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R. Martellucci and F. Paladini de Mendoza contributed equally to this work.

Key Points:

- Dense water masses produced in the Adriatic Sea represent key components of Mediterranean thermohaline circulation
- For the first time, a double pathway of these water masses has been clearly observed
- The observation network was able to reconstruct the fate of these water from their place of origin on its way into the deep Ionian Sea

Supporting Information:

Supporting Information may be found in the online version of this article.

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A Multiobservation Analysis of the 2017 Dense Water Formation Events: Climate Change, Bottom Density Currents, and Adriatic-Ionian Sea Circulation (Mediterranean Sea)

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Abstract The Adriatic Observatory Network has revealed new aspects of dense water spreading in the eastern Mediterranean Sea. By integrating multiple observing infrastructures and producing FAIR (Findable, Accessible, Interoperable, and Reusable) data, the network has uncovered previously unexplored features, highlighting their influence on thermohaline circulation and biogeochemical fluxes in the Mediterranean Sea, a key hot spot of climate change and biodiversity. In 2016–2017, the central Mediterranean experienced significant heat loss, reduced freshwater input, and a cyclonic phase of the Northern Ionian Gyre, which drove salty water into the Adriatic. These conditions facilitated dense water formation in the northern and southern Adriatic by shelf and open-ocean convection. The dense water formed in the north flows southward along the western continental slope, in part cascading into the southern Adriatic Pit, where it mixes with resident waters to form the Adriatic deep water, which then spreads into the Ionian Sea. Our findings revealed that the dense water exiting the Adriatic follows two distinct pathways in the Ionian: a westward branch toward the Gulf of Taranto, which contributed to the reversal of the Northern Ionian Gyre, and a southward branch toward the Kerkyra-Kefalonia Valley, spreading directly into the deep Hellenic Trench, ventilating its deep layers due to its high density and thus playing a key role in the renewal of the basin.

Plain Language Summary The Mediterranean is a well-recognized climate change and biodiversity hot spot with the dense water processes playing a key role in the basin circulation and marine ecosystems. In particular, Adriatic Sea acts as a source of dense water, and thanks to the Adriatic Observatory Network; the basin has become a laboratory for monitoring oceanographic processes. The network is multidisciplinary and uses different oceanographic platforms and model products. In winter of 2016–2017, severe meteorological conditions led to the formation of significant volume of dense water in the Adriatic Sea, which moved southward and mixed with the existing water, forming deep water in the southern Adriatic Pit. This water then flowed through the Strait of Otranto into the eastern Mediterranean. For the first time, two distinct pathways of dense water outflow were clearly observed: one westward and another southward along the Hellenic Trench. These paths have different effects on the Ionian Sea and influence the currents and deep-sea circulation patterns. The westward flow contributes to changes in the surface circulation of the Ionian Sea, while the southward current influences the abyssal plain of the eastern Mediterranean. This study demonstrates the importance of maintaining observing systems that provide FAIR data, which are crucial for understanding ocean processes.

1. Introduction

The Mediterranean Sea is a midlatitude semienclosed basin characterized by faster circulation patterns than the global ocean (Malanotte-Rizzoli et al., 2014) and rich dynamics over a wide range of interacting scales (Chiggiato

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et al., 2023). The heat absorbed at the surface layer is transferred to the deep ocean in the areas where dense water forms (Kubin et al., 2023; Pirro et al., 2024) and/or laterally through boundary currents and mesoscale eddies (Kubin et al., 2019; Pinardi et al., 2019; Waldman et al., 2018). These mechanisms have significant impact on the deep-water circulation and ecosystem dynamics at the basin scale (Ivanov et al., 2004; Pinardi et al., 2023; Vilibić et al., 2023).

The recently observed warming of the Mediterranean Sea altered the dense water formation through the increase of the water column stratification (Josey & Schroeder, 2023; Parras-Berrocal et al., 2022, 2023; Reale et al., 2022). For example, since 2013, the Gulf of Lions has witnessed the absence of deep convection (Bosse et al., 2021; Coppola et al., 2018; Durrieu de Madron et al., 2023; Fourrier et al., 2022; Josey & Schroeder, 2023; Margirier et al., 2020), due to the reduction in winter heat losses and temperature and salinity increase of the intermediate water (Josey & Schroeder, 2023; Margirier et al., 2020).

The dense water can be formed by open-ocean convection (Houpert et al., 2016; Marshall & Schott, 1999; Somot et al., 2018; Testor et al., 2018) and shelf convection (Bensi et al., 2013; Vilibić et al., 2023). Shelf convection occurs at coastal margins due to a combination of several factors affecting the thermohaline properties of the surface water and is mainly driven by heat losses that generate dense water masses via a near-vertical mixing due to their buoyancy properties (Shapiro et al., 2003).

In the Adriatic Sea (Figure 1), a semienclosed basin in the northernmost part of the Mediterranean Sea, both types of convection occur (Manca et al., 2002): (a) shelf convection in the northern Adriatic, producing the North Adriatic dense Water (NAddW, Vilibić et al., 2023; Schroeder et al., 2024) and (b) open-ocean convection (Pirro et al., 2022) in the southern Adriatic Pit (SAP) forming the Adriatic Deep Water (AdDW Schroeder et al., 2024), which represent the main source of dense water outflowing from the Adriatic Sea (Mantziafou & Lascaratos, 2004).

The bathymetry of the basin (Figure 1c), characterized by a relatively shallow northern shelf (maximum depth 40 m), the central Pomo pit (approximately 200 m deep), and the deep SAP (approximately 1,250 m) significantly influence the spreading of dense water. The southern edge of SAP opens at about 800 m across the Strait of Otranto (to a depth of 900 m; Figure 1d) toward the deeper Ionian basin and allows the outflow of dense water.

The formation of NAddW is controlled by heat losses, limited freshwater input from the Po River, cyclonic circulation in the basin, and inflow of saltier water (Raicich et al., 2013; Shapiro et al., 2003; Vilibić et al., 2023) from the south. This inflow is influenced by the decadal reversal of the Northern Ionian Gyre (NIG) (Civitarese et al., 2023; Mihanović et al., 2021), which brings saltier/fresher water to the southern Adriatic during cyclonic/anticyclonic modes of the NIG (Menna et al., 2021). Events characterized by extremely dense NAddW occur almost cyclically, and this phenomenon has been termed as "saw-tooth mechanism" (Querin et al., 2016).

During the winter season, the heat losses are linked to the dry and cold northeasterly wind (bora), which trigger the formation of the dense water in the northern Adriatic, that, once formed, flows southward along the western side of the Adriatic basin, following the isobaths (Benetazzo et al., 2014; Vilibić & Supić, 2005). On their way, these waters partially cascade in the Pomo pit (Le Meur et al., 2025; Marini et al., 2016; Vilibić et al., 2023) before reaching the shelf edge of the southern basin. Here, dense waters mostly sink along the western side of the continental slope, in particular along the Bari Canyon system (Langone et al., 2016; Turchetto et al., 2007). Moreover, a smaller part flows along the Italian shelf reaching the Strait of Otranto (Bignami et al., 1990; Manca et al., 2002; Rovere et al., 2019; Ursella et al., 2012). Once the NAddW enters the SAP, it mixes with the surrounding deep waters and flows out through the Strait of Otranto into the Ionian Sea as the second outflow of AdDW (Mantziafou & Lascaratos, 2004; Querin et al., 2016). For simplicity and clarity in the text, this water mass will be referred to as modified AdDW (mAdDW) to distinguish it from that formed during the convective process (AdDW).

The dense waters outflowing from the Adriatic Sea influence both the surface (Gačić et al., 2021; Rubino et al., 2020) and the deep circulation of the eastern Mediterranean Sea (Manca et al., 2006) driving the entire circulation of the Mediterranean Sea (Menna et al., 2019, 2021, 2022). Along its path, the thermohaline characteristics of the dense water exhibit notable changes, and the range of variation strictly depends on the variability of the drivers (Hainbucher et al., 2006; Sellschopp & Álvarez, 2003). For example, during the extreme event in winter 2012 (Bensi et al., 2013; Chiggiato et al., 2016), strong heat losses (peaking at 2,000 W m^{-2}; Vilibić et al., 2023) and a significant increase in salinity led to a potential density anomaly (σ_θ) exceeding 30 kg m^{-3} for the dense water in the northern Adriatic (Mihanović et al., 2013; Raicich et al., 2013), which decreased to 29.26 kg m^{-3} in the northern Ionian Sea along its path (Kovačević et al., 2015).

