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LETTER

Unprecedented warming and salinization observed in the deep Adriatic

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Scientific Significance Statement

Warming of coastal and semi-enclosed basins is occurring at unprecedented levels, with some regions, such as the Mediterranean Sea, experiencing warming rates higher than the global average. In this study, we documented an additional fivefold increase in warming and a doubling in salinity trends in the deep and near-bottom waters of the Adriatic Sea (the northernmost basin of the Mediterranean) over the past 15 yr. As the source region for deep Mediterranean waters, the Adriatic plays a crucial role in driving the basin-wide thermohaline circulation. The observed changes may indicate a rapid transit toward a new climate regime that may impact sea level trends, vertical mixing and transport of oxygen to the deep sea, nutrient consumption and primary production, as well as changing the whole ecosystem toward species originating from warm and tropical seas.

Abstract

The deep Southern Adriatic is a Mediterranean region highly sensitive to climate change, influenced by dense water cascading from the northern Adriatic and heat/salt transport from the Eastern Mediterranean. Historical (since 1957) and modern (permanent and opportunistic temperature and salinity sampling, Argo floats, fixed moorings) measurements reveal a substantial change since the mid-2000s in thermohaline properties. Historically marked by steady increases in temperature, salinity, and density, with substantial saw-tooth decadal variability, the near-bottom Southern Adriatic has experienced unprecedented warming (0.8°C) and salinization (0.2) over the past decade, accelerating in time and reversing density trends. The inflow of much more saline waters reduced stratification and altered dense water properties at its source in the northern Adriatic. This at least fivefold acceleration of the high-emission regional climate projections may have substantial effects on the Adriatic biogeochemistry and living organisms, changing sea level trends and more.

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Elena Terzić and Ivica Vilibić contributed equally to this study.

Data Availability Statement: The Argo profiling float data has been taken from Euro-Argo ERIC at https://dataselection.euro-argo.eu, ERA5 data has been downloaded from Copernicus Climate Service at https://doi.org/10.24381/cds.adbb2d47, while the remaining data is available at the Zenodo repository at https://zenodo.org/records/13788664 (Terzić et al. 2024).

Introduction

The Adriatic Sea, the northernmost Mediterranean basin, spans 800 × 200 km and features (1) a 300-km wide shelf in the northwest with depths reaching up to 80 m, (2) the middle Adriatic depressions of ca. 280 m in maximum, and (3) the 1220-m deep Southern Adriatic Pit (SAP) in the southeast. The SAP, particularly its regions below 800 m, is connected to the 5200-m deep Ionian Sea through the 800-m deep Otranto Strait (Fig. 1). The Adriatic Sea has been monitored for over a century (Artegiani et al. 1997; Vilibić et al. 2023) and serves as an ideal natural laboratory for studying climate change effects due to its rapid response to various forcings (Tanhua et al. 2013). From its river-exposed shelves to its mouth, through which saline Levantine waters flow, the Adriatic exhibits warming and increased salinity over centennial timescales (Lipizer et al. 2014; Vilibić et al. 2023). However, the Adriatic-Ionian Bimodal Oscillating System (Gačić et al. 2010; Civitarese et al. 2023) can obscure climate change signals by introducing significant decadal variability in thermohaline properties (Mihanović et al. 2015), altering biogeochemical characteristics (Buljan 1953; Batistić et al. 2014), and impacting fish populations and fisheries (Civitarese et al. 2023).

The Bimodal Oscillating System and deep thermohaline circulation in the Adriatic are driven by dense water formation both on the shelf (Orlić et al. 2007; Mihanović et al. 2013) and through open-ocean convection in the SAP (Gačić et al. 2002). North Adriatic dense water (NAddW; Zore-Armanda 1963) is generated on the shelf, spreads over the seabed, and occasionally (every few to 10 yr) cascades to the near-bottom SAP layers (Langone et al. 2016; Querin et al. 2016; Pranić et al. 2024), strengthening the stratification and preventing open-ocean convection from reaching the bottom. Open-ocean convection in the Adriatic generates Adriatic deep water, reaching depths of up to 900 m (Cardin et al. 2011; Vilibić et al. 2023), that—combined with NAddW outflow along the continental shelf—flows into the Ionian Sea. Oppositely, saline Levantine Intermediate Water (LIW) is advected into the Adriatic at intermediate depths (50–500 m; Vilibić and Orlić 2002). The inflow of warmer, saltier waters at these depths promotes diffusive convection and salt-fingering processes in the SAP. Along with open-ocean convection, these processes transport salt and heat toward the bottom (Amorim et al. 2024) and may contribute to changes in near-bottom SAP thermohaline properties even more than dense water cascading and open-ocean convection (Cardin et al. 2020).

