https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

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

Ivica Vilibić[1,2], Elena Terzić[1]

[1]Ruđer Bošković Institute, Division for Marine and Environmental Research, Bijenička cesta 54, 10000 Zagreb, Croatia
[2]Institute for Adriatic Crops and Karst Reclamation, Put Duilova 11, 21000 Split, Croatia

Correspondence to: Ivica Vilibić (ivilibic@irb.hr)

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.

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

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

to the atmosphere, land, and hydrosphere may also be amplified (Small et al., 2001; Khodayar and Hoerner, 2020; He et al., 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; 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 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 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-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., 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 et al., 2025; Khodayar et al., 2025), as well as the sustainability of local food resources, fisheries, and agriculture (Olschewski et al., 2024).

© Author(s) 2026. CC BY 4.0 License.

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

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

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

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

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 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., 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 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), 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 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 (Skliris 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.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

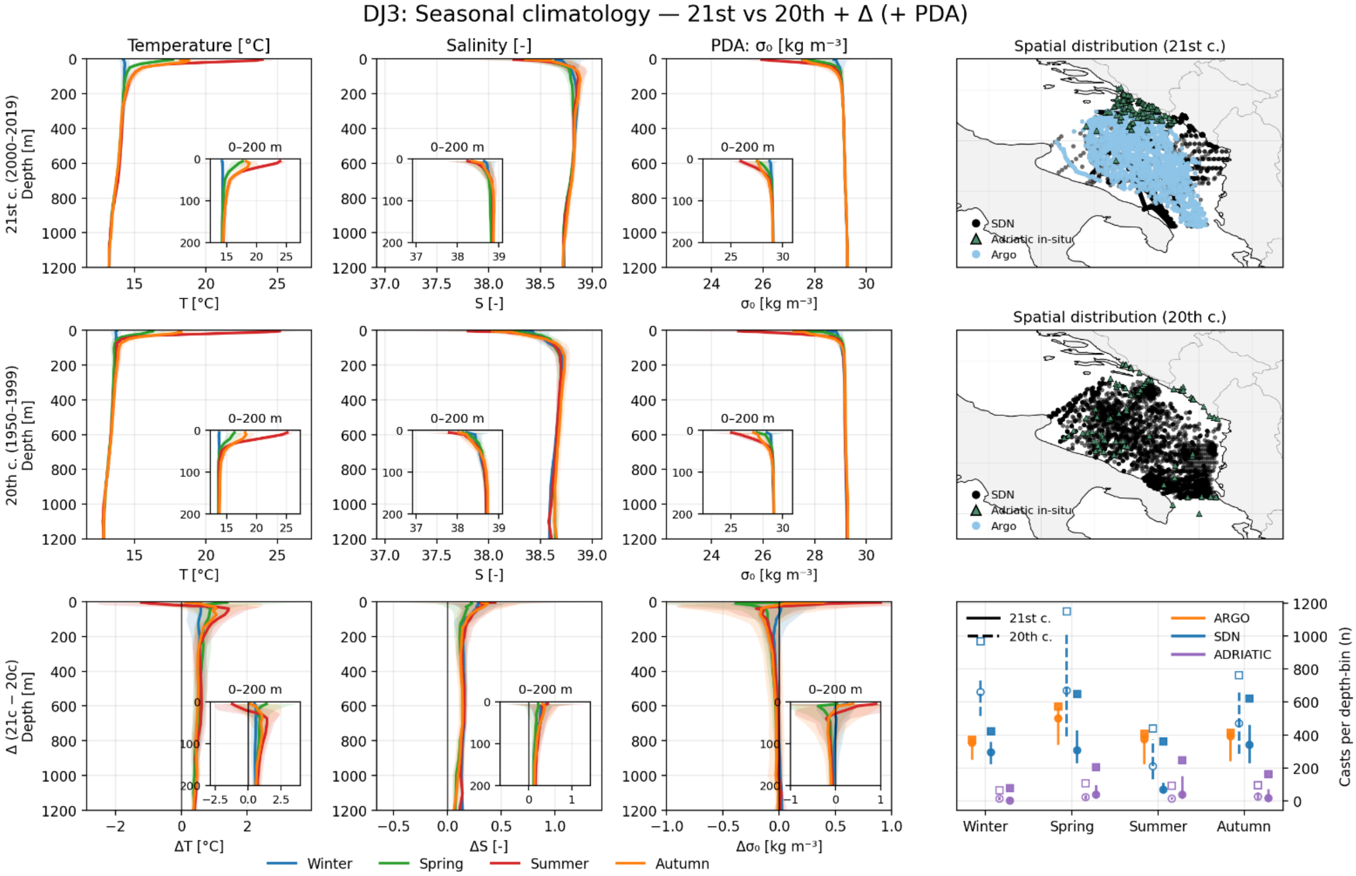

Figure 1. Seasonal profiles of temperature, salinity and potential density anomaly (PDA) in the 21st and the 20th century in the southern Adriatic (also referred as the Mediterranean region DJ3 by Manca et al., 2004) constructed using all available in situ data sources. Right column visualises spatial 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

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

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-3). 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

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

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).

