



# Recent abrupt shifts in the Adriatic Sea physical properties and their potential consequences

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**Abstract.** The Adriatic Sea has recently undergone rapid transitions in its thermohaline properties, affecting the entire water column—from surface layers, influenced by changing atmospheric and hydrological forcings, to the deepest layers, which are increasingly replenished by significantly warmer and saltier waters. The Mediterranean Sea as a whole is warming and salinifying at rates exceeding those of the global ocean and is projected to continue this trend throughout the 21st century. Consequently, the lateral inflow of heat and salt through the Strait of Otranto is modifying the thermohaline structure of the Adriatic Sea. However, available evidence suggests that a substantial portion of these changes arises from locally amplified Adriatic processes, as observed rates are several times higher than those reported for the Mediterranean at large. This paper reviews the key Adriatic changes documented primarily over the past decade, including shifts in the inflow and properties of inflowing Eastern Mediterranean waters, progressive warming of the northern Adriatic shelf, the recurrent formation of surface salinity maxima (so-called “surface saline lakes”), and North Adriatic Dense Water cascading increasingly driven by increased salinity at its formation sites. The rates of these changes are quantified, also through a comparison of 21st-century versus 20th-century thermohaline properties, and their potential impacts on regional climate extremes, biogeochemistry, marine ecosystems, fisheries, and aquaculture are discussed.

## 20 **1 Introduction**

Coastal ocean regions are known to respond more rapidly to climate forcing than the open ocean, whether the forcing originates from the atmosphere (surface forcing), land (hydrological forcing), or lateral boundaries connecting coastal regions with the open ocean (Holt et al., 2025; Richardson et al., 2025; Wagawa et al., 2025). One of the most extensively studied coastal regions is the Mediterranean Sea (Malanotte-Rizzoli et al., 2014), which—although thousands of kilometres long and up to 5 km deep—exhibits changes at much faster rates than the global ocean (Schroeder et al., 2017; Juza et al., 2022). Such changes in the physical systems of coastal seas may have unprecedented consequences for biogeochemical processes, living organisms, and higher trophic levels, including aquaculture and fisheries, which are known to respond to accelerated physical changes (Pairaud et al., 2014; Grbec et al., 2015; Hassoun et al., 2022). Furthermore, feedbacks from the rapidly changing coastal ocean



to the atmosphere, land, and hydrosphere may also be amplified (Small et al., 2001; Khodayar and Hoerner, 2020; He et al.,  
30 2022), resulting in changes in extremes that may be critical for populations in surrounding areas (Bermúdez et al., 2021).

A semi-enclosed sea deeply embedded within the European continent and subject to strongly varying boundary forcing is  
the Adriatic Sea—the northernmost embayment of the Mediterranean Sea, approximately 800 km long, 200 km wide, and up  
to 1 230 m deep. The history and longevity of environmental observations in the Adriatic are exceptionally rich, including  
systematic interdisciplinary field campaigns that began in the early twentieth century (Buljan and Zore-Armanda, 1976;  
35 Artegiani et al., 1997; Lipizer et al., 2014; Fortibuoni et al., 2017). Based on both early and modern data, many physical  
processes that characterize Adriatic dynamics have been documented with increasing understanding over time. These include,  
among others: (i) the generation of North Adriatic Dense Water (NAddW) on the northern Adriatic shelf, which, through  
density currents, transports dissolved oxygen to deep layers and sustains benthic organisms (Zore-Armanda, 1963; Marini et  
al., 2006; Pusceddu et al., 2013; Chiarini et al., 2022a; Vilibić et al., 2023); (ii) decadal-scale modulations of the inflow of  
40 ultra-oligotrophic and saline Levantine Intermediate Water (LIW; Malanotte-Rizzoli et al., 2003) into the Adriatic (Buljan,  
1953; Gačić et al., 2010; Civitarese et al., 2023), which shape the nutrient budget and primary production across much of the  
basin (Civitarese et al., 2010; Vilibić et al., 2012; Ozer et al., 2022); (iii) open-ocean convection in the deep Southern Adriatic  
Pit (Gačić et al., 2002), which represents a major source of deep waters for the Eastern Mediterranean (Schlitzer et al., 1991;  
Li and Tanhua, 2020); (iv) rapid response timescales and a relatively small internal Rossby radius of deformation compared  
45 to the rest of the Mediterranean Sea (Cushman-Roisin and Korotenko, 2007; Kurkin et al., 2020; Pranić et al., 2023), which  
make the accurate reproduction and forecasting of ocean dynamics extremely challenging, requiring sub-kilometre-scale  
numerical models; and more.

Intuitively, changes in these processes, as well as in the overall characteristics of the Adriatic climate system, may have  
profound consequences for physical and biogeochemical systems. These impacts occur on top of quasi-monotonous large-  
50 scale trends, such as increasing temperature and salinity in the Mediterranean and global oceans (Jordà et al., 2017; Iona et al.,  
2018), declining dissolved oxygen concentrations and biological production (Belgacem et al., 2025; Liu et al., 2025), and other  
associated changes. The Adriatic Sea, being semi-enclosed and strongly shaped by surrounding orography, may experience  
these changes more dramatically than more open coastal ocean regions. For example, rising ocean temperatures are driving  
northward species migration (Moraitis et al., 2019; Shlesinger et al., 2024), reducing available marine habitats (Jordà et al.,  
55 2020), and triggering mass mortality events (Rivetti et al., 2014). In the Adriatic, species are constrained by geography and  
cannot migrate beyond the northern basin. Consequently, some cold-water species—particularly those inhabiting deep  
accumulation areas (e.g., the Jabuka Pit)—may face local extinction, as their adaptive capacity might be lower than the rate of  
ongoing climate change (Carlot et al., 2025). Beyond living organisms, other impacts of locally amplified changes may exceed  
the adaptive capacity of coupled human–natural systems, including coastal resilience to sea level rise and flash flooding (Mattei  
60 et al., 2025; Khodayar et al., 2025), as well as the sustainability of local food resources, fisheries, and agriculture (Olschewski  
et al., 2024).



This article presents a selection of physical processes in the Adriatic Sea that have been locally amplified or substantially altered over the past decade, based on comparisons between recent observations and historical records spanning many decades to over a century. These include changes in thermohaline circulation and the hydrological cycle, salinization of shelf regions, and a paradigmatic shift in key processes such as dense water formation and cascading. An assessment of the multi-decadal dataset and eventual biases coming from time-space inhomogeneity are discussed first in Section 2, followed by presentation of selected processes in Section 3. Section 4 subsequently discusses some potential consequences of these changes, including impacts on water density and sea level, the statistics of climate extremes, biogeochemical cycling, and marine biodiversity, as well as implications for species migration, fisheries, and aquaculture. In this way, directions for future research are outlined, ranging from analyses of fundamental physical changes (e.g., circulation and thermohaline variability) to their broader environmental and societal impacts.

## 2 An assessment of the Adriatic multidecadal multiplatform *in situ* observations

Temperature and salinity time series in the Adriatic Sea are among the longest in the world's coastal seas, with systematic basin-scale observations dating back to the 1910s (Vilibić et al., 2023). Unfortunately, the First World War interrupted data collection, which resumed only after the Second World War. At the Palagruža Sill transect in the middle Adriatic, the first systematic observations were initiated in 1952 (Buljan and Zore-Armanda, 1966, 1979; Zore-Armanda et al., 1991) and have since been conducted on a seasonal to monthly basis up to the present day. Nevertheless, sampling procedures and instrumentation have changed over time, raising questions about the homogeneity and long-term reliability of the multidecadal thermohaline records and the possible presence of sampling-related biases.