Climate change, marked by warming and salinity increases across the Mediterranean (Kassis and Korres 2020; Skliris et al. 2025), significantly affects the Adriatic's thermohaline

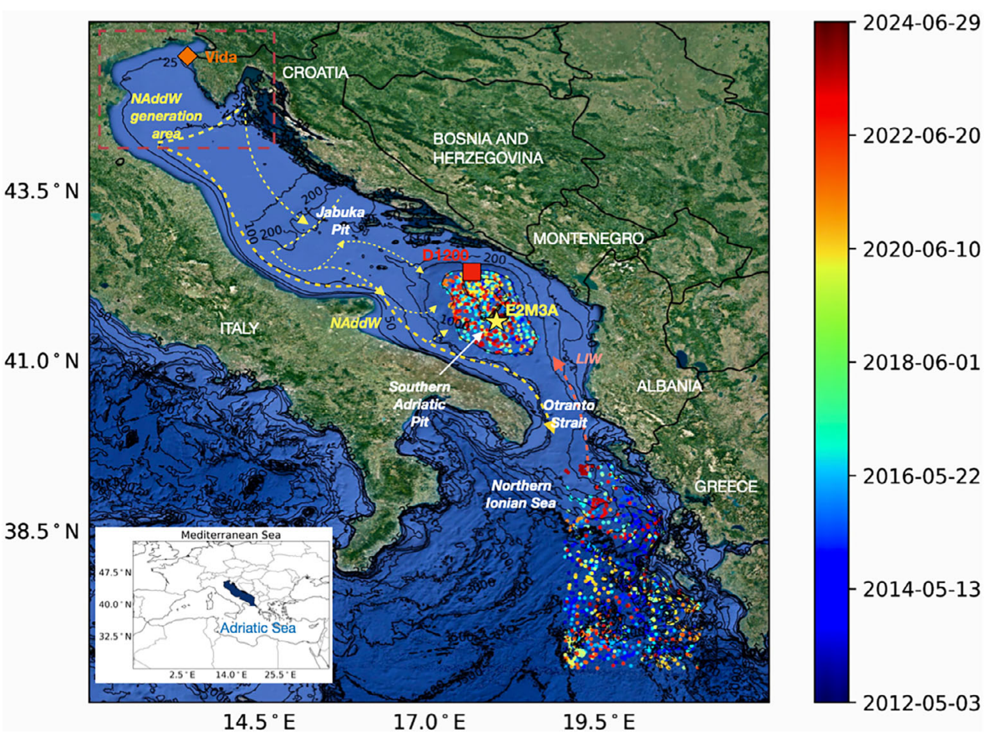

Fig. 1. The Adriatic and northern Ionian Sea bathymetry with locations of the SAP and northeastern Ionian Sea Argo profiles (circles, time of sampling is color-coded), EMSO-E2M3A deep observatory (yellow star), station D1200 (red rectangle), and buoy Vida (orange diamond). The generation area and pathways of North Adriatic Dense Water (NAddW) are indicated. The red dashed rectangle denotes the northern Adriatic shelf over which ERA5 turbulent heat fluxes were averaged.

dynamics. Sea surface warming has been measured at 0.4–0.6°C per decade since the 1970s (Reiners et al. 2024), especially in summer and coastal zones (Amos et al. 2017), though the Atlantic Multidecadal Oscillation explains half of this (Macias et al. 2013). Positive salinity trends have accelerated since 2017 (Amorim et al. 2024), influencing NAddW formation (Tojčić et al. 2023). Notably, despite temperature and salinity increases, NAddW density remained stable between 2012 and 2020 (Paladini de Mendoza et al. 2023), but LIW density has risen, reducing SAP stratification and enhancing mixing. These deep ocean changes prompt questions about whether the "new state of the deep Adriatic" is permanent and linked to climate change or part of decadal variability. Using long-term (since 1957) multi-platform measurements in the SAP, we aim to quantify these changes and assess potential shifts in deep and near-bottom thermohaline properties.

Materials and methods

The temperature and salinity dataset was obtained through various Eulerian and Lagrangian platforms, as well as shipborne measurements in the Southern Adriatic (Fig. 1, Terzić et al. 2024). These sources include: (1) seasonal to interannual sampling at station D1200 conducted by the Institute of Oceanography and Fisheries, Croatia, since 1957 (this data is of the lowest quality and has been subjected to additional quality-check in this study; further details on sampling procedures and data accuracy can be found in Vilibić et al. 2011; here we use the data at 1000 m depth); (2) opportunistic temperature and salinity measurements, carried out by multiprobes within Italian and European projects since 1985 (more can be found in Cardin et al. 2020); (3) EMSO-E2M3A deep-ocean observatory (https://emso.eu/observatories-node/south-adriatic-sea), with (among other) deep temperature and salinity sensors located at 900, 1000, and 1200 m, with hourly resolution and being in operation since 2006 (daily averages are used in this paper); and (4) 15 Argo profiling floats (https://www.euro-argo.eu) that have been active in the Southern Adriatic since 2010, reaching depths of at least 1000 m.

