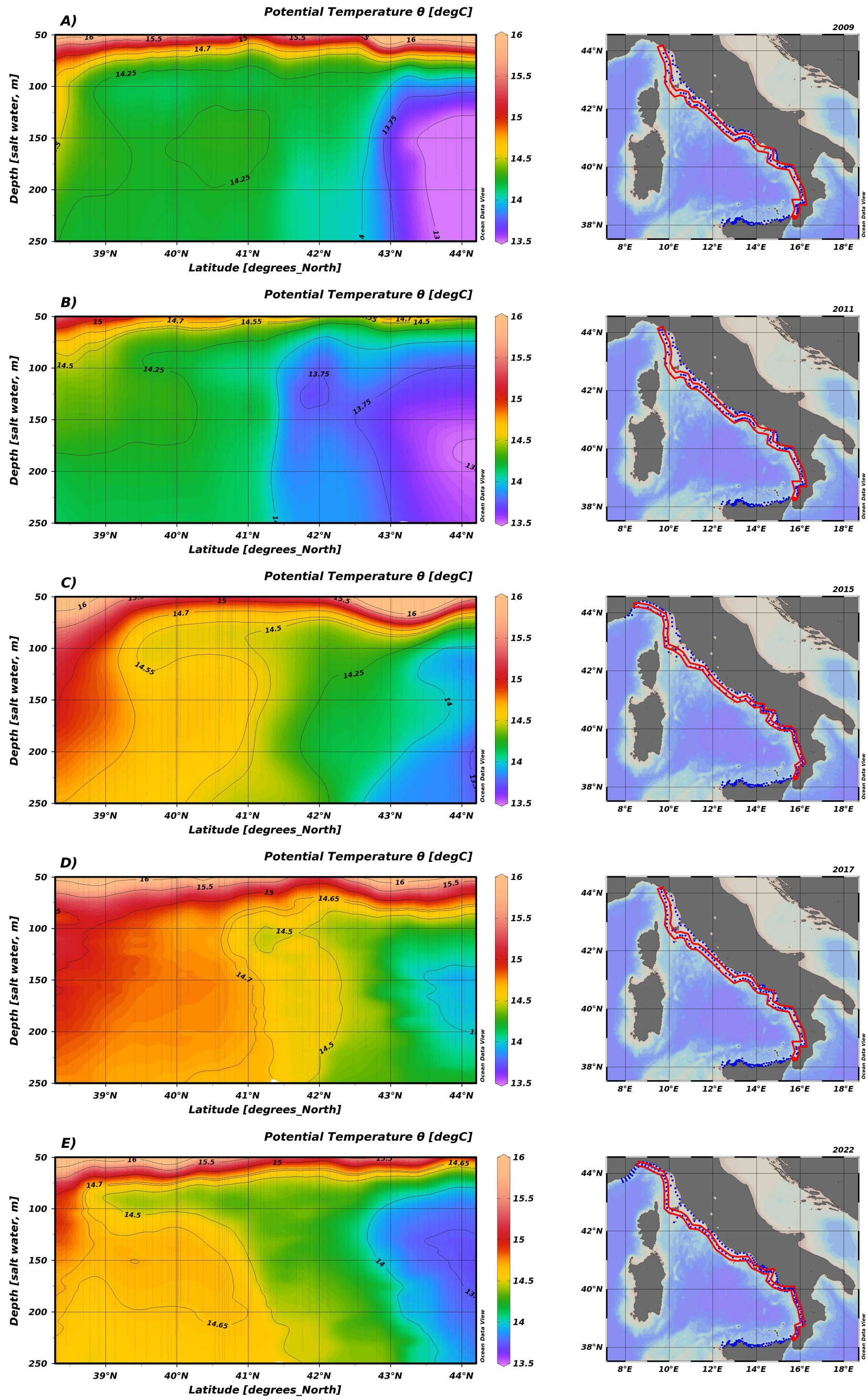

Figure 5. Vertical distribution of potential temperature along-track at the Tyrrhenian and Ligurian shelf observed to the intermediate layer (50-250 m) during the surveys in 2009 (panel A), 2011 (panel B), 2015 (panel C), 2017 (panel D) and 2022 (panel E). The section is latitude based for a better readability.