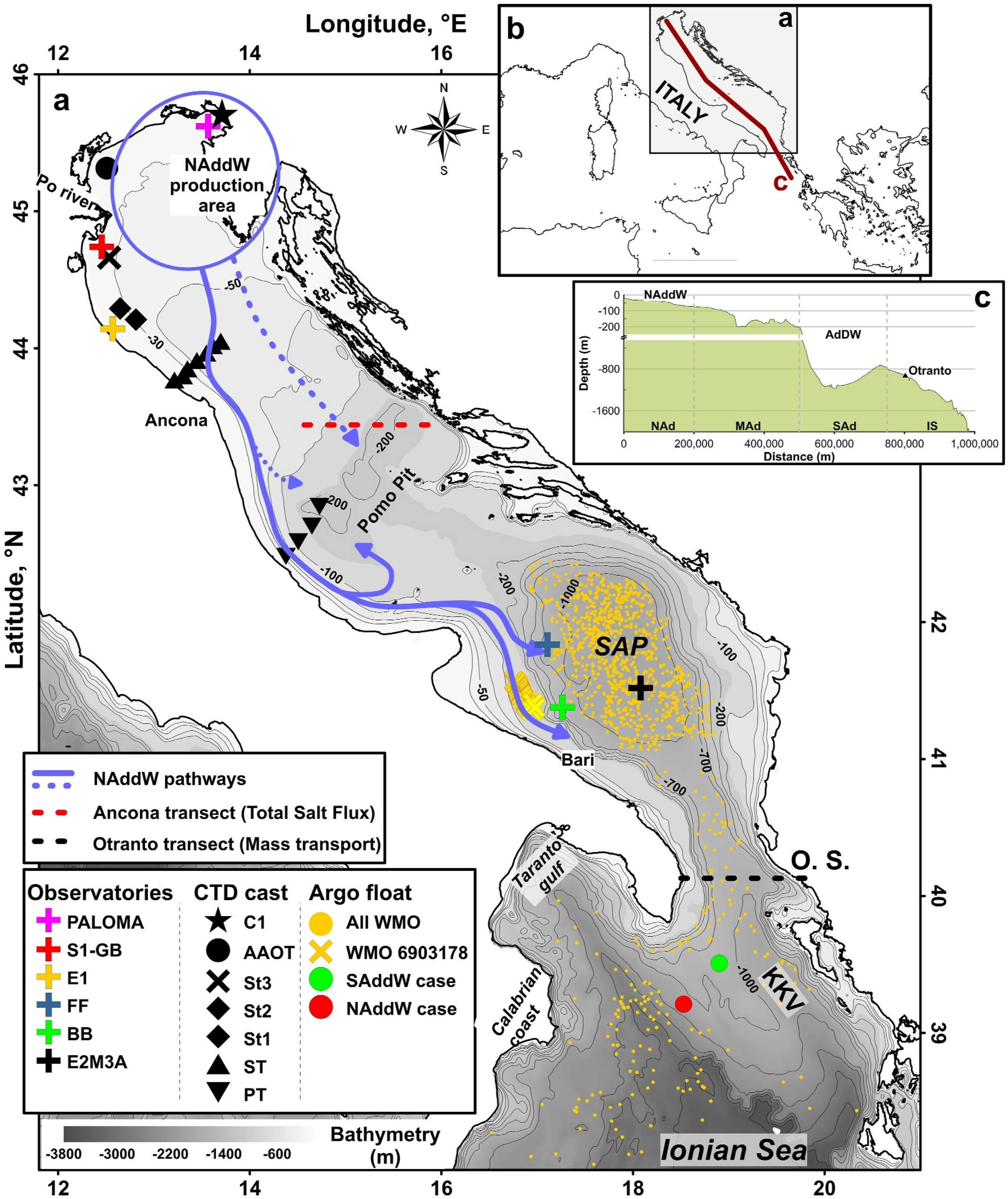

Figure 1. Main panel (a) represents the study area including the bathymetry of the Adriatic and Ionian Seas, the pathways of the NAddW (blue line) according to Mihanovic et al. (2013), Carniel et al. (2016), and Marini et al. (2016), as well as the Adriatic Observatory Network. The green and red circles represent the Argo data used for the Burger number calculation. The trajectory of Argo float WMO 6903178 was highlighted with a yellow cross symbol. Red and black dashed lines represent the sections in which the total water mass and salt transport of the Ancona Section and the Strait of Otranto (O.S.), respectively, were computed. KKV stays for Kerkyra-Kefalonia Valley. In panel "b", a regional view of the study site with the line c where the bathymetric section is extracted and represented in panel "c" with the main water masses in the area is shown (NAd, northern Adriatic; MAd, middle Adriatic; SAd, southern Adriatic; IS, Ionian Sea). The bathymetry was provided by the EMODnet Bathymetry consortium (doi.org/10.12770/ff3aff8a-cff1-44a3-a2c8-1910bf109f85).

The complex mechanisms driving the formation and dynamics of NAddW span multiple temporal and spatial scales, requiring detailed analysis supported by high-resolution observational and numerical tools. In this context, the multiplatform observing system analysis proved essential for unveiling complex dynamic processes across spatiotemporal scales that cannot be resolved using a single-platform approach alone (Berta et al., 2018;

Martellucci et al., 2021). Here, taking advantage of the Adriatic Observatory Network, which integrates multiple data sources (e.g., fixed-point and moored observatories, ship surveys, and CTD/Argo float profiles), we have analyzed the dynamics of the NAddW from its formation area to its fate on the way to the deep Ionian Sea during a particularly intense dense water formation event that occurred in winter 2017, exploiting for the first time, the full potential of the observational network developed in the Adriatic-Ionian region since the late 1990s. By using this network, we were able to detect for the first time two different pathways for the dense water outflowing from the Strait of Otranto. One branch runs westward toward the Gulf of Taranto while a second branch flows down the western Hellenic continental slope directing toward the Kerkyra-Kefalonia Valley.

2. Methods

2.1. Data Set

The data used in this study have been retrieved from different sources and cover the time period spanning from June 2016 to December 2017 (Figure 1, Table S1 in Supporting Information S1).

- CTD surveys in the northern and middle Adriatic Sea with monthly sampling stations in the Gulf of Trieste (C1-LTER); at "Acqua Alta" oceanographic Tower (AAOT) located at the margin of the bora-driven northern Adriatic Gyre, where the peak of dense water formation is normally located (Boldrin et al., 2009); and along the Senigallia (ST) and Pomo (PT) transects (Cerino et al., 2019; Grilli et al., 2005, 2020; Marini et al., 2016; Neri et al., 2022).
- CTD surveys at monitoring stations St1, St2, and St3, obtained from Sea Data Net Portal (Grilli et al., 2005).
- Fixed-point observatories PALOMA elastic beacon (located in the deepest area of Gulf of Trieste; Cantoni et al., 2012; Ravaioli et al., 2016), S1-GB elastic beacon (located at the Po River mouth; Ravaioli et al., 2016; Riminucci et al., 2025), and E1 buoy (off the coast of Rimini, Böhm et al., 2016; Ravaioli et al., 2016; Riminucci et al., 2025).
- The moorings of South Adriatic regional facility of the EMSO-ERIC consortium (De Santis et al., 2022) consisting of the E2M3A "South Adriatic Pit Observatory" (Cardin et al., 2020) and Moorings BB and FF located at 600 and 733 m depth, respectively, in the main flow branch of the Bari Canyon and in the open sector of the continental slope (Langone et al., 2016; Paladini de Mendoza et al., 2022; Turchetto et al., 2007).
- Argo float profiles with delayed mode quality control (last access available https://dataselection.euro-argo.eu/, last accessed on 17/07/2024, Argo (2024); Wong et al., 2020) within the study area (orange circle and yellow crosses in Figure 1a). The yellow cross represents the surfacing of Argo float WMO 6903178 that stayed for almost a year and half along the western margin of the southern Adriatic basin near the Bari Canyon. The variables collected were potential temperature, salinity, and dissolved oxygen (DO).
- The Po River discharge measured at the Pontelagoscuro hydrological station (https://www.arpae.it/it/temi-ambientali/acqua/dati-acque/acque-superficiali/dati-idrometrici-in-tempo-reale-1).