In the analyses presented in Section 3, climatologies were constructed using all available *in situ* temperature and salinity observations collected during the periods 1950–1999 (20th century) and 2000–2019 (21st century). The dataset was compiled from several sources: (1) the SeaDataNet Pan-European infrastructure (<https://www.seadatanet.org>), which archives Mediterranean observations up to 2019; (2) local Adriatic databases, primarily maintained by the Institute of Oceanography and Fisheries and the Ruđer Bošković Institute, with the latest data collected at the end of 2017; and (3) Argo profiling float observations collected in the Mediterranean since 2001 through Euro-Argo ERIC (<https://www.euro-argo.eu>), with measurements in the Adriatic beginning in 2009. Prior to 1950, only sparse thermohaline observations were available (Buljan and Zore-Armanda, 1976; Artegiani et al., 1997; Lipizer et al., 2014), while CTD campaigns conducted after 2019 have not yet been systematically archived in a centralized database. Consequently, the post-2019 period—during which the most rapid increases in temperature and salinity were observed (Terzić et al., 2025a)—is not included in these climatologies.

The data were systematically quality controlled during the processing and archiving of SeaDataNet observations (SeaDataNet, 2010) and through the delayed-mode quality control procedures applied to Argo observations (Wong et al., 2023). For the Palagruža Sill transect dataset, additional quality-control procedures were implemented during previous analyses (e.g., Mihanović et al., 2015, and references therein), resulting in a homogeneous climatological dataset. The



95 remaining Adriatic observations, originating from numerous national (primarily Croatian and Italian) and international research cruises, were quality controlled following SeaDataNet procedures during the assessment of the kilometre-scale Adriatic atmosphere–ocean model described by Pranić et al. (2021).

The analyses were conducted using the original observational dataset, although one may argue that ocean reanalysis products could provide a more homogeneous time–space coverage. However, the study period spans both the pre-satellite and satellite eras, during which the assimilation of sea surface temperature and sea level anomalies evolved substantially over time. Furthermore, the Argo programme was initiated in the Mediterranean Sea in the early 2000s (Poulain et al., 2007), whereas the first Argo profile in the Adriatic Sea was obtained only in 2009. Such abrupt changes in the availability of deep observations may introduce artificial shifts and trends in deep Adriatic thermohaline properties due to changes in data assimilation constraints (E. Terzić, unpublished results). Similar issues have also been recognized in Mediterranean reanalysis products (Escudier et al., 2021; Wang et al., 2023). In addition, ocean reanalyses tend to smooth the intensity of the thermocline and pycnocline in the upper ocean (Adani et al., 2011), which may limit their applicability for resolving strongly stratified events such as surface saline lakes (Terzić et al., 2025b). In the present approach, temporal and spatial averaging was applied to minimize sampling-related biases. Such biases are expected to be relatively small in the deep Adriatic, where observations are quasi-uniformly distributed among different in situ platforms (Fig. 1). However, some biases may remain embedded in the climatologies for shallow regions such as the northern Adriatic, particularly for salinity, owing to pronounced east–west gradients driven by freshwater discharges (Artegiani et al., 1997).

### 3 Abrupt changes observed in the last decade

Following the multi-decadal and even centennial trends observed in the Mediterranean, Adriatic Sea temperature and salinity have also been found to steadily increase over the last century, exhibiting strong interannual to basin-wide decadal variability. This variability is driven by oscillatory processes in the northern Ionian Sea (i.e., the Adriatic–Ionian Bimodal Oscillating System, BiOS; Gačić et al., 2010; Batistić et al., 2014; Civitarese et al., 2023) and by changes in the surface heat budget associated with the Atlantic Multidecadal Oscillation (Mariotti and Dell’Aquila, 2012; Macias et al., 2013). Up to the end of the 20th century, these increases were largely modulated and therefore partially insignificant across large parts of the Adriatic, with trends not exceeding the magnitude of observed variability (Lipizer et al., 2014). Consequently, Adriatic water mass climatology was considered preserved in terms of source characteristics, within uncertainties related to natural variability and sampling bias (Vilibić and Orlić, 2001). However, this situation has changed over the last decade, with the most prominent emerging changes described in the following subsections.

#### 3.1 Salinization, warming and shallowing of saline advection

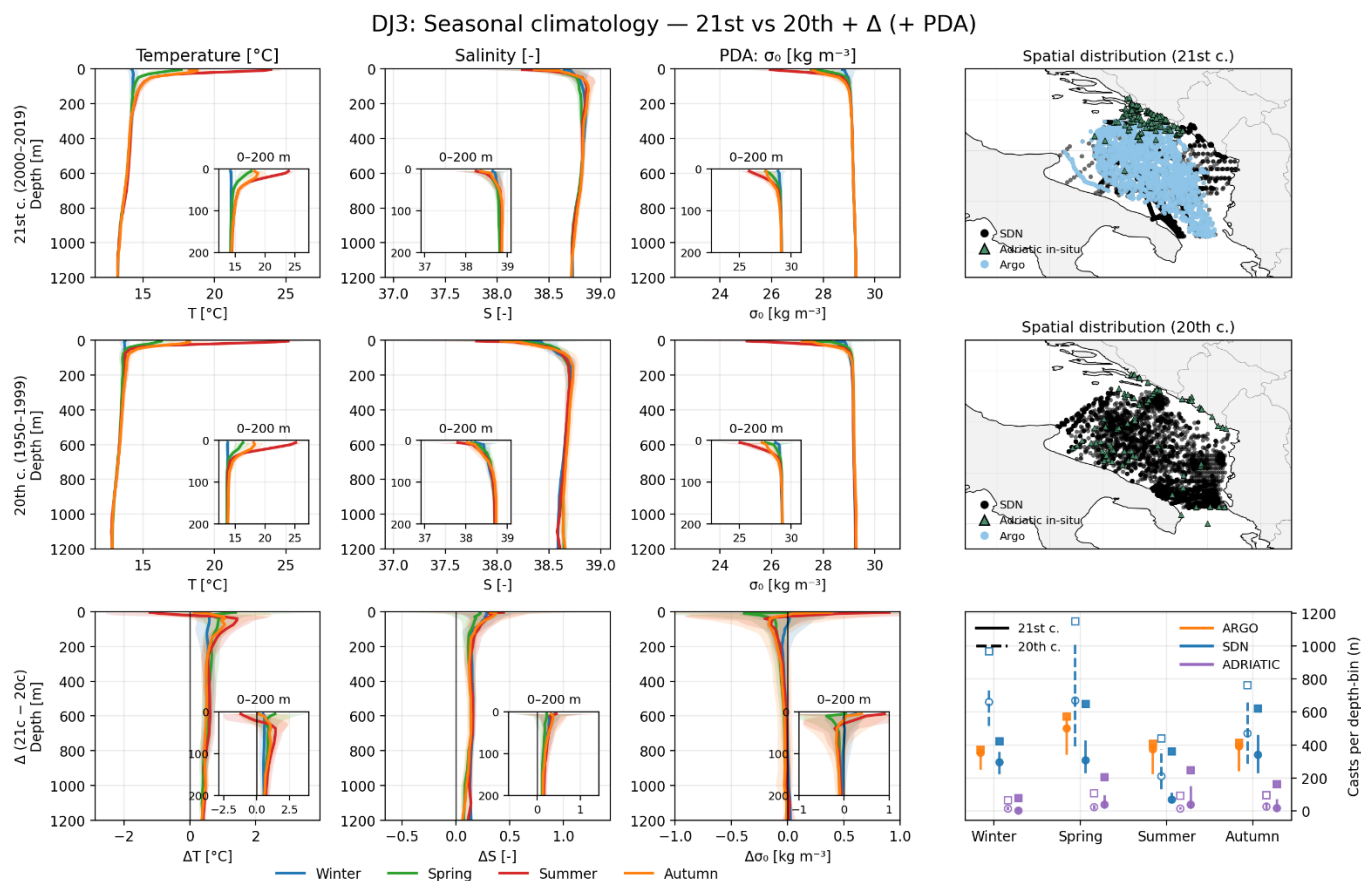
A strong increase in salinity in the Adriatic Sea was initially observed in 2017, a half-decade after a centennial dense water generation event in the northern Adriatic in 2012 (Mihanović et al., 2013), which was so strong to rapidly affect the BiOS