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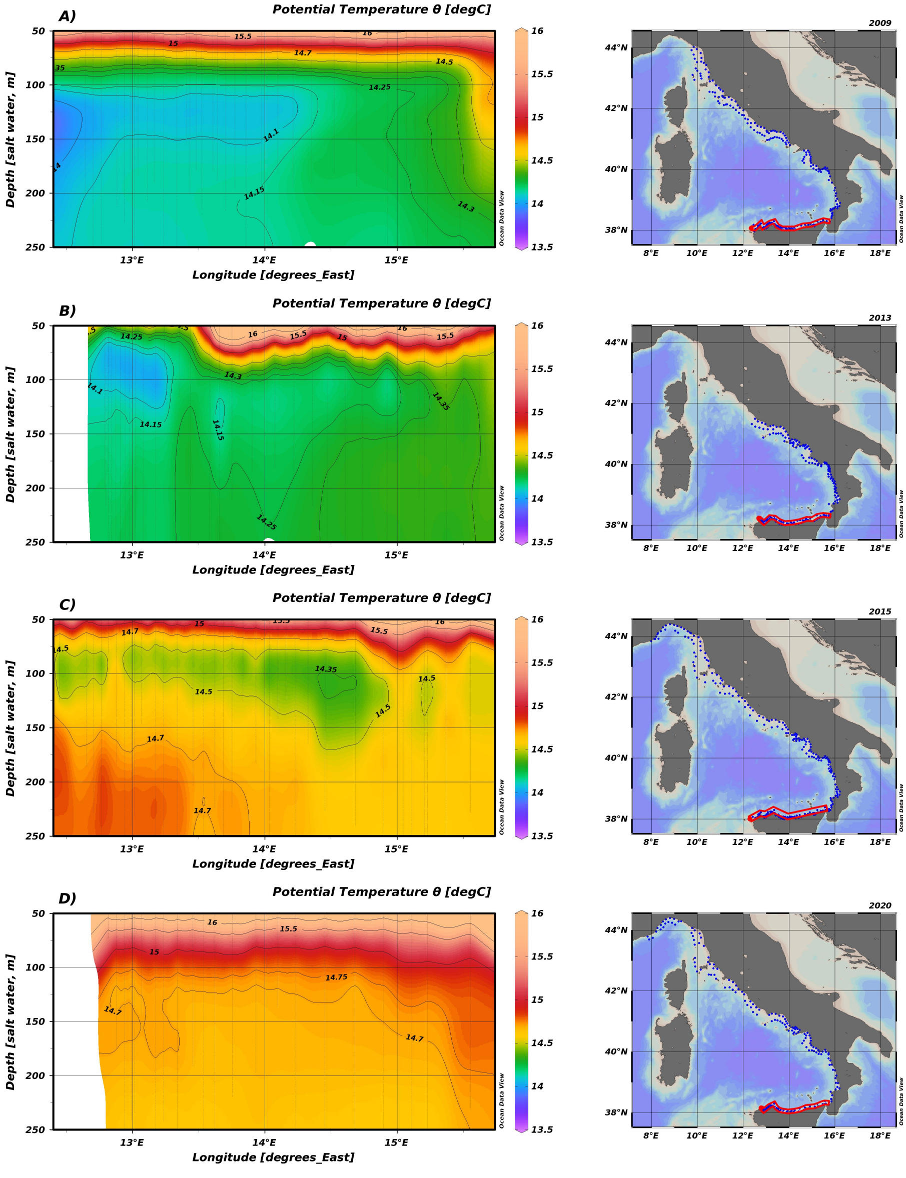

Figure 6. Vertical distribution of potential temperature along-track at the Sicily shelf observed to the intermediate layer (50-250 m) during the surveys in 2009 (panel A), 2013 (panel B), 2015 (panel C) and 2020 (panel D). The section is longitude based for a better readability.