Moreover, we used high-resolution observational and assimilated data sets from the Copernicus Marine Service (CMS):

1. Mediterranean Sea Physics Reanalysis (https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1, Escudier et al., 2020, 2021; Nigam et al., 2021).
2. High-resolution and ultrahigh-resolution satellite data of the sea surface temperature of the Mediterranean Sea (https://doi.org/10.48670/moi-00172, Buongiorno Nardelli et al., 2013).
3. Sea Level European Seas Gridded L4 Sea Surface Heights (Rio et al., 2014) and Derived Variables Reprocessed 1993-Ongoing (https://doi.org/10.48670/moi-00141).
4. Net surface heat flux from *Copernicus Climate Change Services:* ERA5 (Hersbach et al., 2023) data at individual levels from 1940 to present (https://doi.org/10.24381/cds.adbb2d47).

2.2. Methods

The mixed layer depth (MLD) in the SAP was calculated from the Argo data according to the method described in de Boyer Montégut et al. (2004) (i.e., using 0.2°C and 0.03 kg m^{-3} as thresholds, Kokkini et al., 2020). The σ_θ in all data sets was computed using the thermodynamic equation of seawater (TEOS-10, McDougall & Barker, 2011).

Absolute geostrophic velocities (AGV) fields were used to estimate the relative vorticity (ζ), defined as the vertical component of the velocity field curl, as follows:

$$\xi = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}$$

where U and V are the zonal and meridional components of the AGV, respectively. The resulting geostrophic currents vorticity fields were spatially averaged in the region of SAP (area delimited by the 1,000 m bathymetry, Figure 1).

The net surface heat flux (Figure 2b) was calculated using the same method as Pirro et al. (2022) from the Copernicus Climate Change Services data.

The salt (TSF, Figure 2a) and mass (Figures 5d and 5e) transport over the sections were obtained using the CMS Mediterranean Sea Physics Reanalysis.

$$\text{Mass transport} = \iint u dx\, dz$$

$$\text{Salt Transport} = \iint \varrho S u dx\, dz$$

where u, dx, dz, ϱ, and S are, respectively, the velocities normal to the cross-sections (Ancona, 43.4°N; 14.6–16°E and Otranto, 40°N; 18.5–19.5°E, Figure 1) area (ms^{-1}), horizontal and vertical dimensions of a grid cell (m), seawater density (kg m^{-3}) and salinity, respectively. The mas transport over the Otranto section was calculated between 400 m depth and the bottom, to highlight the dense water flow.

This data set reflects well the physical dynamics of the studied area. EOF analysis, computed on temperature and salinity reanalysis data, showed strong agreement between model and observational data in the SAP, with over 90% variance explained by the first modes ($R^2 > 0.9$) (Martellucci et al., 2024).

The seawater density used in the computation of the Burger number (Rétif et al., 2024; Tassigny et al., 2024, detailed in Section 3.3) for the south Adriatic and Ionian Sea (red and green circles Figure 1) were obtained from Argo float profiles during January–February 2017, considering a depth between 600 and 800 m. Conversely, for the NAddW case, seawater density was considered in the 70–120 m depth layer in May 2017 on the south Adriatic shelf (Figure 2b) and in the Ionian Sea (green circle in Figure 1).

The acronyms for the water mass used in this paper follow the recommendation suggested in Schroeder et al. (2024), where lowercase "d" means dense while capital "D" means deep.

3. Results

3.1. Preconditioning and Formation of the NAddW in Early 2017

In 2016–2017, the Po River discharges were characterized by a peak of 5,559 $m^3\ s^{-1}$ in late November–early December 2016 although the discharge remained consistently low throughout the autumn–winter period (below the 10-year average of the dashed blue line in Figure 2a; see details in Paladini de Mendoza, Schroeder, Langone, et al., 2023). In the same period, an inflow of saline water from the south (Figure 2a) was observed in the northern Adriatic basin (~38.9, Matić-Skoko et al., 2022) similar to what happened in 2012 (Janekovic et al., 2014; Mihanovic et al., 2013). The total salt flux (TSF, Figure 2a) calculated on the eastern side of the middle Adriatic along the Ancona transect (Figure 1) showed a peak in October–November 2016 ($TSF > 7 \times 10^6$ kg s^{-1}), in phase with the cyclonic mode of the NIG (Menna et al., 2021; Mihanović et al., 2021). The latter brought the salty waters of Levantine and Aegean origin toward the northern part of the Adriatic Sea (Matić-Skoko et al., 2022) again as it was observed in 2012 (Janeković et al., 2014; Mihanović et al., 2013).

The atmospheric configuration of January 2017 favored significant strong heat losses over the northern Adriatic region. Between 29 December 2016, and 18 January 2017, a strong cold air outbreak occurred (Figure 2b), comparable in magnitude to the event in February 2012 shown by the filled dotted line in Figure 2b

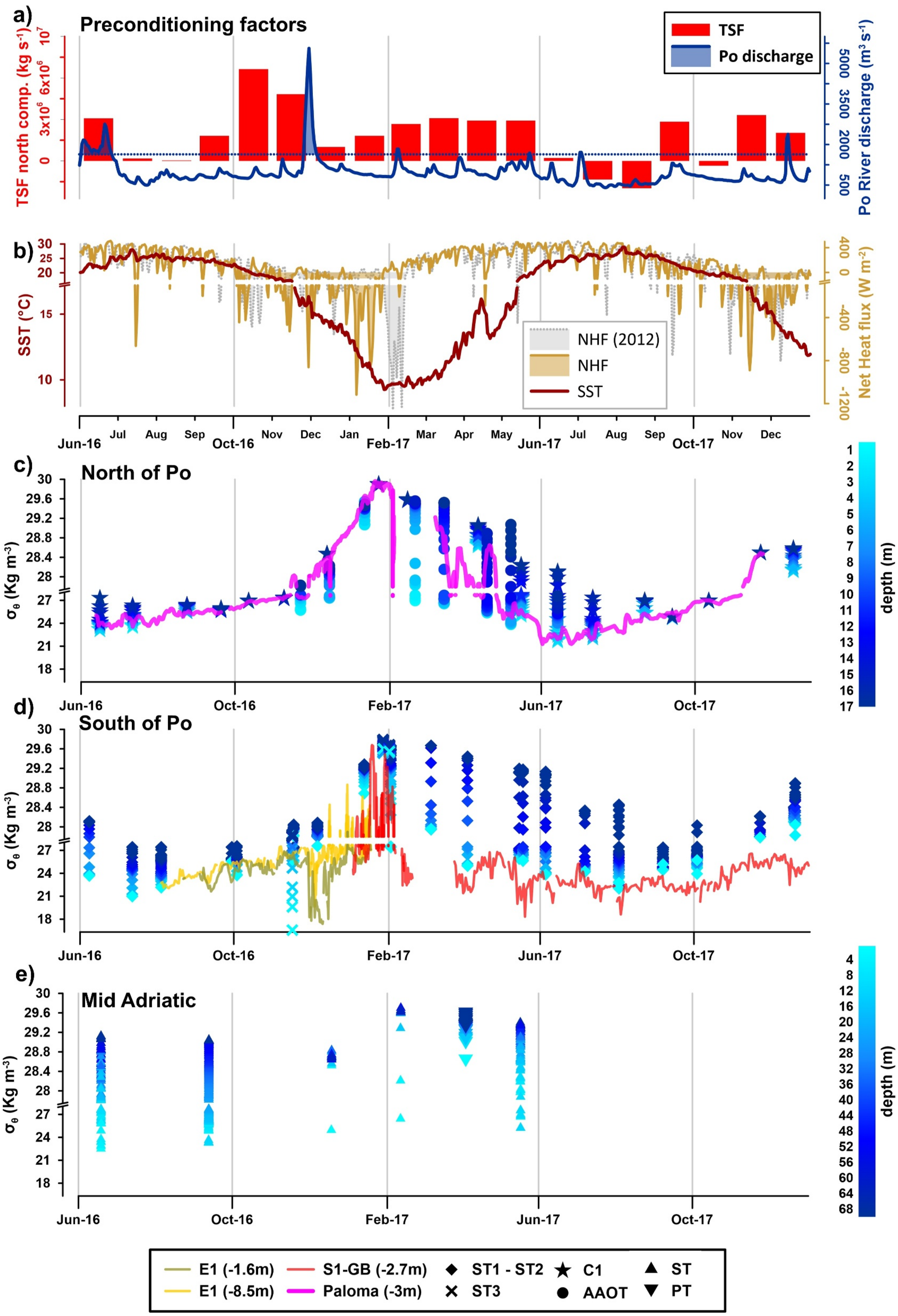
a) Preconditioning factors
TSF
Po discharge
TSF north comp. (kg s-1)
Po River discharge (m3 s-1)
b)
NHF (2012)
NHF
SST
SST (°C)
Net Heat flux (W m-2)
Jun-16 Jul Aug Sep Oct-16 Nov Dec Jan Feb-17 Mar Apr May Jun-17 Jul Aug Sep Oct-17 Nov Dec
c) North of Po
σθ (Kg m-3)
depth (m)
d) South of Po
e) Mid Adriatic
E1 (-1.6m)
E1 (-8.5m)
S1-GB (-2.7m)
Paloma (-3m)
ST1 - ST2
ST3
C1
AAOT
ST
PT