125 regime in the northern Ionian Sea (Gačić et al., 2014). 2017 was particularly dry year, during which salinity maxima was for  
the first time documented at the surface. The maxima have been driven by high evaporation, low vertical mixing (weaker  
winds) and lower-than average river discharges (Mihanović et al., 2021; see details in Section 3.3). Such conditions had been  
very rarely observed previously, even in the well-surveyed Palagruža Sill transect (e.g., during strong Adriatic ‘ingressions’,  
i.e., Zore-Armanda, 1991; Zore-Armanda et al., 1991; Artegiani et al., 1997). In 2017, salinity exceeded 39.0 over most of the  
130 surface layer of the Southern Adriatic Pit (SAP) between late spring and mid-autumn, including most of the Palagruža Sill  
transect (Mihanović et al., 2021). The consequences for the biogeochemical cycles were also considerable, as bacterial  
abundances in coastal eastern Adriatic regions departed from average values by several standard deviations (Beg-Paklar et al.,  
2020). Several other notable thermohaline features were found to precede such conditions, including the occurrence of double  
salinity maxima, of which the upper and stronger maximum was located at relatively shallow depths (50–200 m; Lučić et al.,  
135 2017; Kokkini et al., 2020). Indeed, the depth of this maximum, associated with the inflow of LIW and Cretan Intermediate  
Water (CIW; Schroeder et al., 2024), decreased significantly. Furthermore, salinity at this maximum increased continuously,  
reaching values exceeding 38.9 over most of the deep southern Adriatic (see, e.g., Argo profiling float data available in near  
real-time from the Euro-ARGO ERIC data portal, <https://dataselection.euro-argo.eu/>, last accessed 27 May 2026). The  
spreading of these saline waters towards deep layers has been facilitated both (1) by enhanced salt fingering and weakened  
140 stratification from intermediate to deep layers (Amorim et al., 2024; Terzić et al., 2025a), and (2) dense water cascading from  
the northern Adriatic that rapidly change near-bottom thermohaline properties in the whole deep Adriatic (see more in Section  
3.4).

When comparing thermohaline climatologies of the 21st and 20th centuries (Fig. 1), the increase in SAP salinity is clearly  
evident. Salinity in the 21st century increased quasi-uniformly by approximately 0.10–0.15 at depths below 150 m (Fig. 1),  
145 while the increase was largest in the surface and subsurface layers, averaging up to 0.4. This increase may be attributed to  
more frequent formation of surface saline lakes (see Section 3.3) and to the shoaling of the LIW/CIW inflow, from  
approximately 200–400 m to 50–150 m. This pronounced shoaling is presumably driven by several observed features: (i)  
weakening of vertical mixing in the Adriatic Sea due to enhanced stratification and reduced wind forcing (Pomaro et al., 2018;  
da Costa et al., 2023), which promotes a shallower salinity maximum; and (ii) the spreading of LIW/CIW at shallower depths  
150 in the Levantine, Aegean, and Ionian Seas, with these waters subsequently entering the Adriatic through the Strait of Otranto  
(Kubin et al., 2019; Fach et al., 2021). The latter mechanism has been documented in numerous studies, as significant changes  
in heat and mass budgets at the LIW/CIW source regions have led to strong salinification of the entire eastern Mediterranean  
over the past decade (Skloris et al., 2025). These increasingly saline waters then propagate into the Adriatic (and other basins;  
Mallil et al., 2022), rapidly altering its thermohaline and biogeochemical properties there.

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**Figure 1. Seasonal profiles of temperature, salinity and potential density anomaly (PDA) in the 21st and the 20th century in the southern Adriatic (also referred as the Mediterranean region DJ3 by Manca et al., 2004) constructed using all available in situ data sources. Right column visualises spatial distributions of the data (SDN stands for SeaDataNet) and data statistics (bottom right): mean (rectangles), median (circles) and range in data casts (vertical lines), with full and empty/dashed symbols and lines for 21st and 20th century, respectively.**

As the eastern Mediterranean has experienced substantial warming in recent decades (Kubin et al., 2023), LIW/CIW cores entering the Adriatic Sea are also characterized by markedly higher temperatures, reaching up to 1.5 °C in subsurface layers of the southern Adriatic during summer (Fig. 1). Note that average temperatures may decrease at the very surface (0 m) in the 21st century; however, this may result from a sampling bias associated with different data types and spatial data distributions. For example, Argo floats normally do not measure at the exact surface (the first bin is typically a few metres below the surface). The intensified increase in near-surface heat content is not unexpected, as surface layer warming has been amplified by the Atlantic Multidecadal Oscillation over the past four decades (Vilibić et al., 2019; Pastor et al., 2020; Pisano et al., 2020). Because these cores are now shallower, LIW temperatures in the Adriatic are influenced by both lateral heat advection from



the Ionian Sea and direct heating of the upper portions of this layer, which are now located within the euphotic zone (Buljan and Zore-Armanda, 1976; Kovač et al., 2018; Ozer et al., 2022). Consequently, nutrients supplied by LIW/CIW to the Adriatic (Marasović et al., 1995; Civitarese et al., 2010; Ljubimir et al., 2017) may be partially consumed before entering the basin, potentially altering the Adriatic Sea's biogeochemical balance. Such trends are following globally observed climate-driven strengthening and redistribution of upper-ocean stratification that alters the depth and structure of the nitracline and phosphacline, changing upper-ocean nutrient availability and biological utilization (Gerace et al., 2025).