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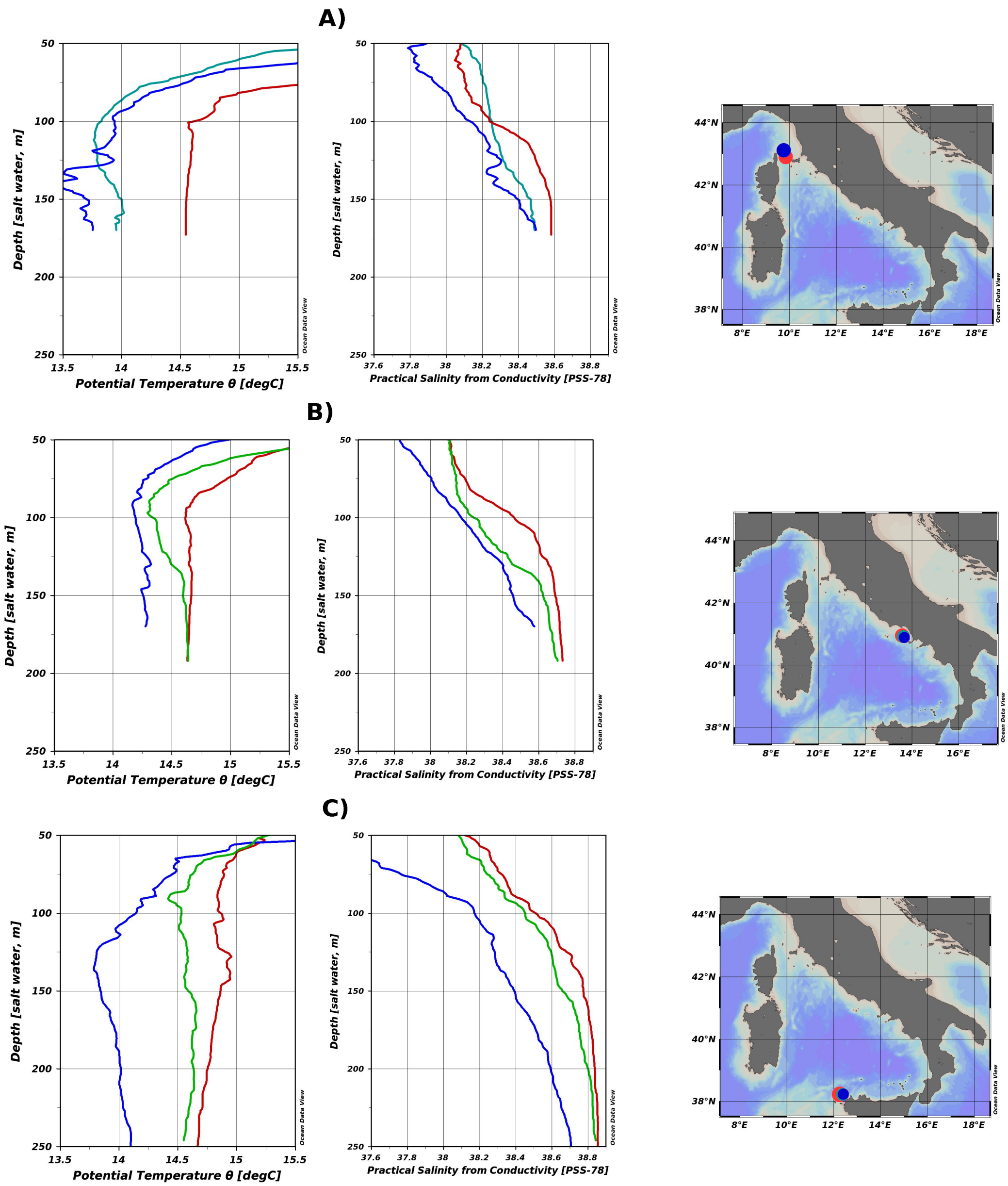

Figure 7. Vertical profiles of potential temperature (left panel) and salinity (right column) observed at CTD casts located at the Corsica Channel (first row; casts STZ T204, ϕ=43.108° N, λ=9.778° E; STZ T229, ϕ=42.944° N, λ=9.778° E), middle of Tyrrhenian continental shelf (central row, casts STZ T135, ϕ=40.04° N, λ=13.727° E, T167, ϕ=40.951° N, λ=13.703° E) and at the western Sicilian (last row, casts ST002, ϕ=38.085° N, λ=12.399° E; STZ T9A, ϕ=38.155° N, λ=12.788° E) in 2009 (blue line), 2016 (red line) and 2022 (green line) between 50 and 250 m depth.