Figure 2.

(>1,100 Wm^{-2}, peaking at 1,250 Wm^{-2} on 4 February 2017). Significant heat losses produced a drop in the temperature of about 8°C (Figure 2b).

These significant heat losses and cold anomalies recorded over the area have been driven by an anomalous negative state of the east Atlantic (EA) pattern during the winter 2016–2017 (see for more details, Demirtaş, 2023; Dunstone et al., 2018). This general circulation pattern has been identified as the second prominent mode of atmospheric variability in the North Atlantic and an important driver of heat losses in the Mediterranean region (Josey et al., 2011; Reale et al., 2020). Its negative state is associated with a significant northeasterly air flow driven by an area of high pressure over the western Atlantic bringing cold and dry air from mainland Europe into the Mediterranean region (Josey et al., 2011), driving strong heat losses and anomalous cold temperatures (Figure 2b).

The combination of heat losses, low discharge in the autumn, and advection of saltwater from the south (Figures 2a and 2b) acted as a precondition for the formation of very dense NAddW as clearly visible in early December at the elastic beacon PALOMA and at the C1-LTER station in the Gulf of Trieste (magenta line and stars in Figure 2c), peaking ($\sigma_\theta = 29.94$ kg m^{-3}) on 20 January after the strong heat loss and resulting in a high density ($\sigma_\theta > 29.8$ kg m^{-3}) till the first week of February (Figure 2c). The same behavior was also observed off the coast of the Venice lagoon, in the profile acquired at the AAOT site, where the σ_θ reached 29.55 kg m^{-3} on January 12 (circle in Figure 2c).

After its formation, the NAddW flowed along the western Adriatic shelf, generating a maximum of σ_θ of 29.70 kg m^{-3} in the area south of the Po River (i.e., buoy E1 and S1-GB elastic beacon) on 18 January 2017 (Figure 2d). Similarly, from late December to the end of January, on St1, St2, and St3 the density increased throughout the water column, reaching 29.6 kg m^{-3} (diamonds and cross symbols in Figure 2d). The increase in seawater density above 29.6 kg m^{-3} involved the whole water column (i.e., when all the points of the profile appear as a single point, they indicate full depth mixing); in the surface layer, the highest σ_θ lasted for almost 2 days (17–20 January). Then, from the end of January, the density at surface decreased to the values observed prior to December, while the signature of dense water, below 15 m depth, lasted until April (Figure 2d). In late spring, the near-bottom dense water on the Italian shelf (Figure 2d) was replaced by lighter (<27 kg m^{-3}) adjacent water as observed during previous dense water events (Orlić et al., 2006; Vilibić et al., 2023).

The first signature of the NAddW in the middle Adriatic was detected 100 km to south of St1 in February 2017 (Figure 2e). By December 2016, the water column had changed from stratified to well-mixed, with the σ_θ increasing from 28.6 kg m^{-3} to over 29.6 kg m^{-3} on February 11 (Figure 2e). The dense water signal (Figure 2e and Figure S2 in Supporting Information S1) was clearly observed in the Pomo pit, presenting the same values observed in February along the ST transect spanning almost 30 km in the cross-section (Figure S2 in Supporting Information S1). The dense water was found in the deepest layer of the pit (>160 m depth, i.e., σ_θ reaches 29.6 kg m^{-3} in the terminal part of the profile), highlighted by the maximum in σ_θ except for the shallowest station, that was not affected by dense water passage (Figure S2 in Supporting information S1).

3.2. Spreading of NAddW in the Southern Adriatic

The timing of the occurrence of the NAddW in the southern Adriatic depends on its travel dispersion through the Pomo pit (Benetazzo et al., 2014; Janeković et al., 2014), which is driven by the density gradient between the NAddW and the adjacent water masses (Querin et al., 2016; Vilibić & Mihanović, 2013). So far, the timing of the arrival of NAddW to the continental margin of the southern Adriatic after its formation has not been clearly evaluated although previous studies suggest a value of 2 months on average (Bensi et al., 2013; Chiggiato et al., 2016; Le Meur et al., 2025; Querin et al., 2016; Vilibic et al., 2023). Observations indicate that dense water

Figure 2. (a) Time series of preconditioning factors: Po River discharge measured at Pontelagoscuro (blue line). The line is filled in blue if the discharge is greater than the average 10-year discharge value; total salt flux, TSF (red bars). (b) Sea surface temperature, (SST, dark red line) and net surface heat flux (NSHF) averaged over the NAddW formation area for 2017 (golden shaded filled line) and 2012 (dotted gray filled line for the same period of 2017; the time axis for the year 2012 is not shown). (c) Measurements north of the Po River: σ_θ values calculated from the CTD profiles at AAOT (circles) and C1-LTER (cross) where depth is color coded; hourly σ_θ values calculated from CTD records by the PALOMA elastic beacon (pink line). (d) Hourly σ_θ values calculated from CTD at two depths by the E1 buoy (yellow and green line) and by the S1-GB elastic beacon, (orange line); σ_θ values calculated from the CTD profiles at St1 and St2 (square) and St3 (triangle); the depth is color coded. (e) σ_θ values from shipboard CTD profiles repeated from June 2016 to May 2017 along the transect of Pomo (PT) and Senigallia (ST) in the middle Adriatic; depth is color coded (see Figure 1a for the transects location).