Additionally, we analyzed temperature and salinity data collected since 2004 at buoy Vida (https://www.nib.si/mbp/en/oceanographic-data-and-measurements/buoy-2) in the northern Adriatic. Sensors at buoy Vida are positioned at a depth of 2.5 m. This buoy is located within the NAddW formation area and is not affected by rivers during cold wintertime bora outbreaks (Raicich et al. 2013). For each year, we extracted the daily average of temperature and salinity during the period of NAddW formation, that is, for a day when maximum density is reached.

Potential temperature, practical salinity, and potential density anomaly (PDA) were estimated from measurements using the TEOS-10 standard (https://www.teos-10.org).

To quantify year-to-year cooling changes in the NAddW formation area, we analyzed anomalies in daily latent and sensible heat fluxes from the ERA5 reanalysis (Hersbach et al. 2020), averaged over the northern Adriatic (red rectangle in Fig. 1) for the period from December to February, during which dense water preconditioning and formation occurs (Paladini de Mendoza et al. 2023). The sum of latent and sensible heat fluxes is referred to as turbulent heat fluxes. Notably, ERA5 cooling rates are underestimated along the bora jets (Denamiel et al. 2021), yet they exhibit the changes between years attributed to dense water formation potential.

Deep Adriatic as a climate change hot spot

The composite series from SAP observations at 1000 m (Fig. 2) shows an overall rise in salinity and temperature, with significant decadal temperature variability before the 1990s (one should note that the oldest 1000-m temperature and salinity measured during the 1911–1914 cruises equal to ca. 12.8°C and 38.5, respectively; Vilibić et al. 2023). Although the historical data are of lower accuracy and reliability, our analysis follows the literature on the Adriatic thermohaline variability. For example, major cooling events in the winters of 1981 (Artegiani and Salusti 1987) and 1983 (Brankart and Pinardi 2001) followed a large inflow of LIW (Mihanović et al. 2015), generating much cooler dense waters that cascaded into the near-bottom SAP. Less saline Western Mediterranean waters entered in the late 1980s and the early 1990s, preconditioned by the Eastern Mediterranean Transient (Klein et al. 1999) along with milder winter cooling (Josey 2003; Cardin and Gačić 2003). Both prevented dense water cascading to the near-bottom SAP between 1992 and 2000 due to its lower density (Pranić et al. 2024). Salinity rose sharply in the mid-2000s, coinciding with several NAddW formation events (in winters of 2002, 2005, and 2006; Verri et al. 2018; Pranić et al. 2024), transporting salt to the near-bottom SAP. Since 2006, near-bottom SAP thermohaline changes clearly reflect two key processes: dense water cascading (Bignami et al. 1990; Paladini de Mendoza et al. 2023; Le Meur et al. 2025) and steady temperature and salinity increases driven by double-diffusive processes (Querin et al. 2016; Amorim et al. 2024). This 'saw-tooth' pattern, linked to cascading events occurring every few to 10 yr (Querin et al. 2016), is more evident post-2006 due to better data; however, our data suggest that such **a** pattern occurred in the 1970s–1980s and 1990s–2000s. Another period without NAddW cascading to **the** near-bottom SAP was between 2006 and 2012, again connected with anticyclonic Bimodal Oscillating System that induced lower salinity conditions in the Adriatic.

From 1957 to 2024, 1000-m composite trends show significant increases in temperature (0.088°C), salinity (0.036), and PDA (0.0097 kg m^{-3}) per decade ($p < 0.001$). Two distinct PDA regimes emerged: until the mid-2000s, PDA increased steadily, driven by salinity, while from 2006, temperature and salinity accelerated, causing PDA to decrease almost linearly