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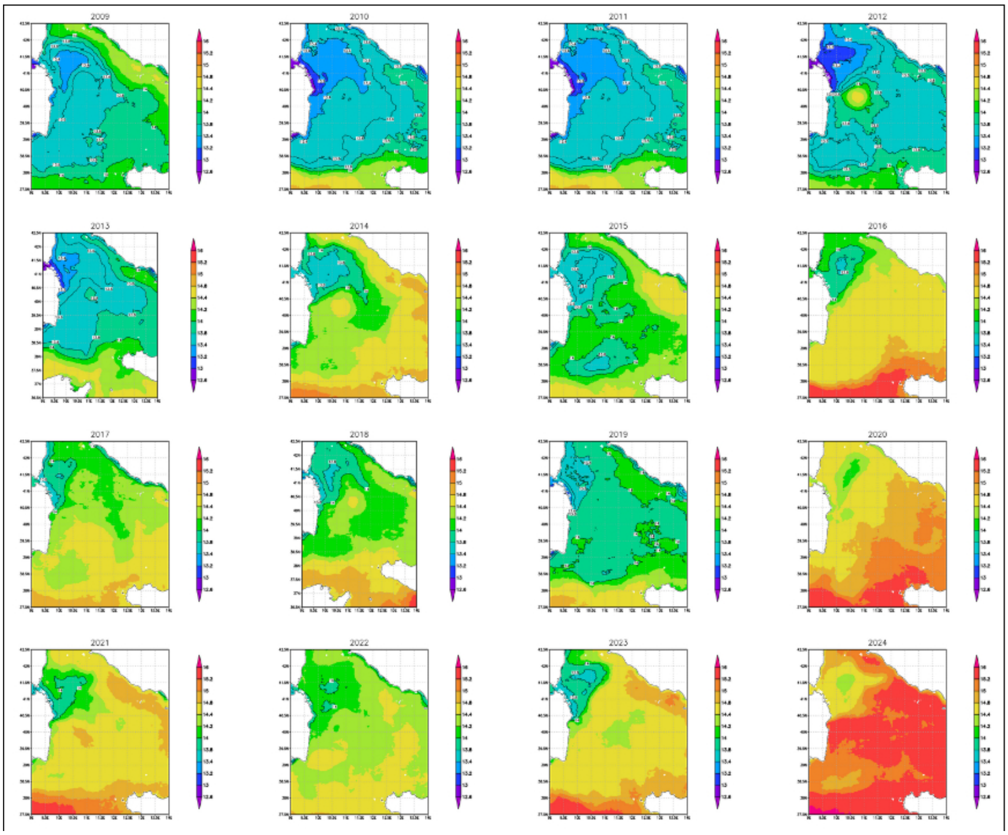

Figure 8. Interannual variability of the February mean field from 2009 to 2024 derived by daily (night-time) fields of satellite Sea Surface Temperature with a horizontal resolution of 0.05° (about 4 km) into the Tyrrhenian basin. The unit is °C. The contour intervals are depicted when the sea surface temperature SST<= 14.0°C.