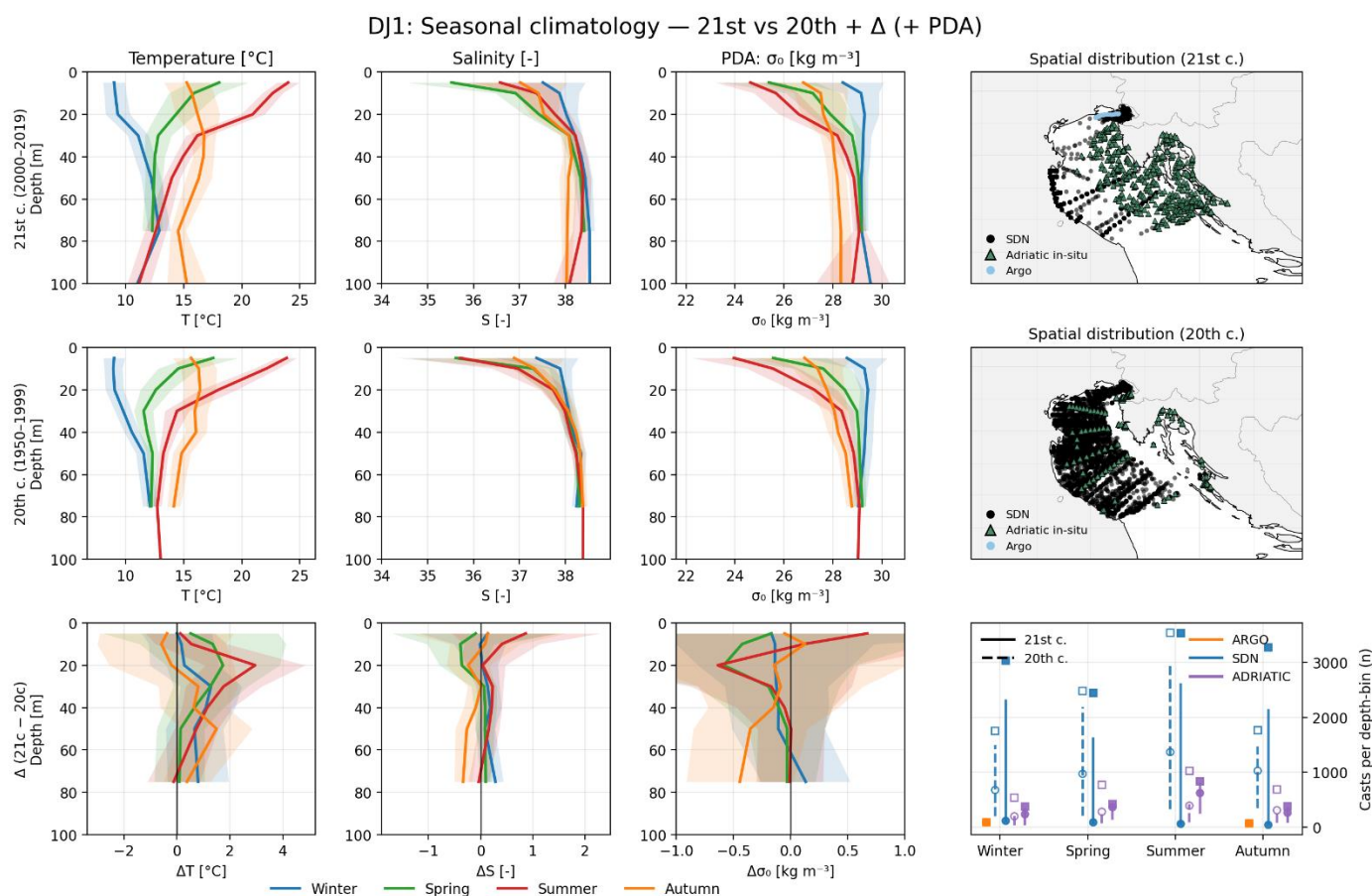
At depths below 200 m, the temperature in the southern Adriatic is increasing steadily between the 21st and 20th centuries across seasons, and equals 0.4–0.6 °C (Fig. 1). Such an increase indicates thorough and quasi-uniform warming of the entire deep Adriatic, which was already documented in the 20th century (Lipizer et al., 2014), accelerated at the turn of the century, and intensified in deep layers over the past decade (Terzić et al., 2025a). Interestingly, density does not change substantially in deep layers (below 600 m, Fig. 1), as temperature-induced lightening is fully compensated by salinity-induced densification. However, in the 21st century, thermosteric expansion is much stronger than halosteric contraction at subsurface and intermediate depths (20–400 m, Terzić et al., 2025a), reaching a maximum at the LIW/CIW core (density decrease of approximately 0.2 kg m<sup>-3</sup>). Over the entire water column, density has been found to decrease on average, consistent with climate projections for the Adriatic and potentially contributing to future sea level rise (Sannino et al., 2022).

### 3.2 Thermohaline changes in the northern Adriatic

A long (several decades) time ago, the northern Adriatic shelf, being under strong impact of large rivers—primarily of the largest Adriatic river, Po River, draining one third of riverine freshwaters into the Adriatic (Raicich, 1996; Janeković et al., 2014)—has been recognized as an eutrophic area in which primary production is driven by large nutrient load (Degobbis and Gilmartin, 1990; Franco and Michelato, 1992; Degobbis et al., 2000; Solidoro et al., 2009). Due to heavy freshwater load, seasonal salinity changes were quite large, with higher values during winter in which horizontal/barotropic processes were dominant, while thermally-driven stratification favours off shore spreading of freshwaters towards the eastern coastline during warm part of a year (Kourafalou, 1999). For that reason, salinity in the eastern section of the northern Adriatic (off the city of Rovinj) ranged in the 20th century from 36.5±2.0 during summer to 37.8±0.3 during wintertime (Supić et al., 2004), while bottom salinity was quasi-steady and hitting values around (37.6-37.8) ± (0.3-0.4) throughout a year. The latter has been the result of the inflow of more saline waters from the middle Adriatic, which partially took their path inside the shelf (Orlić et al., 1992). Historical climatology (up to 1980s) based mostly on the western Adriatic data (Artegiani et al., 1997) gives the range for mean surface salinity between 35.4 during summer and 37.3 during winter, while the deep values range between 38.0 and 38.2 (at 30 m). Still, this climatology was encompassing the whole northern Adriatic shelf, from the middle Adriatic depressions, and is not comparable to the climatology off the city of Rovinj. However, these values have changed rapidly in the last decade or so, including rapid oligotrophication observed in the last two decades (Vlašiček et al., 2025). There are



several reasons for that: (i) Adriatic-wide changes that affect also the northern Adriatic over yearly scales (Vilibić et al., 2020), and (ii) reduced freshwater load, in particular during some years such as 2022 (Bonaldo et al., 2023; Aragão et al., 2024).



**Figure 2. As in Fig. 1, but for the northern Adriatic (also referred as the Mediterranean region DJ1 by Manca et al., 2004).**

When examining the available in situ temperature and salinity data in the northern Adriatic in the 20th and 21st centuries (Fig. 2; data sources are the same as in Fig. 1), an overall warming trend is apparent despite the large variability expected over wide shelves and rapidly changing regions. As observed in the southern Adriatic, warming in the northern Adriatic is most pronounced in the subsurface layers (10–30 m), where—particularly during summer—21st century temperatures exceed 20th century values by up to 3 °C. In deeper layers, where waters are primarily advected from the southeast, the temperature increase reaches up to 1 °C, similar to the subsurface warming observed in the southern Adriatic.



215 It should be noted that the sampling distributions vary somewhat between the two centuries, which may introduce biases into the thermohaline climatologies. In particular, 20th-century samples are more concentrated along the western coastline, where freshwater discharges, especially from the Po River, occur (Artegiani et al., 1997). However, such biases are likely to primarily affect salinity, which is generally higher along the eastern coastline (Vilibić et al., 2019).