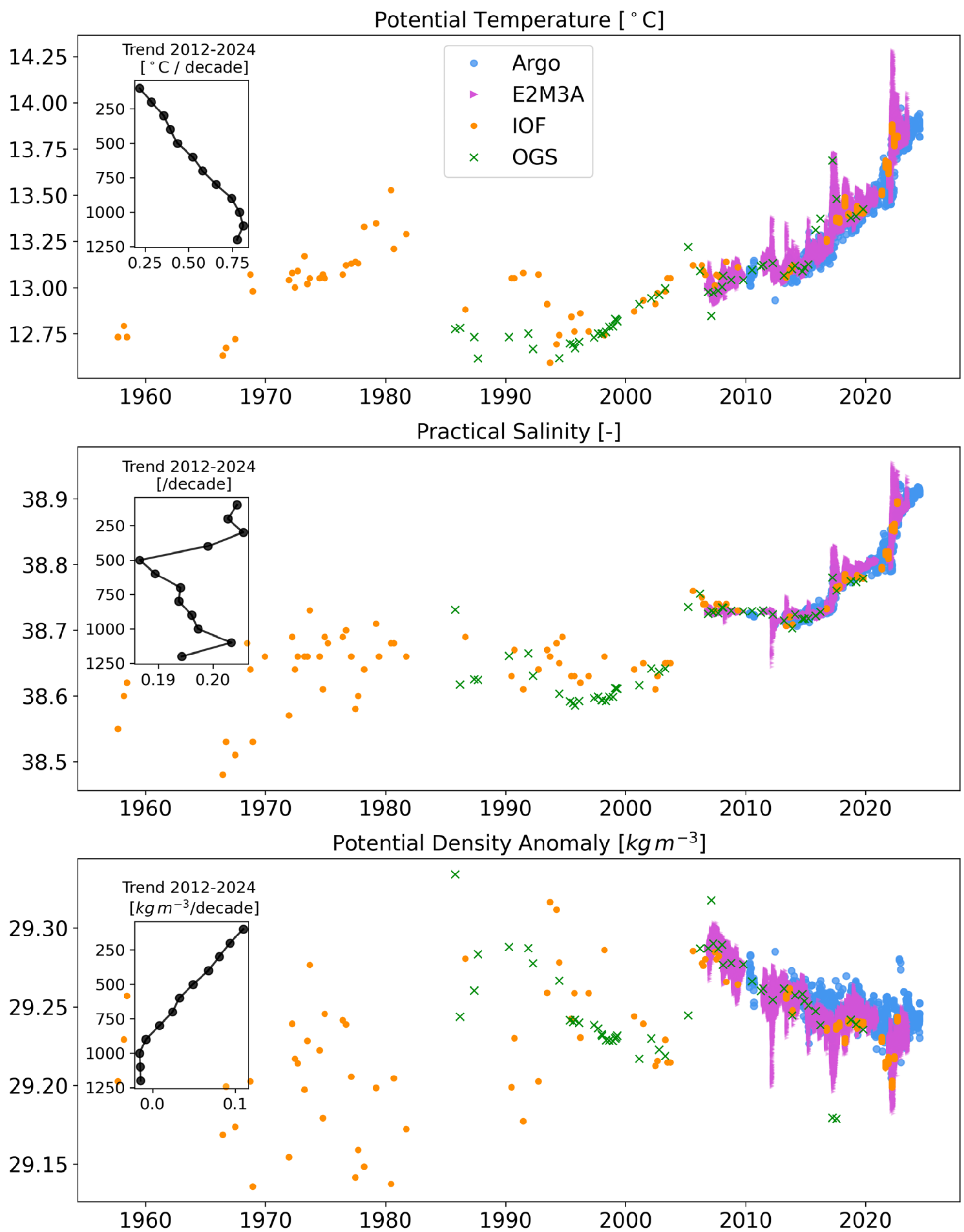

Fig. 2. Potential temperature (up), practical salinity (middle), and potential density anomaly (PDA, bottom) obtained from all SAP observations at 1000 m since 1957 (IOR—measurements carried out by the Institute of Oceanography and Fisheries at station D1200; OGS—cruises as part of Italian and European projects; and other datasets in PANGEA Data Repository [https://www.pangaea.de/] and MEDATLAS Dataset [https://nodc.inogs.it/nodc/] in the SAP). Trends presented in insets are estimated from the Argo data in the period 2012–2024 (this period was chosen as sparse data and major data gap occurred before 2012).

(-0.03 kg m^{-3} per decade, $p < 0.001$). Between presumed or documented cascading events, temperature trends at 1000 m remained steady, around 0.38°C, 0.35°C, and 0.36°C for the periods 1967–1980, 1994–2004, and 2012–2016, respectively (computed using annual averages from all measurements). Heat transport was driven by salt-fingering (Amorim et al. 2024), though no deep salinity increase was observed during the post-Eastern Mediterranean Transient period (1994–2004). However, the drop in temperature of the dense waters cascading into the near-bottom SAP steadily decreased from about 0.5°C in the early 1980s to 0.2–0.3°C in the early 1990s and to less than 0.2°C in 2012, the latter being characterized by record-breaking cooling, densities, and dense water generation in the northern Adriatic (Mihanović et al. 2013).