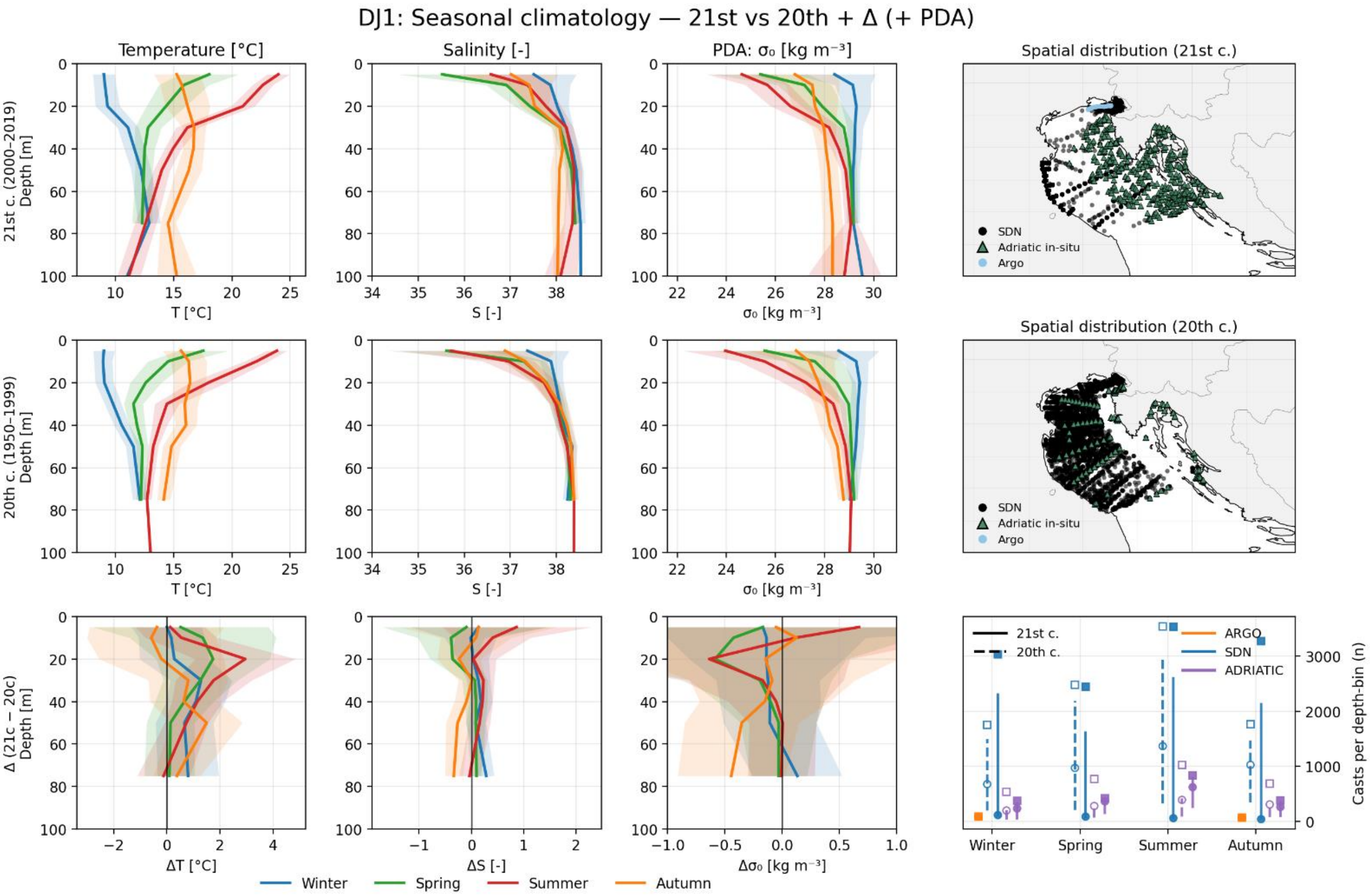

Figure 2. As in Fig. 1, but for the northern Adriatic (also referred as the Mediterranean region DJ1 by Manca et al., 2004).

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.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

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).

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 (Skliris 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 open 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.

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, 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 ^{o}C m^{-1}, -0.05 m^{-1} and 0.2 kg m^{-3} 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 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 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.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

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).