220 Despite these potential biases, salinity exhibits an increasing tendency in the surface layers, reducing the seasonal differences between summer, when Po River waters spread across the open northern Adriatic, and winter, when these waters are largely confined to the western coastline. Surface salinity increase is most pronounced during summer, which might be reflect—in addition to the changes in freshwater load and dynamics (Montanari et al., 2023)—the increased evaporation in the 21st century (Skiris et al., 2018; Kraus et al., 2019). Apart from summer surface increase, the salinity changes appear to be moderated by enhanced baroclinicity of the water column, which tends to redistribute freshwater more toward the  
225 northern Adriatic and retain it there—thereby decreasing salinity—rather than transporting it along the coastline toward the middle and southern Adriatic (Vilibić et al., 2019). Thermosteric expansion exceeds halosteric contraction, resulting in a general decrease in water density. However, the recent decline in sea level in the northern Adriatic has been attributed to a deficit in the regional water budget, a trend projected to persist in the future (Verri et al., 2024), while steric effects are likely of limited importance in such shallow regions.

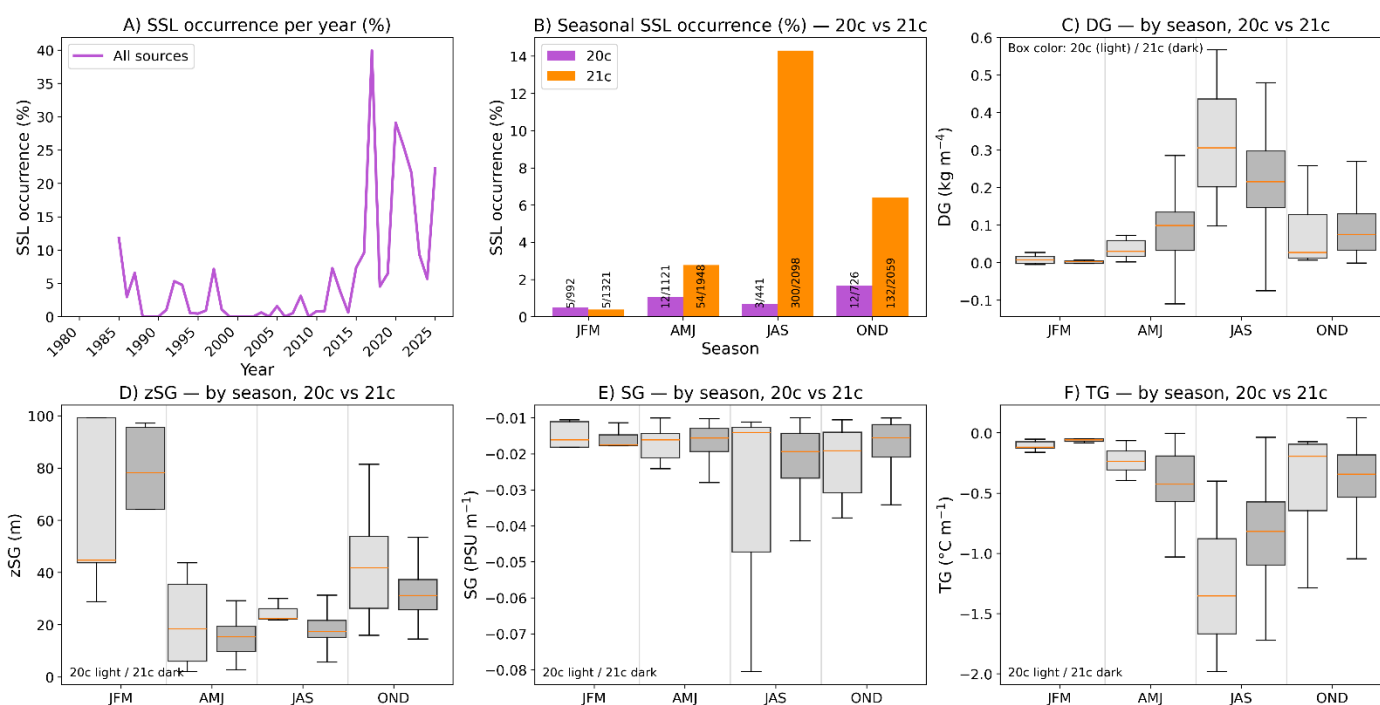
### 230 3.3 Frequent occurrence of surface saline lakes

Surface saline lakes (SSLs), a term coined by Terzić et al. (2025b), resemble near-surface stratifications (e.g., down to ~200 m) in which surface-layer salinity strongly exceeds the salinity below a very sharp negative halocline. The positive density stratification is maintained by strong heat accumulation in the surface layer, such that temperatures in the upper layer are significantly higher than below the strong thermocline, which typically coincides with the negative halocline. The thermocline,  
235 halocline and pycnocline are spanning over thin vertical section, typically a few metres wide, and all occurring at the same depths with rates of changes that may exceed (for extreme manifestations)  $-0.5\text{ °C m}^{-1}$ ,  $-0.05\text{ m}^{-1}$  and  $0.2\text{ kg m}^{-3}\text{ m}^{-1}$ , respectively (Terzić et al., 2025b). SSLs are generated during springtime heating under conditions of weak wind-driven mixing, when enhanced solar heating is followed by increased evaporation and the separation of the surface (10–20 m) layer from the underlying water column. During summer and early autumn, these features may intensify as heat accumulation and water  
240 losses increase, while they are typically deepened and eventually destroyed during autumn or early winter. The destruction is preconditioned by a weakening of pycnocline intensity at SSL's basement due to salinity increase and temperature decrease in autumn, allowing from wind-driven mixing to break the stratification during first intense storms hitting a region. SSLs are expected to occur mostly occurring at the open ocean, while freshwater discharges may prevent their occurrence in coastal regions, or regions affected by freshwater load (which may nullify the salinity increase near the surface). In a way, SSLs are a  
245 phenomenon opposing to barrier layers observed in the tropical oceans (Sprintall and Tomczak, 1992), in which surface freshening on top of thermally-driven pycnocline is increasing the stratification.



SSLs are frequently observed in the Levantine Basin (Kassis and Korres, 2020) and appear to be common in other Mediterranean basins as well, including the Adriatic Sea (Terzić et al., 2025b). In the era of climate change, characterized by enhanced evaporation, reduced precipitation, and decreased river discharge across most of the Mediterranean (Skliris et al., 2018; Soto-Navarro et al., 2020; Mamoutos et al., 2022; Liu et al., 2025), the frequency of occurrence of SSLs appears to be increasing compared to the 20th century. However, this increase may include biases due to major shifts in observational capabilities (e.g., Argo profiling floats versus shipborne and moored measurements; Tintoré et al., 2019).

Surface saline lakes may play a crucial role in maintaining downward salt fluxes from the surface to deeper layers, thereby modifying the properties of Levantine Intermediate Water (LIW) and Cretan Intermediate Water (CIW) and contributing to the overall salinization of the Mediterranean Sea (Fedele et al., 2022). In the Adriatic Sea, such conditions have historically been detected during dry and hot years, associated with reduced river discharge, enhanced evaporation, and strong inflow of saline waters from the Ionian Sea, i.e., during cyclonic BiOS regimes (Mihanović et al., 2021).