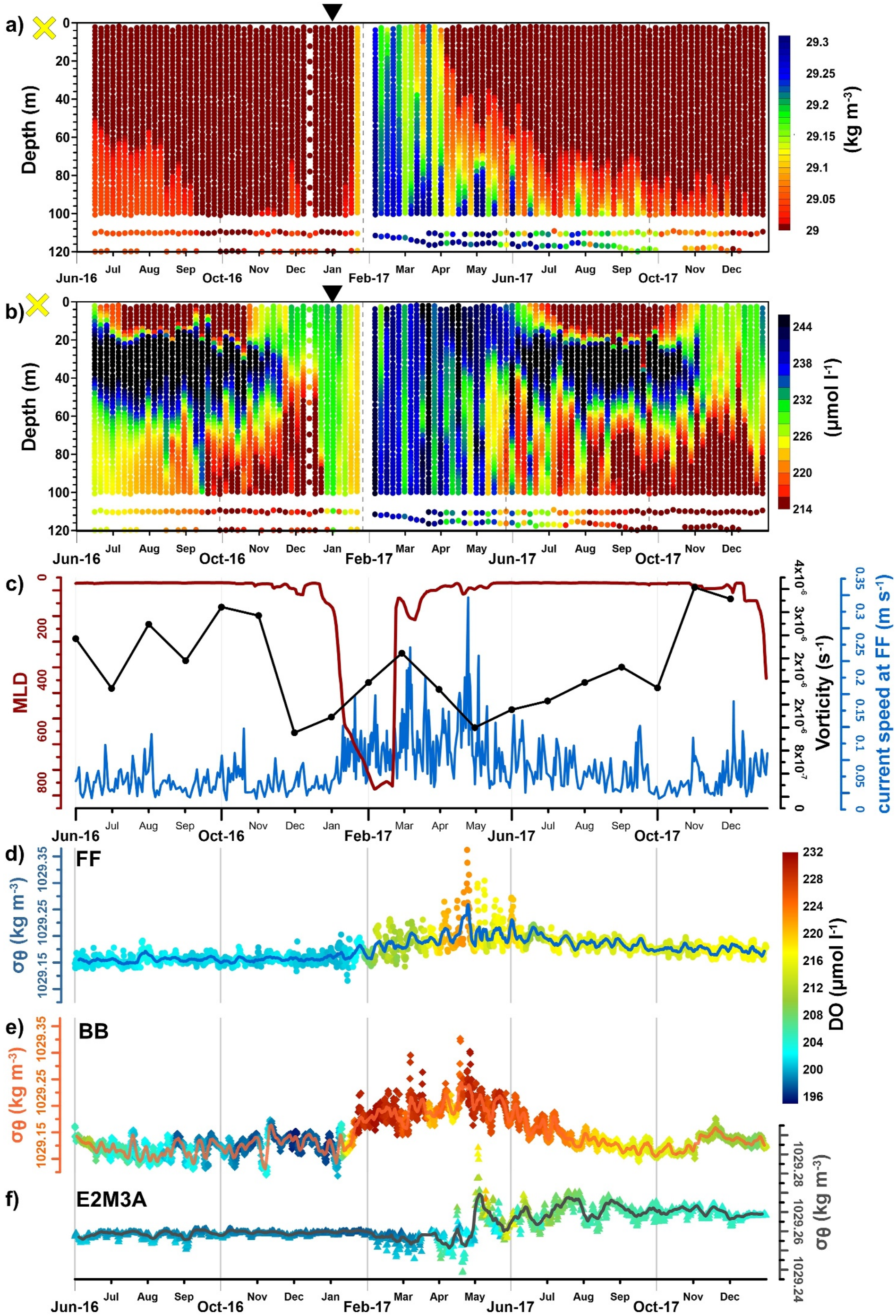

Figure 3. σ_θ (a) and DO concentration (b) measured by the Argo float WMO 6903178 in the shelf area near the Bari Canyon (position of the black triangles on top of figure "a" and "b" indicate the period in which the float sampled on the continental shelf (120 m depth, yellow cross in Figure 1). (c) Vorticity field computed in the southern Adriatic Sea (black line, within the 1,000-m isobath; see Menna et al., 2021) and mixed layer depth (MLD, dark red line) in the SAP. Current speed recorded at FF site near the bottom (blue line). (d, e, and f) Time series of density and DO concentration measured respectively at FF (723 m), BB (590 m) and E2M3A (1,200 m) moorings (continuous line is daily average density while symbols are hourly density value), the color coding of symbols refer to the corresponding DO oxygen concentration.

passage persists for approximately 6 months and occurs in intermittent short-lived pulses (Chiggiato et al., 2016; Paladini de Mendoza et al., 2023).

The observations (Figures 3a and 3b) of the Argo float WMO 6903178 at the shelf edge of the Bari Canyon (June 2016–December 2017) showed a well-stratified water column until January 2017, when σ_θ ranged from 25.5 kg m^{-3} in the surface layer (supersaturated color in Figures 3a) to 29 kg m^{-3}, near the bottom. The stratification, clearly visible until September 2017, was influenced by the Western Adriatic Current (WAC), which is characterized by low salinity (Mauri et al., 2016). A high dissolved oxygen (DO) concentration was observed in the water column (between 20 and 60 m) until November 2016 (>240 μmol L^{-1}), while below 60 m, the concentration gradually decreased from June 2016 until the onset of winter mixing at the end of December (Figure 3b), when it increased again to 226–232 μmol L^{-1}. From June 2016 to January 2017, a stable increase in the σ_θ signal (Figures 3c, 3d and 3e) was observed when moving from the shelf edge toward the SAP at 1,200 m (average value of 29.15 kg m^{-3}, between June 2016 and May 2017). In fact, until January 2017, the σ_θ in BB in the Bari Canyon at 590 m depth fluctuated around the mean value of 29.12 kg m^{-3}, while it was more stable and slightly higher (29.17 kg m^{-3}) in the deeper areas of the open slope at 723 m depth (in FF). The measurements of the Argo floats during the same period in the SAP (within the 1,000-m isobath) showed homogeneous thermohaline properties corresponding to the fixed observations of E2M3A (Figure 3f).

During winter, the SAP, identified as a site of dense water formation (Pirro et al., 2022), was also influenced by cold meteorological events, which triggered convective processes that mixed the water column to depths of up to 800 m (Figure 3c) (Kokkini et al., 2020; Martellucci et al., 2024; Mihanovic et al., 2021). The process started in January 2017 and produced the AdDW (Schroeder et al., 2024). The deepening of the MLD to 800 m (Figure 3c) led to an increase in current velocity DO and σ_θ, all indicating the same convective event. These changes were first detected in the middle of January by the shallower mooring in the Bari Canyon (BB, Figure 3e) and 2 weeks later, also by the deeper northern mooring (FF, Figure 3d). After the strong initial increase in DO concentration, the signal showed a first gradual decline until early March. During 2017, the strong velocity pulses attributed to the cascading NAddW flow, were clearly detected from early March (particularly evident at the FF site, Figure 3c), when a renewed increase in σ_θ and DO concentration occurred due to the arrival of NAddW cascading down the slope (Figure 3d). The current velocity behavior (Figure 3c) recorded at the open slope (FF) showed the passage of NAddW as intermittent strong pulses (Chiggiato et al., 2016; Marini et al., 2016; Paladini de Mendoza, Schroeder, Miserocchi, et al., 2023) as a result of the propagation of continental shelf waves along the Adriatic basin (Bonaldo et al., 2016) with velocity peaks corresponding to the σ_θ and DO concentration maxima. On the shelf, the dense water flow first affected the deeper layers (15 March) at around 80 m depth and then (25 March) almost the entire water column ($\sigma_\theta > 29.25$ kg m^{-3} in Figure 3a). The same trend was also observed in the canyons, with σ_θ increases by 0.05 kg m^{-3} at BB and 0.03 kg m^{-3} at FF, as well as the DO concentration (Figures 3d and 3e). The highest σ_θ value (>29.4 kgm^{-3}) due to NAddW was observed at the end of April, with a duration of 5 days, resulting in the highest increase in σ_θ in the canyons (BB and FF in Figures 3d and 3e). After 20 days of travel along the shelf, NAddW reached the deepest layer of the SAP (E2M3A in Figure 3f) and resulted in an increase in σ_θ of 0.03 kg m^{-3} at 1,200 m depth and a significant increase in DO concentration (about 25 μmol L^{-1}). On the continental shelf (Figure 3a), the NAddW was gradually replaced by lighter water and returned to the state observed in summer and fall 2016. The passage of NAddW currents confined to the deepest layers of the water column (40 m thick) continued until September, but with a strong decrease in σ_θ, as previously observed in 2012 (Mihanović et al., 2013; Vilibić & Mihanović, 2013). These pulsations confirmed that the outflow of NAddW persisted for months after its formation (Figures 3d, 3f, 4a and 4b). The downward motion of NAddW contributes to the filling of the deeper layers of the Adriatic (Figure 3f) resulting in an increase of the temperature of 0.1°C and of the salinity of 0.05, which affected the wider Adriatic circulation.

At the beginning of winter, a decrease in the vorticity field in the SAP (Figure 3c) was observed, which reached its minimum in May 2017, coinciding with the maximum increase in the σ_θ at BB and FF. The observations indicated that changes in the vorticity observed in winter and spring were caused by the combined effect of convection on the open ocean and NAddW propagation. The effect of convection caused a homogenization in the SAP, which led to a change in the isopycnals and consequently in the density gradient within the SAP. At the same time, the NAddW along the western boundary of the Adriatic Sea reduced the cross-shore density gradient, thereby weakening the baroclinic contribution to the overall cyclonic vorticity field and limited the baroclinic shear resulting in a reduced intensity of the southern Adriatic Gyre (Figure 3c).