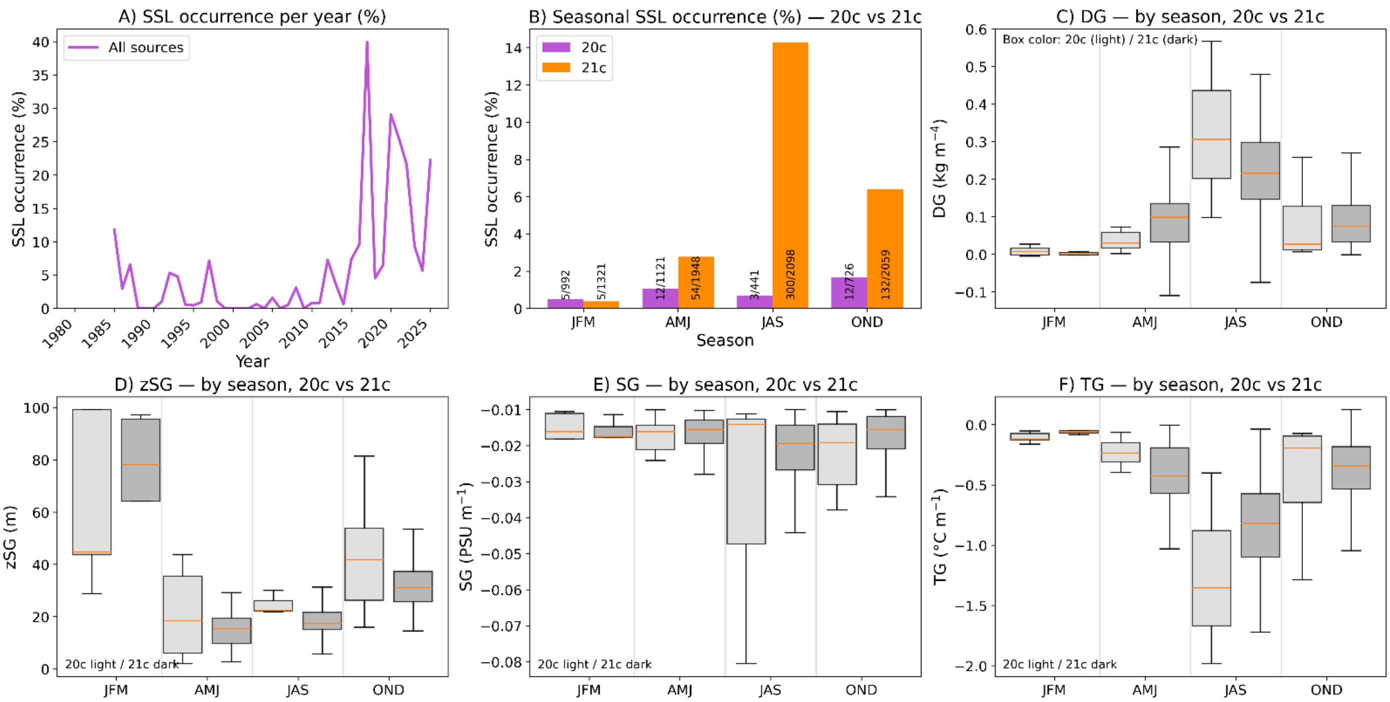

Figure 3. Percentage of surface saline lakes (SSLs, as defined by Terzić et al., 2025b) occurrence in the upper ocean layer in the southern Adriatic detected on available shipborne CTD and Argo profiling float data between 1985 and 2025: yearly percentage in all casts (top left), separately for 20th 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).

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

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

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

Dense water generation in the northern Adriatic and the cascading of North Adriatic Dense Water (NAddW) have been 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^{-3}; 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 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 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 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 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).