260 **Figure 3. Percentage of surface saline lakes (SSLs, as defined by Terzić et al., 2025b) occurrence in the upper ocean layer in the southern Adriatic detected on available shipborne CTD and Argo profiling float data between 1985 and 2025: yearly percentage in all casts (top left), separately for 20th and 21st century and seasons (numbers denote number of SSLs per number of casts, top middle), and 21st vs. 20th century seasonal box plots for SSL’s density gradient (DG, top right), depth (zSG, bottom left), salinity gradient (SG, bottom middle) and temperature gradient (TG, bottom right).**

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Following the methodology introduced by Terzić et al. (2025b), and using all available high-resolution vertical temperature and salinity data from the southern Adriatic (CTD data obtained from the SeaDataNet Pan-European Infrastructure, local Adriatic databases, and Argo data collected by Euro-ARGO ERIC), the number of SSLs appears to have been relatively low during the 20th century, with a maximum yearly percentage occurrence of up to 10% (Fig. 3). Such a low percentage also persisted at the beginning of the 21st century, until 2017, after which the percentage began to exhibit strong interannual variability, ranging between 5% and 30–40%. This variability is presumably associated with pronounced interannual differences in late-spring to early-autumn surface forcing (surface heating, precipitation and river discharge, and wind-induced vertical mixing). As previously documented, 2017 stands out as the onset year of strong Adriatic SSLs (Mihanović et al., 2021), after which SSLs began occurring much more frequently. Seasonally, the increase in SSL occurrence is most prominent during summer (July–September), by roughly an order of magnitude, while increases are also observed in autumn (October–December) and, to a lesser extent, in spring (April–June). A minimal SSL percentage persists during winter in both centuries, and the absence of any detectable increase likely indicates that vertical mixing during winters did not weaken between the two periods. Salinity gradients gradually develop from spring towards autumn, indicating that evaporation is constantly taking the water from the upper ocean layer. The temperature, however, show typical seasonality driven by heat fluxes: weak SSL temperature gradients (TG) in spring, during the formation of SSLs, and in autumn, during the deterioration of SSLs, while being the strongest during summer. Such gradients are similar to average thermocline seasonality in the Adriatic (Buljan and Zore-Armanda, 1976; Artegiani et al., 1997), which—together with seasonality of SSL salinity gradients—indicate that SSL deterioration is preconditioned by temperature decrease and salinity increase in autumn, resulting in weakening of SSL’s pycnocline and allowing for wind-induced vertical mixing to break up the stratification of SSLs in full.

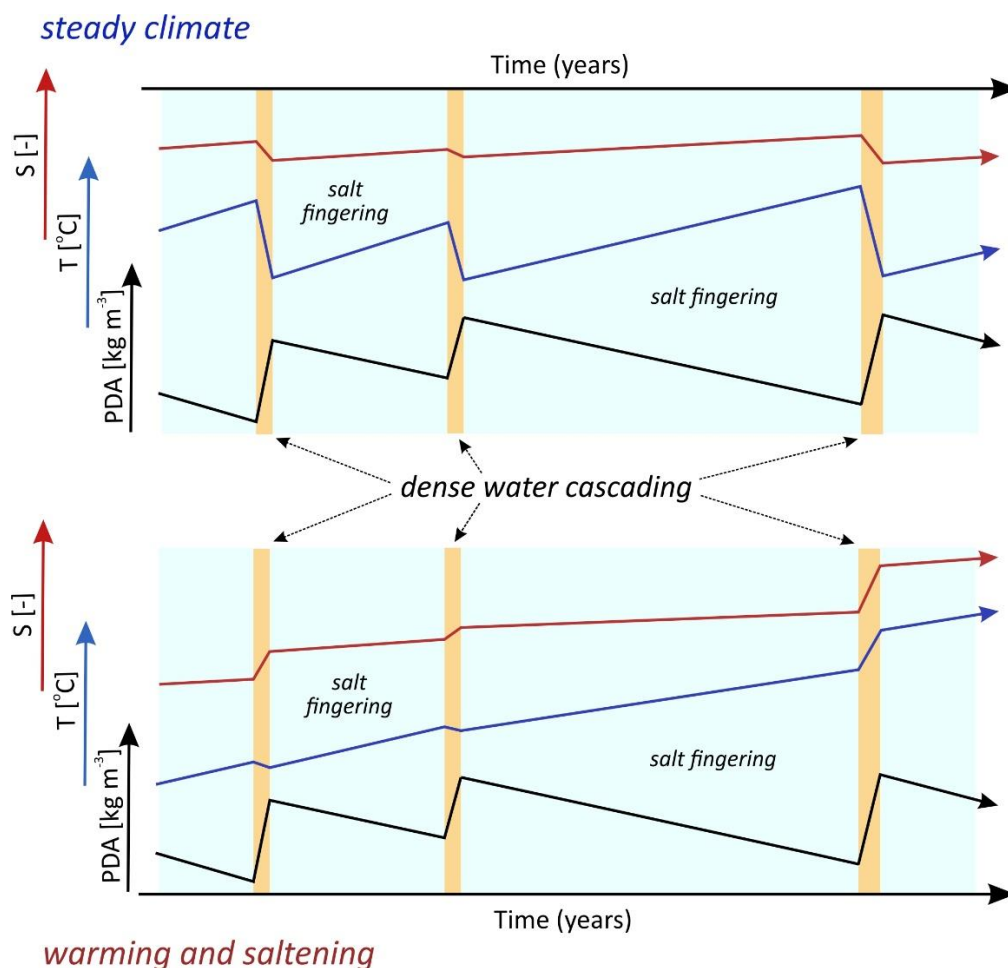
When comparing 21st vs 20th century box plots in Fig. 3, the structure of SSLs changed slightly between the two centuries. The depth of the SSL (zSG) decreased by 15–25% in summer and autumn, suggesting that SSLs became shallower, thereby retaining heat and salt closer to the surface. Salinity gradients (SGs) show a general strengthening during summer but weakening during autumn and spring, while the associated temperature gradients (TGs) exhibit the opposite behaviour. This pattern suggests a predominance of temperature effects during the SSL formation phase in spring, after which salinity plays a greater role in maintaining the SSL structure during summer, while decreasing the stratification intensity during autumn (as SSL’s temperature are decreasing in that part of a year). Temperature again appears more influential during the SSL decay phase in autumn, implying that warmer autumn conditions may prolong stronger ocean stratification. Finally, density gradients (DGs) show a decrease during summer, which may be linked to weaker summertime winds and reduced precipitation and basin-wide river discharge in 21st century, which have already been documented in both present conditions as well as projected future climates (Soto-Navarro et al., 2020; Bonaldo et al., 2023; Montanari et al., 2023; da Costa et al., 2024; Tojčić et al., 2024).