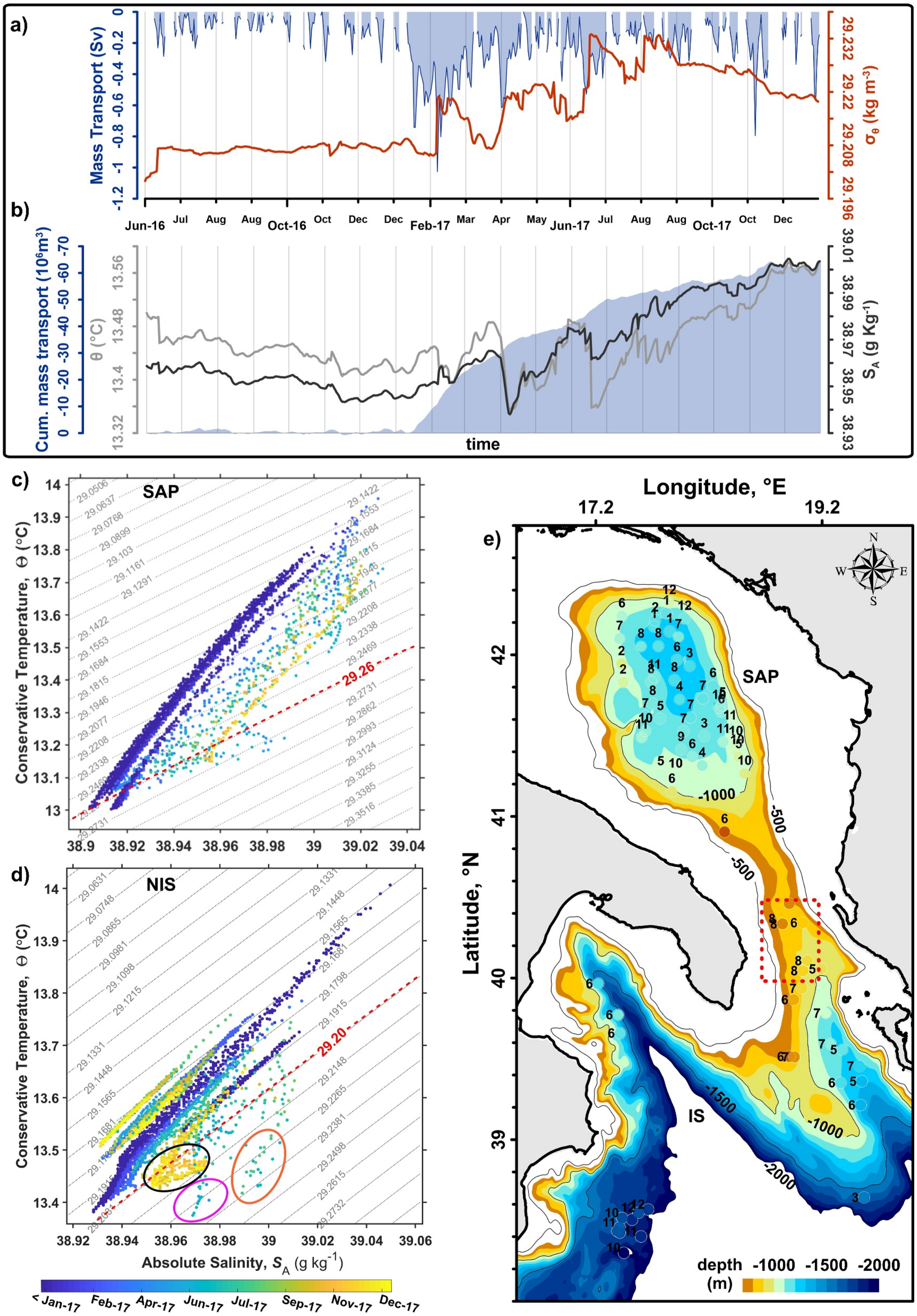
a)
b)
Mass Transport (Sv)
σθ (kg m-3)
Cum. mass transport (10⁶m³)
θ (°C)
SA (g Kg-1)
time
c)
SAP
Conservative Temperature, Θ (°C)
d)
NIS
Absolute Salinity, SA (g kg-1)
29.26
29.20
e)
Longitude, °E
Latitude, °N
SAP
IS
depth (m)
< Jan-17
Feb-17
Apr-17
Jun-17
Jul-17
Sep-17
Nov-17
Dec-17

Figure 4.

3.3. Spreading of the AdDW in the Ionian Sea: First Observation of Two Different Pathways

Until February 2017, the thermohaline properties of the Strait of Otranto remained relatively stable; however, following this period, a general increase in density, temperature, and salinity was observed (Figures 4a and 4b). The transport in the deep layer below 400 m across the section in the Strait of Otranto (blue filled area of Figure 4a) was southward and exhibited strong variability. The largest amount of outflow occurred during the convection period (February–March), which is related to the open-ocean convection in the SAP and the formation of AdDW (i.e., deepening of the MLD in Figure 3c) reflecting the previous observations of dense water formation in the area (Mantziafou & Lascaratos, 2004). After the convection period, the outflow was related to the outflow of NAddW and mAdDW. These two water masses were identified by marked decreases in temperature and increase in salinity (Figure 4b) occurring in April and July. These three different water masses have been generated by the three temperature and salinity changes (Figure 4b), which also correspond to the peaks observed at the moorings BB, FF, and E2M3A (although shifted in time, Figure 3).

The signature of these peaks appears in the temperature-salinity (TS) diagram of Figure 4d (highlighted by colored circles), which highlights the spreading of the different dense water masses in the northern Ionian basin ($\sigma_\theta > 29.2$ kg m^{-3}). Crossing the Strait of Otranto, the overflow water mixed during transport (as shown by the decrease in the $\sigma_\theta \sim 0.02$ kg m^{-3}), the σ_θ values in the Ionian Sea are consistent with those measured by Kovačević et al. (2015) in 2012, where the σ_θ was above 29.2 kg m^{-3} (with a maximum value of 29.26 kg m^{-3}). Figure 4e shows the location of measurements where the density exceeds the 29.2 kg m^{-3} threshold and highlights the paths of the newly formed dense water outflows.

In June, two different water masses were observed in the northern Ionian Sea: one moving westward in the Gulf of Taranto and the other one moving southward from the Strait of Otranto. The first was characterized by a temperature and salinity of about 13.8°C and 38.8, respectively, while the second was slightly colder and fresher with a temperature of 13.7°C and a salinity of 38.75. Considering the area where these water masses were located and the distance from the source (i.e., SAP), they represent the signature of the dense water formed in the SAP during the convection period (AdDW) and NAddW. The data show the densest values about 50 km south of the Strait of Otranto at about 870 m depth on 17 June (Figure 4e). This signal provides further evidence that the portion of NAddW that does not cascade down the slope toward the SAP instead spreads along the western continental shelf. This confirms and corroborates earlier results obtained in the winters of 1997/98 by Manca et al. (2002), the modeling results of Rubino et al. (2012), and the interpretation of large-scale bedform patterns by Rovere et al. (2019) and Ceramicola et al. (2024).

In contrast to earlier observations indicating a single branch of dense water flowing along the western margin of the Ionian Sea (Hainbucher et al., 2006; Sellschopp & Álvarez, 2003), the present data suggest a bifurcation in the dense water pathway beyond the Strait of Otranto: one branch flows into the Gulf of Taranto and emerges along the eastern Calabrian coast between October and December, while the other descends the western Hellenic continental slope toward the Kerkyra-Kefalonia Valley.

The dual outflow routes can be interpreted by estimating the Burger number (Rétif et al., 2024; Tassigny et al., 2024), which is defined as the ratio between the Rossby radius of deformation (LR) and the horizontal characteristic length scale (L), both evaluated for the Strait of Otranto; specifically, $Bu = (\mathrm{LR}/L)^2$ where $\mathrm{LR} = g' H^{0.5}/f$ with f showing the value of the Coriolis parameter (9.37e^{-5} s^{-1} for a mean latitude of 40°N), $H = 900$ m, and $L = 80$ km are the characteristic depth and length scale at the Strait of Otranto, respectively, and $g' = g\Delta\rho/\rho 0 = g\ \frac{\rho\ \text{adriatic} - \rho\ \text{ionan}}{\rho\ \text{ionian}}$, is the reduced gravity. A small Bu value indicates that the transport of the dense water is constrained by the Coriolis effect flowing, therefore, through the Gulf of Taranto. Conversely, for a large Bu value, the dense water is less affected by rotation and potentially aligns with density-driven currents.