After 2017, dense water cascading events reversed the temperature shifts at 1000 m (Fig. 2), with temperatures rising by 0.2°C and 0.3°C during the 2017 and 2022 events, and salinity increasing by 0.02 and 0.08, respectively. The details of the cascading events measured by bottom-mounted observatories at the western SAP slope are documented in detail by Paladini de Mendoza et al. (2023) and Le Meur et al. (2025). At the very bottom of the SAP (1200 m), temperature and salinity shifts were even larger during the 2022 event, by about 0.40°C and 0.12 (Fig. 3). The positive trends between cascading events have accelerated in time, with values of 0.40°C, 0.67°C, and 0.64°C (temperature), and 0.062, 0.118, and 0.218 (salinity) per decade for the periods July 2012–December 2016, July 2018–December 2021, and July 2022–June 2024, respectively (estimated from Argo data at 1000 m only). Indeed, we found the entire Southern Adriatic warming and salinification (Fig. 3), with the 14°C isotherm deepening from 100 m in the early 2010s to near the bottom by 2024, while salinity above 38.9 was sporadically present in **the** early 2010s but encompassed almost the entire SAP in 2024 (except at the very surface and below 1000 m).

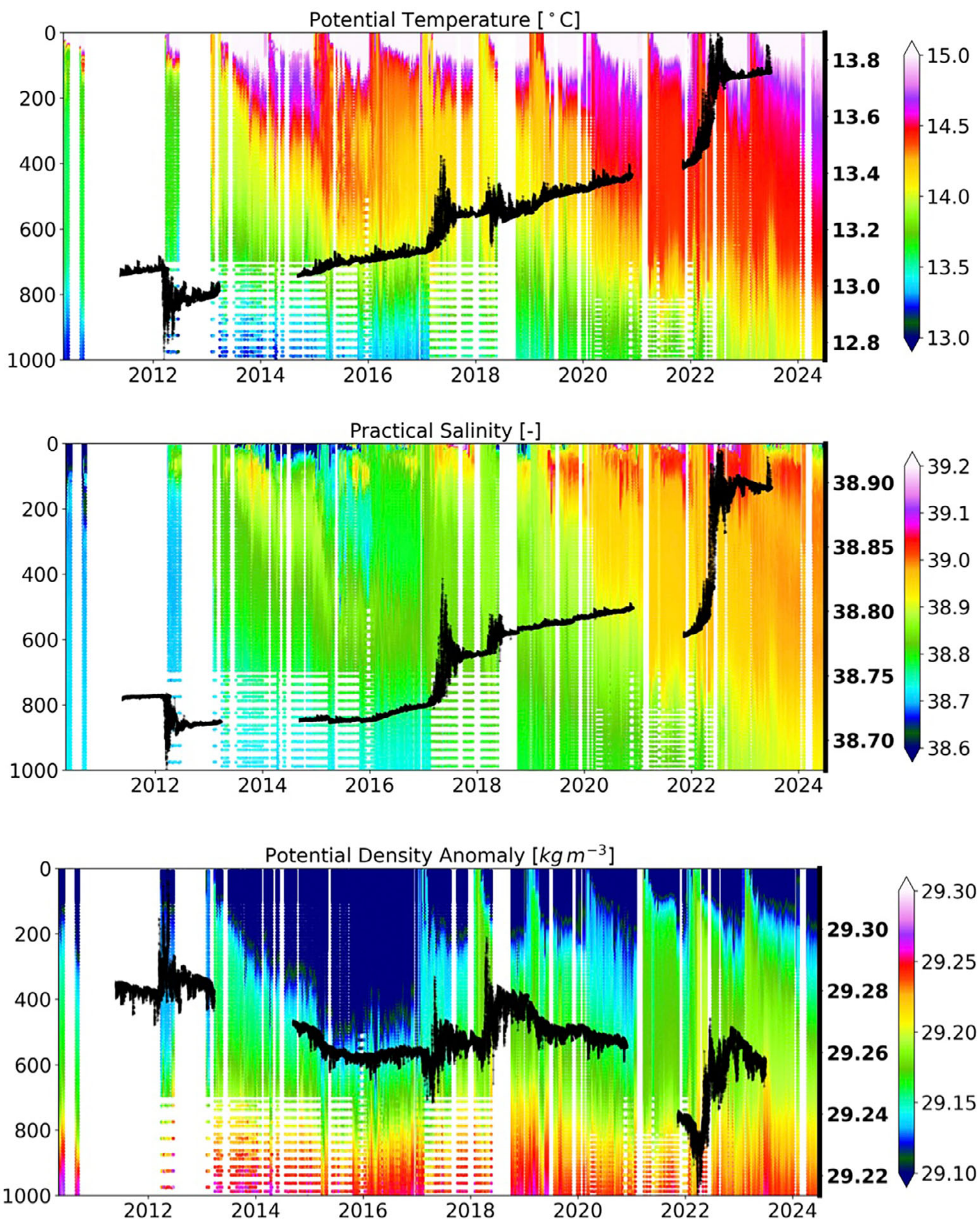

Fig. 3. Argo-based Hovmöller diagram of the SAP potential temperature, practical salinity and PDA since 2012, with overlying EMSO-E2M3A time series (black line) measured at 1200 m.