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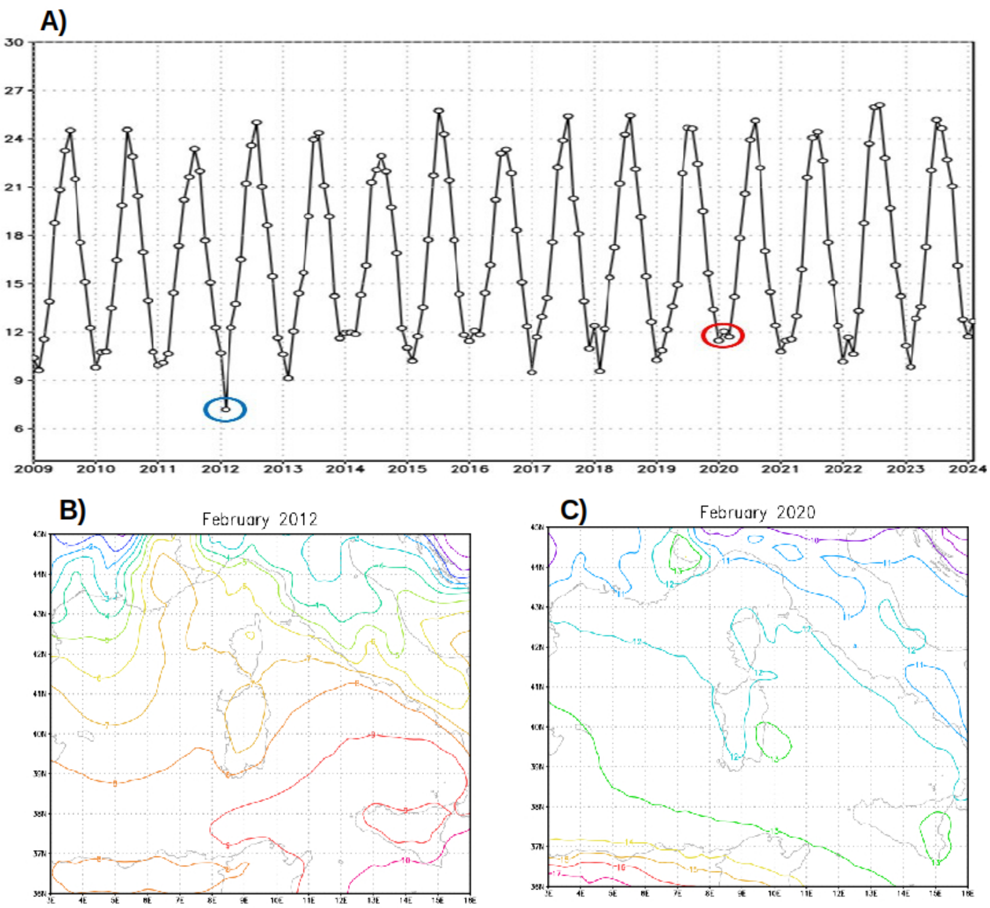

Figure 9. Monthly mean time series of the air temperature from January 2009 to Decembre 2024 (panel A) and the monthly mean field in February 2012 (panel B) and 2020 (panel C) derived by ERA5 re-analysis. The unit is °C. The contour interval is 1°C.

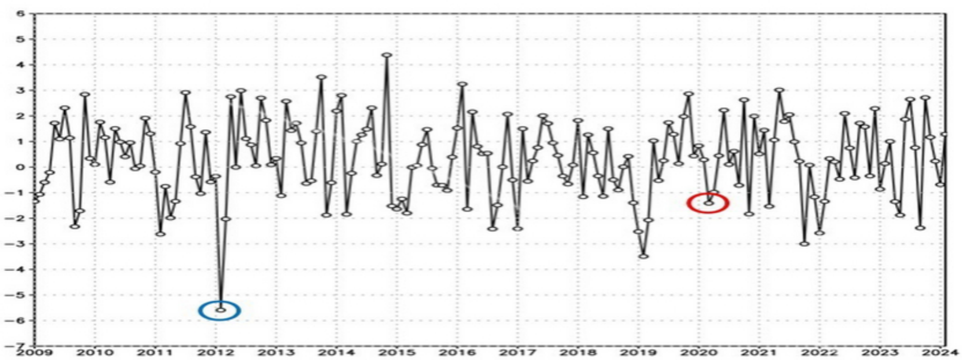

Figure 10. Monthly mean time series of the north-south wind speed component in the Bonifacio Cyclonic Gyre area. The unit is m s^{-1}. Negative values indicate southward components.