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

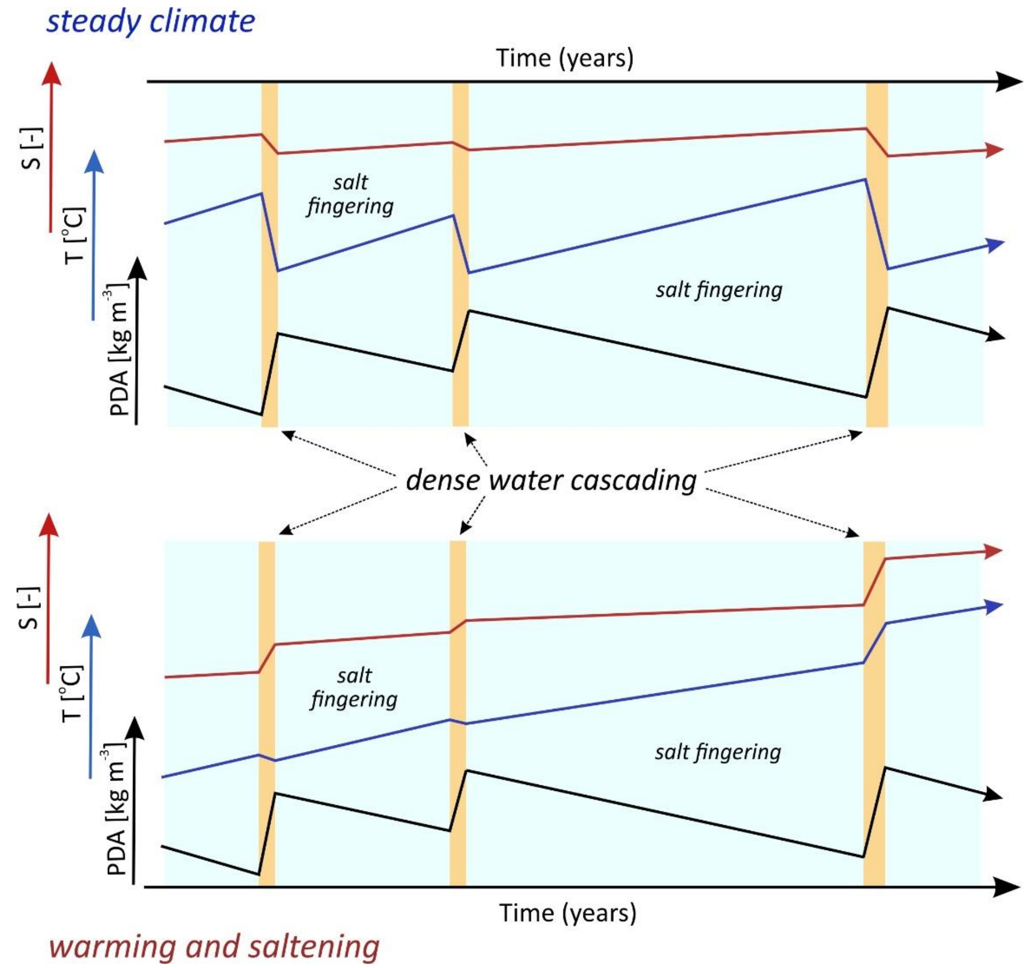

Figure 4. Saw-tooth modulation over time at the bottom of the Southern Adriatic Pit, showing dense water cascading and intermittent periods of salt-fingering double diffusion, before early 2010s (up, for PDA adopted from Querin et al., 2016) and in the warming and saltening climate as observed in the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

4 Potential consequences

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

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

thereafter (Terzić et al., 2025a). Recent estimates indicate that thermosteric expansion of the water column amounts to approximately 2.0 cm yr^{-1}, slightly exceeding halosteric contraction estimated at about 1.7 cm yr^{-1} (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.

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 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

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 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 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 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

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

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).

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., 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 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 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 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).

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

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

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.

© Author(s) 2026. CC BY 4.0 License.

Instructively, the discussed impacts are not standalone in relation to other climate impacts. Therefore, a proper assessment 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 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

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/).

Acknowledgements