To quantify the recent changes in stratification in the SAP, we estimated temperature, salinity, and PDA differences across 100 m water layers (below the seasonal pycnocline) using Argo data (Fig. 3). The reduction in vertical temperature gradients is particularly evident in the upper 700 m, where the gradients decrease by more than 40% over a decade, with a maximum of 60% decrease between 500 and 600 m. The trends in salinity gradients are less pronounced, except between 300 and 500 m, where a strong decrease in vertical salinity gradient is detected, due to higher overall salinity trends at depths shallower than 400 m. Consequently, stratification below 100 m has eroded over most of the SAP, with rates of 0.010–0.015 kg m^{-3} over a decade and 100 m layers, except at the very bottom (1100–1200 m) where stratification has slightly increased. However, the latter may be attributed to much lower availability of Argo data at 1200-m depth.

Recent changes in near-bottom SAP water mass source regions

Several key processes influence the near-bottom SAP: dense water generation (on the northern Adriatic shelf and through open-ocean convection in the SAP), double-diffusive processes, and water exchange with the Mediterranean via the Otranto Strait. However, open-ocean convection was never recorded to reach depths below 900 m (Gačić et al. 2002; Cardin et al. 2011), which are normally occupied by the NAddW cascaded from the northern Adriatic characterized by higher thermally driven density and slowly eroding due to heat and salt exchange with overlying waters (Querin et al. 2016; Vilibić et al. 2023).

The northern Adriatic winter turbulent heat flux anomalies over the northern Adriatic, where NAddW forms, have been predominantly higher between 2004 and 2024 than during the 1980–2010 baseline (Fig. 4, top). Notably, the years in which major NAddW cascading events to the near-bottom SAP occurred (2012, 2017, 2018, and 2022) exhibit varying turbulent heat flux anomalies, with winters of 2018 and 2022 showing positive anomalies (the winter of 2018 was preceded by a cold autumn; Paladini de Mendoza et al. 2023). Intuitively, despite low heat losses in 2022, haline contributions may have significantly influenced NAddW density and cascading potential to the near-bottom SAP.

To support this statement, daily averages of temperature, salinity, and PDA at the Vida buoy (northern Adriatic) during the day in a year when the PDA maximum is reached reveal significant changes in NAddW properties (Fig. 4, middle), though the buoy was non-operational during the winters of 2007, 2008, and 2019. The buoy is located inside the northern Adriatic dense water generation area (e.g., Raicich et al. 2013) and qualitatively reflects the wider thermohaline conditions. In 2005–2006, high PDA (ca. 29.7 kg m^{-3}) was driven by heat loss, while in 2004, both lower temperatures and higher salinity led to high PDA values. These waters then cascaded to the near-bottom SAP (Vilibić and Šantić 2008), raising salinity levels in mid 2000s. In 2012, both severe cooling and high salinity produced record NAddW PDA values at its source (Mihanović et al. 2013), while in 2017 and 2018, similar conditions to 2004 were observed. In 2022, low temperature and high salinity from droughts (Bonaldo et al. 2023) resulted in the second-highest PDA value (29.82 kg m^{-3}) at the Vida buoy, bringing even warmer and higher salinity waters through cascading to the near-bottom SAP (Le Meur et al. 2025).

In the northeastern Ionian Sea, Argo data from 2012 to 2024 (Fig. 4 bottom) show much slower increases in temperature and salinity compared to the SAP (Fig. 2, inset). Temperature trends are approximately 0.1–0.2°C per decade (Fig. 4 bottom), which is two to four times lower than observed in SAP, while salinity trends were mostly 0.05–0.10 per decade, again two to four times lower than observed in SAP. Overall, weak positive PDA trends exist in the northern Ionian, opposing the trends in the near-bottom SAP. This suggests that local Adriatic processes, influenced by changes in wintertime heat losses, precipitation, and river discharge (Vodopivec et al. 2022; Bonaldo et al. 2023), play a larger role in shaping NAddW and consequently near-bottom SAP thermohaline properties.

Discussion

The salinization and warming of the deep Mediterranean waters have been observed on a centennial scale (Vargas-Yáñez et al. 2017, 2021), but these processes have accelerated since the 1950s (Rohling and Bryden 1992), and even more in the last decade (García-Lafuente et al. 2021; Kubin et al. 2023). These trends are also evident in the LIW, which has exhibited temperature and salinity increases of 0.2°C and 0.06 per decade, respectively, between 2001 and 2019 (Fedele et al. 2022). However, our analysis indicates that in the Southern Adriatic, in particular in its deepest parts, these trends have accelerated dramatically to 0.4–0.8°C and 0.2 per decade between 2010 and 2024—two to four times higher than in the rest of the Mediterranean. Notably, the most significant temperature increases have been observed at the bottom of the SAP, where dense waters from the northern Adriatic cascade every few years, signaling a major shift in the source region of these cascading waters. Furthermore, double-diffusive transport, driven by an unprecedented influx of warm, saline waters into the Adriatic, is contributing to further warming and salinization of the Southern Adriatic and Adriatic in general.