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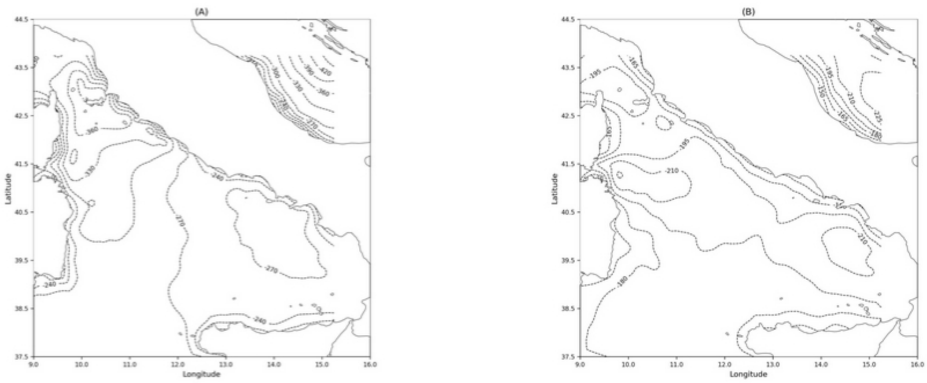

Figure 11. Spatial variability of the monthly mean loss heat flux in February 2009 (panel A) and 2020 (panel B) derived by ECMWF re-analysis. The unit is W m^{-2}. The contour interval is 30 W m^{-2} in panel A and 15 W m^{-2} in panel B.

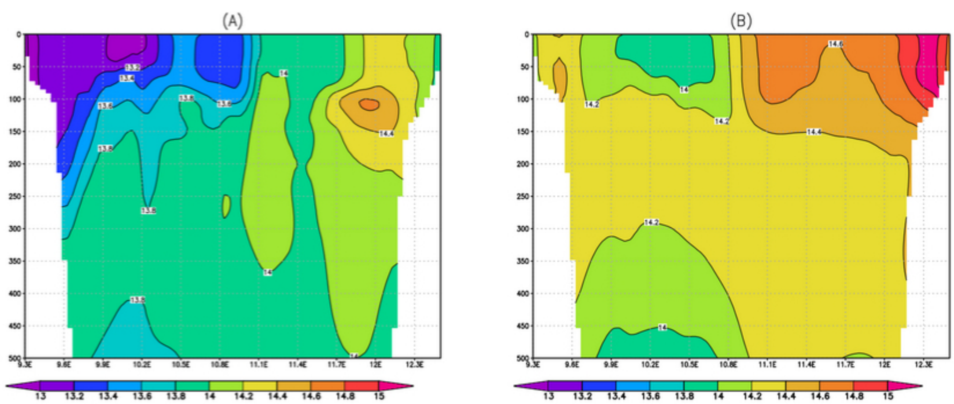

Figure 12. Simulation of the monthly mean field of the potential temperature through the Bonifacio Cyclonic Gyre (at 41.5° N) in February 2012, and 2020 from surface to 500 m depth. The unit is °C.

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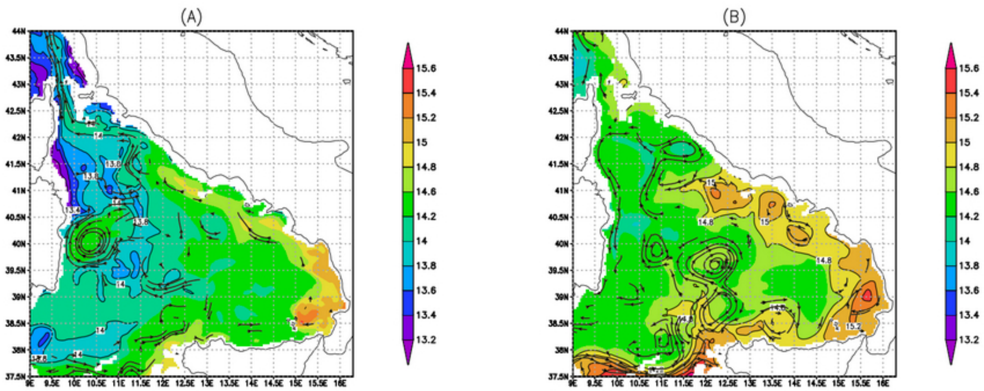

Figure 13. Simulation of the monthly mean field of the potential temperature in February 2012 (panel A), and 2020 (panel B) at 150 m depth superimposed the velocity current's streamlines. The units are °C for temperature and m s^{-1} for the velocity. The contour intervals are depicted when the sea surface temperature SST<= 14.0°C and SST>14.8°C.