### 3.4 Haline-driven dense water cascading



Dense water generation in the northern Adriatic and the cascading of North Adriatic Dense Water (NAddW) have been  
300 recognized for decades as key processes maintaining ventilation and oxygenation of most near-bottom Adriatic waters (Zore-  
Armanda, 1963; Buljan and Zore-Armanda, 1976; Vilibić et al., 2023). Dense waters are generated in two main regions of the  
northern Adriatic: (i) the shallow northern Adriatic shelf (Vested et al., 1998; Beg Paklar et al., 2001; Kuzmić et al., 2007;  
Benetazzo et al., 2014), where severe bora events cool shallow waters to temperatures as low as 4 °C (Vatova, 1934; Mihanović  
et al., 2013; Raicich et al., 2013), occasionally producing potential density anomalies (PDAs) close to or exceeding 30 kg m<sup>-3</sup>;  
305 and (ii) a deeper (up to ~100 m) coastal region of the northeastern Adriatic, recently identified as a secondary dense water  
formation site, where bora-induced cooling is particularly intense (Grisogono and Belušić, 2009; Janeković et al., 2014;  
Mihanović et al., 2018). Due to strong thermal forcing, these waters reach high densities, spread along the bottom as density  
currents (Nof, 1983), and cascade into the Adriatic depressions, namely the Jabuka Pit and the South Adriatic Pit (Artegiani  
and Salusti, 1987; Marini et al., 2006; Langone et al., 2016; Pranić et al., 2024). At the bottoms of the Jabuka and South  
310 Adriatic pits, a characteristic pattern emerges, consisting of rapid dense-water cascading (lasting several months) followed by  
slower restoration phases (from years to decades) governed by double-diffusive and other mixing processes (Amorim et al.,  
2024). This behaviour is commonly referred to as the saw-tooth pattern (Querin et al., 2016; Mihanović et al., 2018).

Until about a decade ago, the saw-tooth pattern was primarily thermally driven, as density variability in the Adriatic  
depressions was dominated by cooling in the northern Adriatic, resulting in cascading waters of higher density due mainly to  
315 lower temperatures (Fig. 4 upper plot; the scheme is based on Querin et al., 2016). However, this regime has changed over the  
past decade due to salinization of NAddW formation sites in the northern Adriatic (see previous chapters). Concurrently, since  
2012, winters and associated bora events have not reached historical levels of severity or duration, including reduced rates of  
heat loss from the sea (Terzić et al., 2025a). A decline in bora wind intensity and frequency—combined with reduced  
freshwater discharge and enhanced evaporation—has been projected by numerous climate studies, including regional ensemble  
320 simulations (Bonaldo et al., 2017; Belušić Vozila et al., 2019; Moulin et al., 2024) and kilometre-scale climate models  
(Denamiel et al., 2020). As a result, the dense waters formed in 2017, 2018, and 2022 were predominantly haline-driven,  
produced by relatively weak wintertime cooling of highly saline waters in the dense water formation regions (Terzić et al.,  
2025a). These haline-driven dense waters were observed to cascade into the Adriatic depressions, reaching even the ~1200 m  
deep South Adriatic Pit, where newly formed waters exhibit higher salinity and substantially higher temperatures than the  
325 resident deep waters (Le Meur et al., 2025; Martellucci et al., 2025a). This shift has resulted in an inversion of the traditional  
saw-tooth pattern, which now departs markedly from its classical form (Fig. 4 bottom plot; the scheme is based on Terzić et  
al., 2025a).



330

**Figure 4. Saw-tooth modulation over time at the bottom of the Southern Adriatic Pit, showing dense water cascading and intermittent periods of salt-fingering double diffusion, before early 2010s (up, for PDA adopted from Querin et al., 2016) and in the warming and saltening climate as observed in the last decade (bottom).**

#### 4 Potential consequences

##### 335 4.1 Water density and sea level changes

The documented changes in temperature and salinity are expected to affect sea level trends in the Adriatic Sea (and beyond), particularly in the deep southern Adriatic. Historically, sea level trends in the Mediterranean have been somewhat lower than global trends, largely due to sterically driven increases in seawater density (Tsimplis and Baker, 2000; Marcos and Tsimplis, 2008). An increase in density was also observed in the deep Adriatic until the early 2000s; however, this trend reversed



340 thereafter (Terzić et al., 2025a). Recent estimates indicate that thermosteric expansion of the water column amounts to approximately 2.0 cm yr<sup>-1</sup>, slightly exceeding halosteric contraction estimated at about 1.7 cm yr<sup>-1</sup> (Terzić et al., 2025a). Together with increasing mass input into the Mediterranean Sea (Sannino et al., 2023; Parras-Berrocal et al., 2025), these processes may result in a somewhat higher rate of sea level rise compared to previous decades, not just in the Adriatic Sea but in the Mediterranean Sea.

345 Nevertheless, at least in the northern Adriatic, recent strong salinization and reduced river discharge have resulted in a water deficit, which has been shown to reduce the rate of sea level rise (Verri et al., 2024). Whether this trend will persist in the future, as projected by climate simulations (Zanchettin et al., 2021), remains uncertain, as even decadal-scale increases in freshwater discharge may substantially alter present trends (Rubinetti et al., 2022). Under such scenarios, and in combination with the phasing of different contributors to extreme sea levels (e.g., tides, storm surges, seiches; Šepić et al., 2022), coastal  
350 flooding in the Adriatic could increase markedly, particularly in historic cities with valuable cultural heritage (Reimann et al., 2018). Moreover, the increasing frequency of MOSE barrier closures in the Venice Lagoon may have severe ecological consequences (Cibic et al., 2025), not only for the lagoon itself but also for other low-lying Adriatic coastlines (Krvavica and Ružić, 2020; Favaretto et al., 2025).

#### 4.2 Biogeochemical implications

355 The observed physical changes may have several biogeochemical consequences. First, the increased occurrence of surface saline lakes may strongly reduce vertical fluxes of dissolved oxygen, nutrients, and carbon between surface and subsurface or intermediate layers (Jacox and Edwards, 2011; Breitburg et al., 2018; Bourgeois et al., 2022). Such reductions may substantially alter primary production and microbial food webs (Beg Paklar et al., 2020) and decrease the ocean's capacity for carbon uptake (Cantoni et al., 2024; Martellucci et al., 2025b). Furthermore, changes in the characteristics of North Adriatic  
360 Dense Water (NAddW) and its cascading into deep layers may affect oxygen, sediment, and carbon fluxes, as these processes are closely linked to dense water formation events (Ingrosso et al., 2017; Paladini de Mendoza, 2023). For instance, warmer dense waters may transport less oxygen to deep ecosystems, including those in major Adriatic nursery areas such as the Jabuka Pit depressions (Chiarini et al., 2022a,b). In addition, a stronger haline contribution relative to thermal forcing in dense water formation may alter the intensity and frequency of cascading events. Reduced cooling requirements for dense water formation  
365 could locally enhance deep-layer ventilation, contrary to projections from regional climate models that suggest an overall decline in dense water formation and a shallowing of the Adriatic thermohaline circulation (Parras-Berrocal et al., 2023).

In the shallow northern Adriatic, extreme precipitation events may produce pronounced peaks in freshwater discharge and—as observed in 2024—result in rapid transport of freshened waters over strongly stratified, warm, and saline surface layers. Such events may trigger sudden phytoplankton blooms and mucilage formation when these waters reach the eastern  
370 Adriatic coastline (Vilibić et al., 2025; Neri et al., 2025). Future mucilage events may thus become rarer but more intense, occurring mainly during extreme springtime precipitation episodes, with strong impacts on tourism, fisheries and human health



along the Adriatic coast (Rinaldi et al., 1995; Funari and Ade, 1999; Giani et al., 2005, 2012). Overall, increasing stratification in the northern Adriatic may reduce vertical fluxes of oxygen, carbon and nutrients, leading to non-linear ecosystem responses (Vichi et al., 2003) and further oligotrophication (Mentaschi et al., 2024).