This raises the question of whether these changes are exceptional and represent a transit in the deep Adriatic waters. Deep-water transits have been documented in the Mediterranean over the last few centuries, such as the Eastern Mediterranean Transient (Klein et al. 1999), a unique event with possible centennial recurrence times (Incarbona et al. 2016),

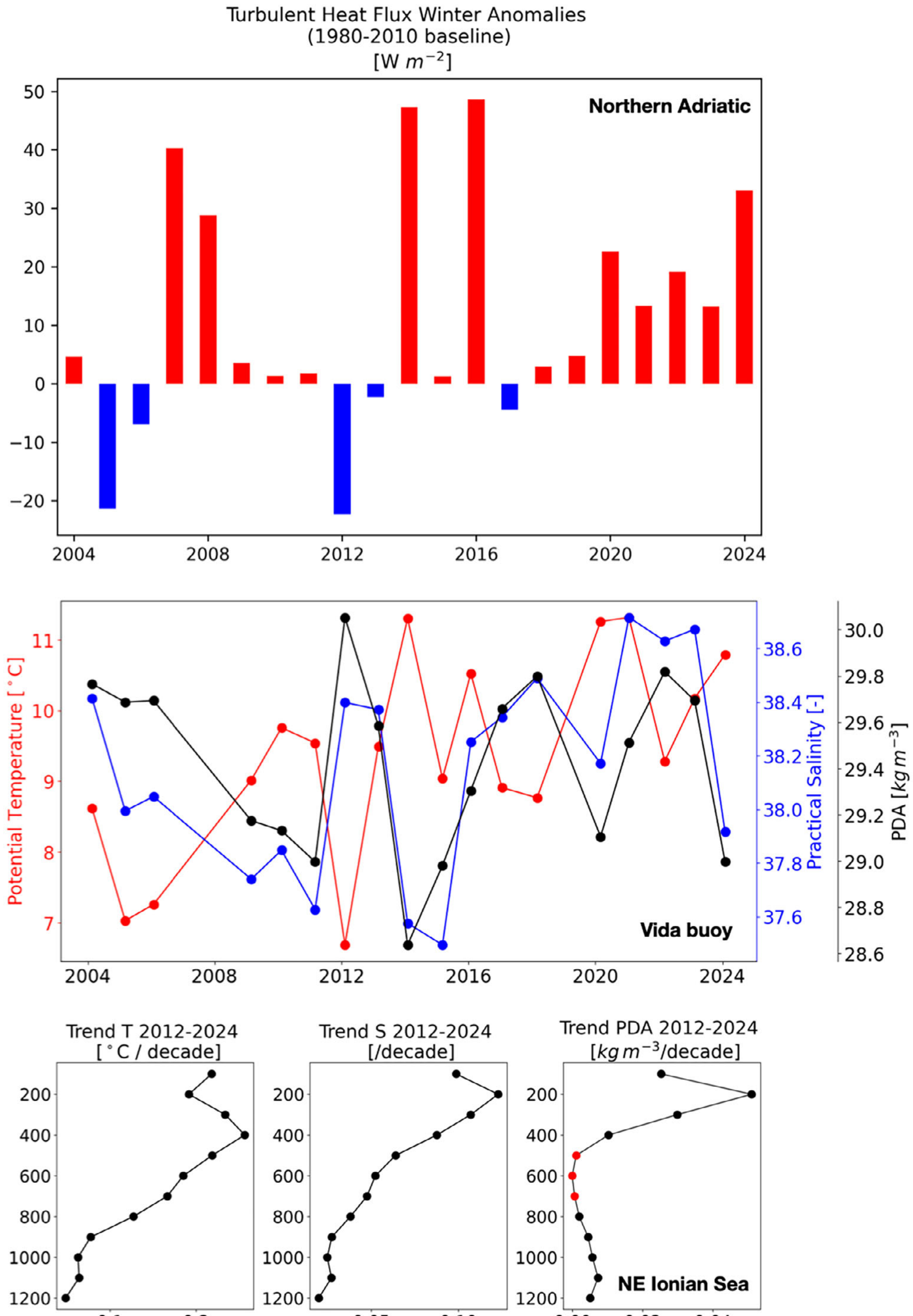

Fig. 4. Average wintertime (DJF) ERA5 turbulent (latent + sensitive) 2004–2024 heat flux anomalies over the northern Adriatic in respect to the 1980–2010 baseline period (top), daily temperature, salinity, and PDA values measured at the buoy Vida in a day of a year with maximum PDA value (middle), and 2012–2024 trends in the northeastern Ionian Sea as derived from the Argo data (bottom; red dots represent trends that are not significant at the 95% confidence level).