Figure 4. Top panel: (a) time series of mean σ_θ (red line), calculated from Argo floats data, in the red dashed box in the map e and water mass transport (blue filled area) across the Otranto section between 400 m and bottom (O.S.: dashed black line in Figure 1), (b) time series of mean temperature (gray line) and salinity (black line) calculated in the red dashed box in the map e and cumulated mass transport (blue filled area), across the Otranto section between 400 m and bottom. Bottom panel: TS diagrams of the Argo measurements in the SAP (c) and in the northern Ionian Sea (d) below 800 m. The colored circles in panel d indicate the different water masses—orange: mAdDW, magenta, NAddW, and black; AdDW. (e) Map with the positions of the measurements that exceeded the density 29.2 kg m^{-3} threshold (red dashed lines in c and d; numbers refer to the corresponding month of each observation).

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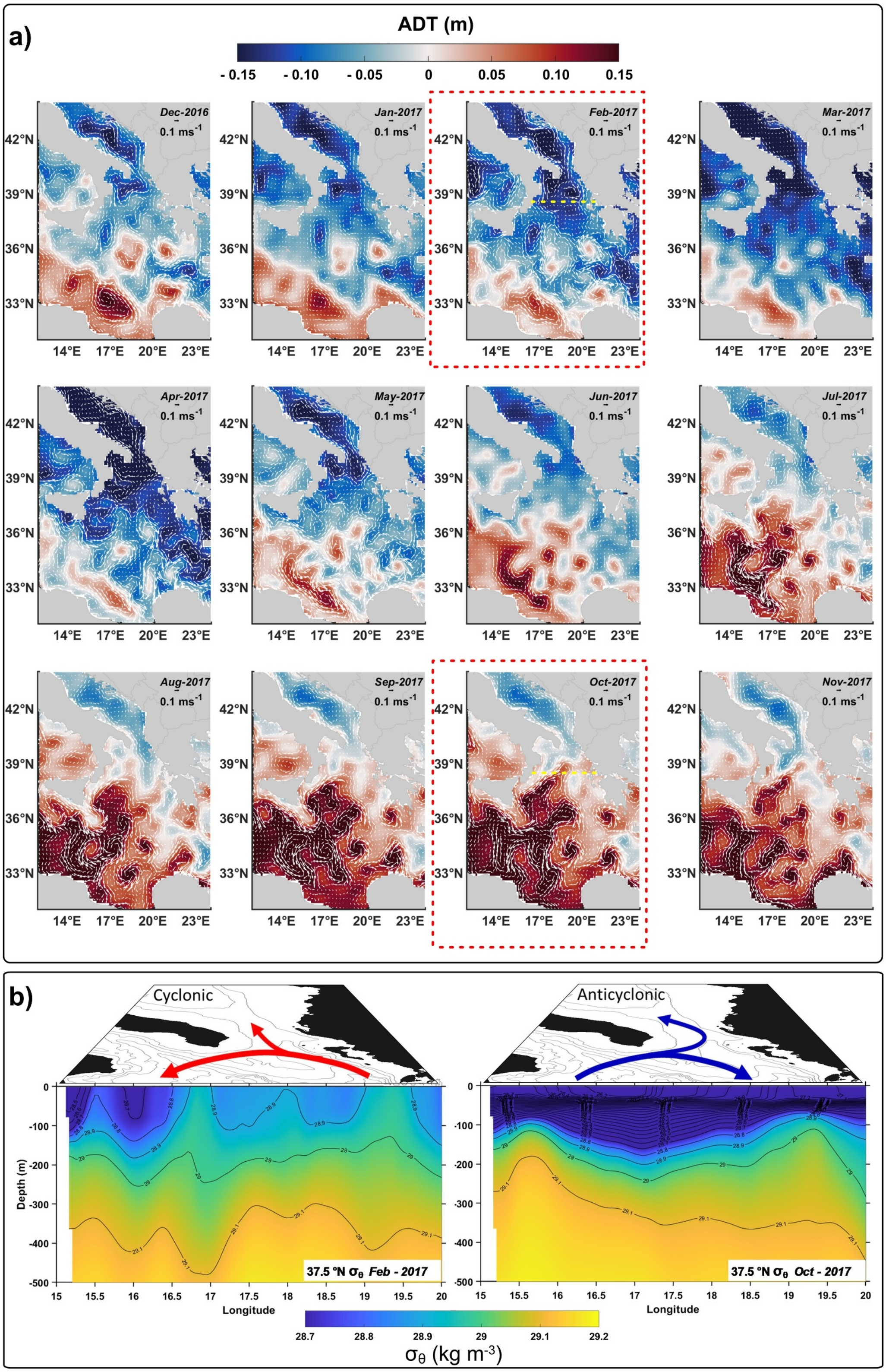

Figure 5. (a) Monthly mean geostrophic currents (arrows) superimposed on monthly mean distribution of absolute dynamic topography ADT (colors) for the period June 2016–December 2017 (https://doi.org/10.48670/moi-00141). (b) Water column distribution of the σ_θ (computed from MEDSEA_MULTIYEAR_PHY_006_004_E3R1) along a transect crossing the Ionian Sea at 37.5° N (yellow dotted lines of panel a) during the two different circulation phases (cyclonic and anticyclonic); months are enclosed in red boxes of panel (a).

Considering the dense water forming within the SAP, the value of ρ Adriatic computed from Argo floats profiles is equal to = 1,029.19 kgm^{-3} averaged over January–February 2017 between 600 and 800 m depth. In comparison, the value of ρ *Ionian* is equal to 1,029.19 kgm^{-3}, calculated for the same period in the range 600–800 m depth using the Argo float highlighted by the green circle in Figure 1. This yields to Bu = −0.16 <1 explaining why the dense water is deflected toward the Gulf of Taranto. Conversely, for the NAddW case, ρ Adriatic = 1,029.26 kgm^{-3} calculated in the SAP for the layer 70–120 m of depth and for May 2017, while ρ Ionian = 1,029.015 kgm^{-3} (red circle in Figure 1), computed for the same period and depth range from the Argo float shown by the green triangle in Figure 1. This results in a *Bu* of 1.33, which exceeds unity and thus permits the southward flow of dense water. Consequently, a significant release of the densest NAddW occurred through multiple passages along the northern and western margins of the SAP, leading to a marked weakening of the southern Adriatic Gyre (Figure 3c) due to the change in the baroclinic term of density gradient between the center and the edge of the gyre. The deep-water outflow (i.e., AdW and mAdDW) from the Strait of Otranto resulted in a substantial release of dense water into the Ionian Sea, inducing significant variations in the vorticity field of the NIG (Figure 5). These changes are associated with alterations in the density gradient within the Ionian basin (Figure 5b). As demonstrated by Rubino et al. (2020) and Gačić et al. (2021), the dense water outflow leads to a reversal of the surface circulation in the Ionian basin, rendering it anticyclonic and promoting the presence of the water of Atlantic origin in the northern Ionian Sea.

The change of the Ionian surface circulation is clearly visible in Figure 5a. During winter 2017, the minimum dynamic height and cyclonic circulation with northward current along the east coast of the basin favored the flow of Levantine waters near the Strait of Otranto and a broad current from the Sicilian Channel flowing eastward toward the Levantine basin. Between May and June 2017, a decrease in the northward Levantine flow is observed, and between July and August 2017, the circulation becomes anticyclonic. From November 2017, a new decrease in the anticyclonic phase is observed, due to low pressure in the eastern part of the basin and the interruption of Atlantic water flow from the Sicilian Channel. These changes also affect the vertical dynamics of the water column, which results in a change in the arrangement of isopycnals (density sections of Figure 5b in the two phases of February and October 2017).