We are grateful to all researchers that bring forward concepts and did hard work on the Adriatic climate studies and in collection of the ocean data. In particular, we acknowledge the provision of temperature and salinity data by the SeaDataNet Pan-European Infrastructure, https://www.seadatanet.org, Euro-ARGO ERIC, https://www.euro-argo.eu, the Institute of Oceanography and Fisheries, http://www.izor.hr, the Ruđer Bošković Institute, https://www.irb.hr, and various Italian marine research institutions.

Financial support

This research has been supported by Croatian Science Foundation through projects GLOMETS (Grant IP-2022-10-3064), C3PO (Grant IP-2022-10-9139) and the incoming mobility scheme for postdoctoral researchers (MOBDOL-2023-12), Interreg

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

Italy-Croatia Programme 2021–2027 project AdriaClimPlus (Grant ITHR0200333) and EU NextGeneration project AdriaClimRisk (Grant PK.3.4.17.0001).

Competing interests

The authors declare no competing interest.

References

Adani, M., Dobricic, S., Pinardi, N.: Quality assessment of a 1985–2007 Mediterranean Sea Reanalysis. J. Atmos. Ocean. Technol., 28, 569–589, https://doi.org/10.1175/2010JTECHO798.1, 2011.

Amorim, F. L. L., Le Meur, J., Wirth, A., Cardin, V.: Tipping of the double-diffusive regime in the southern Adriatic Pit in 2017 in connection with record high-salinity values. Ocean Sci., 20, 463–474, https://doi.org/10.5194/os-20-463-2024, 2024.

Aragão, L., Mentaschi, L., Pinardi, N., Verri, G., Senatore, A., Di Sabatino, S.: The freshwater discharge into the Adriatic Sea revisited. Front. Clim., 6, 1368456, https://doi.org/10.3389/fclim.2024.1368456, 2024.

Artegiani, A., Salusti, E.: Field observation of the flow of dense water on the bottom of the Adriatic Sea during the winter of 1981. Oceanol. Acta, 10, 387–391, 1987.

Artegiani, A., Bregant, D., Paschini, E., Pinardi, N., Raicich, F., Russo, A.: The Adriatic Sea general circulation. Part I: Air–sea interactions and water mass structure. J. Phys. Oceanogr., 27, 1492–1514, https://doi.org/10.1175/1520-0485(1997)027<1492:TASGCP>2.0.CO;2, 1997.