and the Western Mediterranean Transient, which brought waters with different temperatures and salinities to the bottom (Zunino et al. 2012). These events were driven by extraordinary wintertime forcings, as is the case here, where dense water cascading has introduced much warmer and saltier water. It is also worth considering whether such deep-water conditions will become more frequent in future climates. The state-of-the-art Med-CORDEX ensemble (Soto-Navarro et al. 2020) projects increases in surface (0–150 m) and intermediate (150–600 m, primarily LIW) temperature/salinity of 2–4°C/0.2–1.0 and 2–3°C/0.2–1.0, respectively, in the far future (2075–2100) under the RCP8.5 scenario. Kilometer-scale models project similar changes, for example, approximately 0.6°C and 0.15 for temperature and salinity, respectively, for the mid-future (2031–2050) RCP8.5 scenario (Verri et al. 2024). Observations in the SAP over the last 10–15 yr suggest that the projected level of centennial changes may occur in just 10–20 yr, representing at least a fivefold amplification of regional climate changes projected by extreme high greenhouse emission scenarios.

The significantly higher temperature and salinity trends in the SAP, particularly in its near-bottom layers, compared to the northeastern Ionian Sea—through which the saline LIW is advected to the Adriatic—indicate that locally driven warming of the deep Adriatic waters plays a more important role in the observed Adriatic transit than the advection of heat and salt from the Levantine Basin. These conditions resemble those observed during the positive phases of the Bimodal Oscillating System, during which the Adriatic exhibits high-salinity conditions, facilitating the cascading of NAddW due to the higher density of saltier waters (Paladini de Mendoza et al. 2023; Pranić et al. 2024; Le Meur et al. 2025). The documented deep Adriatic changes clearly introduce the paradigm: local drying and warming may become more important for deep layers than heat and salt advection from the Ionian Sea. This interplay between processes may be perceived as a preview of future climate change (Bonaldo et al. 2023).

These observed changes in thermohaline properties are already impacting Adriatic biogeochemistry and marine life. Species residing in warmer seas are likely to benefit and increase in abundance (Belmaker et al. 2012). In contrast, cold-water species, primarily found in the Jabuka Pit—an area known for the lowest temperatures in the Adriatic and protected as a no-take zone due to its rich biodiversity and demersal resources (Chiarini et al. 2022)—will be particularly threatened by the rapid changes in NAddW properties. All biogeochemical projections indicate that a warming Mediterranean will exhibit a decline in dissolved oxygen and nutrient availability (Reale et al. 2022), leading some species to reduce their habitat range and/or migrate northward (Palermino et al. 2024; Panzeri et al. 2024). This transient will likely exacerbate these changes, particularly for deep benthic organisms (Angeletti et al. 2015; Taviani et al. 2019), which are not adapted to such large and irreversible temperature shifts.

The shift in intermediate and deep-water density trends has the potential to change sea level trends in the Adriatic. By applying a simplified methodology by Wang et al. (2017) for the whole water column, the steric sea level trend between 2014 and 2024 equals 3.3 mm yr^{-1}, in which the thermosteric and halosteric contributions equal to 20.5 and -17.2 mm yr^{-1}, respectively, the first prevailing in the upper 100 m while the second having a maximum in intermediate layers. During the second half of the 20th century, sea level rise trends were mitigated (compared to global trends) due to an increase in deep-water density (Tsimplis and Baker 2000). Our study indicates that deep density trends have reversed since 2006, aligning with climate projections (Soto-Navarro et al. 2020), and potentially amplifying sea level rise in coastal regions (Vecchio et al. 2024). The complexity of interactions between different drivers of thermohaline changes introduces uncertainty in determining whether these events represent decadal variability or rapid transits toward a projected warmer climate. These uncertainties, along with other observed changes in the Mediterranean, should be carefully investigated to develop appropriate mitigation and adaptation strategies, where possible.

Author Contributions

Elena Terzić and Ivica Vilibić co-led the entire manuscript effort and contributed equally. Ivica Vilibić came up with the research questions and designed the study approach. Vanessa Cardin, Julien Le Meur, Natalija Dunić, and Martin Vodopivec collected and analyzed the E2M3A, D1200, and Vida buoy data, while Elena Terzić merged these results with the analysis of the Argo profiling data. Elena Terzić prepared all figures, while Ivica Vilibić wrote the initial version of the manuscript. All authors reviewed, edited, and approved the manuscript.

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Conflicts of Interest

The authors have no conflicts of interest to declare.

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