In February 2017, when the cyclonic circulation prevails, circulation is characterized by diverging flow in the central part that produces higher surface salinity. In October, during the anticyclonic phase, converging flow is observed in the center of the basin, which is reflected in the general decrease of salinity in the northern Ionian Sea, as can be seen from the density change in Figure 5b. The results suggest an impact of dense water dynamics on the reversal of the Northern Ionian Gyre adding new findings to recent work that investigated the causes of this rotation using both laboratory experiments and model simulations (Eusebi Borzelli & Carniel, 2023; Eusebi Borzelli et al., 2024; Gačić et al., 2010, 2021; Liu et al., 2022; Mieli, 2024; Reale et al., 2016, 2017; Rubino et al., 2020). The sinking into the Kerkyra-Kefalonia Valley and consequent spreading into the Hellenic Trench by a fairly dense and fast flowing dense water branch, does not feed the flow toward the gulf of Taranto responsible for the reduction of the vorticity field in the northern Ionian Sea, reducing the contribution to the mechanism (Gačić et al., 2021; Rubino et al., 2020) determining the NIG rotation.

4. Summary and Conclusion

The Mediterranean Sea is a complex and interconnected system of semienclosed basins where the deep-water circulation plays a key role in the local dynamics. The national observatory network built in the Adriatic Sea, (including coastal fixed stations, deep moorings, Argo floats, and vessel surveys) represents a unique sea laboratory where complex oceanic processes can be studied. This network enabled us to follow the route of dense water during an event in 2017 from its source revealing new dynamics and implications of ocean circulation at basin scale and in the eastern Mediterranean circulation system. In particular, we have been able to detect for the first time two pathways of the dense water outflow from the Adriatic Sea: the first toward the Gulf of Taranto and the second toward the Hellenic Trench.

The autumn–winter period 2016–2017 was characterized by concurrent conditions that favored enhanced dense water formation (Matić-Skoko et al., 2022) both in the northern and southern Adriatic Sea. Comparing NAddW formed in 2017 ($\sigma_\theta = 29.94$ kg m^{-3} at PALOMA and 29.55 kg m^{-3} at AAOT, Figures 2c and 2d) with that formed in 2012, the coldest ever recorded temperature (Bensi et al., 2013; Mihanović et al., 2013; Raicich et al., 2013; Vilibić et al., 2023) revealed that the waters produced in 2012 were denser (30.59 and 30.35 kg m^{-3} in the Gulf of Trieste and at the AAOT station, Mihanović et al., 2013). In terms of absolute value of heat loss, the 2017 event was comparable with that of 2012 and the main differences regarded (a) the longer duration of the 2012 cold break event, (it lasted almost 2 weeks, Davolio et al., 2015), (b) the timing (in 2017, the strong heat loss occurred in early January), and (c) the general 2017 positive trend in temperature that involved both the Adriatic Sea (Menna et al., 2021, 2022; Mihanović et al., 2021) and the Mediterranean basin (Fedele et al., 2022; Kubin et al., 2023; Pastor et al., 2020). The density difference between the 2 years was also evident in the Pomo pit: in 2012, the NAddW was characterized by σ_θ in the range of 29.67–29.69 kg m^{-3} while in 2017, the observed value was around 29.60 kg m^{-3}.

During January 2017, coinciding with the formation of NAddW, open-ocean convection in the SAP (Mihanović et al., 2021) mixed the water column down to 800 m depth (Figure 3c) forming the AdDW. The passage of the NAddW along the continental margin of the southern Adriatic was clearly detected since early March 2017 (Figure 3) through the physical and biochemical changes in seawater properties in phase with strong intermittent current pulses (i.e., velocity peaks corresponding to σ_θ and DO concentration maxima in Figure 3). After about 20 days from the cascading event into the Bari Canyon, the NAddW reached the bottom of the SAP causing a decrease in vorticity associated with an increase in horizontal current observed at the two mooring sites (Figures 3c–3f).

The three dense waters, which originated in the Adriatic Sea (i.e., NAddW formed in the North Adriatic and the AdDW and mAdDW originated in the SAP), spread at different times in the Ionian basin (Figure 4e) and took different pathways. One branch (i.e., AdDW) of the dense water current went westward toward the Gulf of Taranto (Bignami et al., 1990; Gačić et al., 2014; Hainbucher et al., 2006; Kovačević et al., 2015; Manca et al., 2002; Rovere et al., 2019; Ursella et al., 2012) while a second branch (i.e., NAddW that did not cascade down the slope toward the SAP but sank by gravity and spread along the western continental shelf) broke the geostrophic constraints directing toward the Kerkyra-Kefalonia Valley down the western Hellenic continental slope at depth greater than 3,000 m. The westward dense water flowing to the Gulf of Taranto favored the NIG reversal and changed the vertical structure of the isopycnal in the Ionian Sea (Figure 5b). In general in a cyclonic eddy structure, a dense flow at the edge causes a reduction or inversion of the vorticity field (Gačić et al., 2021). Consequently, we can assume that a very dense and rapid outflow from the Strait of Otranto sinking directly southward into the Kerkyra-Kefalonia Valley and spreading directly into the Hellenic Trench did not reverse the surface circulation of the NIG. Evidence of deep flow was found in sedimentological data from the Kerkyra-Kefalonia Valley (Poulos et al., 1999), indicating active sediment transport and seabed modification.

To further explore this hypothesis, we can focus on the 2012 cold outbreak, during which the densest NAddW formed. At that time, the vorticity field in the northern Ionian Sea was anticyclonic for only 6 months (Gačić et al., 2014; Kovačević et al., 2015; Menna et al., 2022), appearing marginally influenced by dense water cascading (Eusebi Borzelli & Carniel, 2023; Eusebi Borzelli et al., 2024) while the other inversion lasted until 2019 (Menna et al., 2022).

In that year (i.e., 2012), most of the NAddW flowed along the Italian shelf (Chiggiato et al., 2016), while only a portion reached the SAP cascading along the continental slope (Paladini de Mendoza, Schroeder, Miserocchi, et al., 2023), contributing to the formation of mAdDW. This water mass played a key role in maintaining the density gradient in the Ionian Sea after the transit of AdDW, which sustained the anticyclonic phase of the NIG. The majority of the NAddW, however, was advected toward the Kerkyra-Kefalonia Valley, reaching the deep Hellenic Trench within a few months (thus becoming undetectable by Argo floats). As a result, it did neither contribute significantly to the formation of mAdDW, nor to the maintenance of the density structure needed to sustain the anticyclonic phase of the NIG, which likely explained why it lasted only 6 months.

Within the context of an evolving global climate, the dense water formation events in 2017 represent a profound manifestation of the intricate interplay between the atmosphere and the ocean. The rise in ocean temperature observed in recent years in the Mediterranean Sea could favor the production of warmer NAddW (Denamiel et al., 2025; Pastor et al., 2020) unable to reach the deepest part of the eastern Mediterranean Sea with direct consequence on deep heat transfer and ventilation. The density values of 2017 reflect the combined effects of temperature and salinity balance, making NAddW dense enough to spread in the deep layers of the eastern Mediterranean basin. However, considering the current case of the northwestern Mediterranean Sea (i.e., 10 years without strong dense water events, Josey & Schroeder, 2023; Li et al., 2024) and the climate projection (Darmaraki et al., 2019; Parras-Berrocal et al., 2022, 2023; Reale et al., 2022), salinification may not fully counterbalance the increase in temperature. As a result, the NAddW could become less dense and fail to reach the deepest layers of the eastern Mediterranean, potentially impacting significantly the circulation of the basin.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The bathymetry data were obtained from EMODnet Bathymetry Consortium, (doi.org/10.12770/ff3aff8a-cff1-44a3-a2c8-1910bf109f85).

Physical and biogeochemical measurements were obtained from the different network platforms (see Table S1 in Supporting Information S1 for details about their repository address).

Climate index were obtained from *Climate prediction Center (NOAA)* Northern Hemisphere large-scale teleconnection patterns indexes (NAO, EA, EAWR, SCAN) (www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml, last accessed 8/8/2023).

Atmospheric forcing data were obtained from the European Centre for Medium-Range Weather Forecasts at https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download.

The Po River discharge data were obtained from the website https://www.arpae.it/it/temi-ambientali/acqua/dati-acque/acque-superficiali/dati-idrometrici-in-tempo-reale-1.

High-resolution observational and assimilated data sets were obtained from Copernicus Marine Environment Monitoring Service at https://data.marine.copernicus.eu/product/MEDSEA_MULTIYEAR_PHY_006_004/services.

Argo data were collected and made freely available by the International Argo Program and the national programs that contribute to it (https://dataselection.euro-argo.eu/, https://www.ocean-ops.org). The Argo Program is part of the Global Ocean Observing System.

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