375 In the deep Adriatic, a shoaling of Levantine and Cretan Intermediate Water (LIW/CIW) inflows could bring these waters closer to the euphotic zone. If such shoaling also occurs in the Ionian Sea, nutrient concentrations may decrease, promoting further oligotrophication of the Adriatic. Conversely, if the LIW/CIW core remains deeper in the Ionian prior to entering the Adriatic, these waters may locally enhance primary production in the South Adriatic Pit through nutrient supply. Similar effects of LIW shoaling on primary production have already been documented in the Levantine Basin (Ozer et al., 2022; Reich et al., 380 2026).

#### 4.3 Shifting regional climate and oceanic feedbacks

Changes in heat and freshwater exchange between the Adriatic Sea and the atmosphere due to ocean warming may induce substantial impacts on surrounding continental regions, particularly in terms of extreme events (Iakunin et al., 2021; Kunkel et al., 2022; Yang et al., 2024). This is especially relevant for phenomena such as snow enhancement over the Apennines 385 during persistent bora events (Davolio et al., 2017) and increased precipitation intensity along Adriatic coastlines (Ivatek-Šahdan et al., 2018). Warming of the Adriatic Sea surface is expected to enhance moisture fluxes into the atmosphere, and regional climate projections consistently indicate an increase in extreme precipitation events along surrounding coasts (Fedele et al., 2024; Ivušić et al., 2024). Changes in precipitation seasonality, including altered snowfall and snowmelt regimes, are projected to modify river discharge patterns and flood frequency (Tramblay et al., 2022), leading to increased intensity and 390 destructiveness of flash floods (Ojeda et al., 2022).

Beyond direct terrestrial impacts, intense precipitation events may strongly affect coastal marine systems by delivering large amounts of nutrients and sediments over a short period, thereby enhancing rapid productivity in an already warming coastal ocean (Gao et al., 2023). These effects are likely to be particularly pronounced on the northern Adriatic and Albanian shelves, as well as in estuaries and river deltas (Wetz and Yoskowitz, 2013)—from the Po River delta to smaller systems such 395 as the Jadro catchment, the Ofanto estuary and the Krka estuary in the Middle Adriatic (Aragão et al., 2024).

Closely linked to ocean surface warming, increased evaporation relative to precipitation, and declining mean river discharge, a projected rise in the frequency and intensity of surface saline lakes in the Adriatic and Mediterranean may further amplify marine heatwaves, which are already expected to increase substantially (Darmaraki et al., 2019; Denamiel, 2025). These trends are anticipated to exert strong impacts on marine biogeochemistry and ecosystems (Smith et al., 2023).

#### 400 4.4 Biological effects, fisheries and aquaculture

A substantial increase in bottom water temperature and salinity driven by changes in NAddW source properties has the potential to significantly alter Adriatic benthic ecosystems. Deep-sea ecosystems and marine protected areas are particularly



vulnerable to temperature increases (Chimienti et al., 2021; Kružić et al., 2025), with elevated mortality rates already linked to warming (Kružić et al., 2016). Overall, these changes may substantially reduce Adriatic benthic biodiversity, in line with trends observed across the Mediterranean Sea (Chatzimentor et al., 2022; Hassoun et al., 2025).

In response to warming, some benthic species are migrating toward northern Adriatic coastlines (Matić-Skoko et al., 2022; Bellin and Rossi, 2024). However, the availability of suitable cold refugia is limited. For instance, the middle Adriatic depressions serve as nursery areas for many cold-adapted benthic species (Ercegović, 1956–1958; Chiarini et al., 2022a,b), whose survival depends on the regular renewal of bottom waters by NAddW. As these species cannot migrate further north, they face either adaptation to warmer and more saline conditions or local extinction. Some of these species are commercially exploited (Martinelli et al., 2023), and their decline may substantially impact Adriatic fisheries under future climate conditions, as already observed in the present climate (Kamberi et al., 2025).

The spreading of larvae along the pycnocline may also be influenced by projected increases in stratification and water-column stability, particularly those associated with the strengthening of surface saline lakes. The migration of many organisms is strongly related to stratification intensity (Röpke et al., 1993; Guillam et al., 2020; Barrier et al., 2024; Granata et al., 2024). A more stable and intensified pycnocline may inhibit vertical migrations, while increasing the potential for horizontal transport. In addition to benthic organisms, increased mortality of other marine species has been linked to ocean warming in the Adriatic. For example, elevated temperatures in coastal waters, river deltas, and estuaries have triggered mass mortality events in mussels (Capriotti et al., 2025). Strong freshwater flushing of estuaries during flash floods may further impact aquaculture activities, including mussel farming (Marguš and Teskeredžić, 1986; Cetinić, 2024). Overall, the impacts of climate change on Adriatic fisheries and aquaculture are diverse and complex (e.g., Santojanni et al., 2006; Dragičević et al., 2017; Cavraro et al., 2023; Haberle et al., 2024; Kamberi et al., 2025). Beyond the physical processes discussed here, many additional factors contribute to these changes and are therefore not addressed in this study.

#### 4 Concluding Remarks

This article documents several tremendous changes in the Adriatic physical properties and dynamics that are documented to occur in the last decade or so: (1) salinization and warming of the Adriatic, in particular of northern Adriatic shallow regions, including changes in the saline inflow characteristics, (2) changes in the NAddW properties, with less pronounced thermal effect in its generation compared to the haline effect, and (3) more frequent occurrence of so-called surface saline lakes, i.e., vertical stratification characterized by negative halocline near the surface that prevent any fluxes through the pronounced pycnocline. There are many other changes in the physical system, either not documented or locally connected with the observed ones, which are not discussed in this article. Impact and consequences to water density, sea level changes, biogeochemistry, and biological, fisheries and aquaculture impacts coming out of these changes are discussed, being just a selection to these connected with the presented changes among a wide impact of climate changes in the region and globally.



Instructively, the discussed impacts are not standalone in relation to other climate impacts. Therefore, a proper assessment  
435 of climate change impacts would require an assessment of compound effects and nonlinear interactions in the system (Byrne  
and Przeslawski, 2013), including adaptability of the system (i.e., marine organisms) to the changes (Somero, 2010). Further,  
the Adriatic Sea is not self-standing in respect with all discussed physical changes and consequent impact, with  
biogeochemistry, biology, fisheries and aquaculture connected with the rest of the Mediterranean and beyond (Pertesi et al.,  
2025). We hope that presenting these changes might instruct researchers to become aware of these potentially structural  
440 changes in the Adriatic physical properties and to eventually modify their research activities to take them into account.

### Author Contributions

**Ivica Vilibić:** Conceptualization; Methodology; Writing - Original Draft; Writing - Review & Editing; Funding acquisition.

**Elena Terzić:** Formal analysis; Investigation; Data curation; Visualization; Writing - Review & Editing.

### Data availability

445 The Adriatic *in situ* datasets analysed in the current study are taken from <https://zenodo.org/records/5707773>. Publicly  
available datasets were also used. Argo float observations were accessed using the ArgoPy Python library and taken from  
Euro-Argo ERIC database (<https://www.euro-argo.eu/Argo-Data-access>), which provides standardized access to the global  
Argo data system. Historical hydrographic data were obtained from the SeaDataNet aggregated dataset (version 2;  
[https://files.seadatanet.org/aggregated\\_datasets/Med\\_Sea/SDC\\_MED\\_DATA\\_TS\\_V2/](https://files.seadatanet.org/aggregated_datasets/Med_Sea/SDC_MED_DATA_TS_V2/)).

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### Competing interests

The authors declare no competing interest.

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