Barrier, C., Ternengo, S., El Idrissi, O., Piacentini, L., Barrier, N., Lett, C., et al.: Edible sea urchin (Paracentrotus lividus) larval dispersal and connectivity modelling in the northwestern Mediterranean Sea. J. Sea Res., 197, 102464, https://doi.org/10.1016/j.seares.2023.102464, 2024.

Batistić, M., Garić, R., Molinero, J. C.: Interannual variations in Adriatic Sea zooplankton mirror shifts in circulation regimes in the Ionian Sea. Clim. Res., 61, 231–240, https://doi.org/10.3354/cr01248, 2014.

Beg Paklar, G., Isakov, V., Koračin, D., Kourafalou, V., Orlić, M.: A case study of bora-driven flow and density changes on the Adriatic shelf (January 1987). Cont. Shelf Res., 21, 1751–1783, https://doi.org/10.1016/S0278-4343(01)00029-2, 2001.

Beg Paklar, G., Vilibić, I., Grbec, B., Matić, F., Mihanović, H., Džoić, T., et al.: Record-breaking salinities in the middle Adriatic during summer 2017 and concurrent changes in the microbial food web. Prog. Oceanogr., 185, 102345, https://doi.org/10.1016/j.pocean.2020.102345, 2020.

Belgacem, M., Schroeder, K., Alvarez, M., Lauvset, S. K., Chiggiato, J., Borghini, M.: A consistent regional dataset of dissolved oxygen in the western Mediterranean Sea (2004–2023): CTD-O2WMED. Earth Syst. Sci. Data, 17, 5315–5336, https://doi.org/10.5194/essd-17-5315-2025, 2025.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

Bellin, N., Rossi, V.: Modeling the effects of climate change on the habitat suitability of Mediterranean gorgonians. Biodivers. Conserv., 33, 929–948, https://doi.org/10.1007/s10531-024-02779-z, 2024.

Belušić Vozila, A., Güttler, I., Ahrens, B., Obermann-Hellhund, A., Telišman Prtenjak, M.: Wind over the Adriatic region in CORDEX climate change scenarios. J. Geophys. Res. Atmos., 124, 110–130, https://doi.org/10.1029/2018JD028552, 2019.

Benetazzo, A., Bergamasco, A., Bonaldo, D., Falcieri, F. M., Sclavo, M., Langone, L., et al.: Response of the Adriatic Sea to an intense cold air outbreak: dense water dynamics and wave induced transport. Prog. Oceanogr., 128, 115–138, https://doi.org/10.1016/j.pocean.2014.08.015, 2014.

Bermúdez, B., Farfán, J. F., Willems, P., Cea, L.: Assessing the effects of climate change on compound flooding in coastal river areas. Water Resour. Res., 67, e2020WR029321, https://doi.org/10.1029/2020WR029321, 2021.

Bonaldo, D., Bucchignani, E., Ricchi, A., Carniel, S.: Wind storminess in the Adriatic Sea in a climate change scenario. Acta Adriat., 58, 195–208, 2017.

Bonaldo, D., Bellafiore, D., Ferrarin, C., Ferretti, R., Ricchi, A., Sangelantoni, L.: The summer 2022 drought: a taste of future climate for the Po valley (Italy)?. Reg. Environ. Change, 23, 1, https://doi.org/10.1007/s10113-022-02004-z, 2023.

Bourgeois, T., Goris, N., Schwinger, J., Tjiputra, J. F.: Stratification constrains future heat and carbon uptake in the Southern Ocean between 30°S and 55°S. Nat. Commun., 13, 340, https://doi.org/10.1038/s41467-022-27979-5, 2022.

Breitburg, D., Levin, L. A., Oschlies, A., Grégoire, M., Chavez, F. P., Conley, D. J.: Declining oxygen in the global ocean and coastal waters. Science, 359, 6371, https://doi.org/10.1126/science.aam7240, 2018.

Buljan, M.: Fluctuation of salinity in the Adriatic (in Croatian). Izvješća-Reports, 2, 1–64, 1953.

Buljan, M., Zore-Armanda, M.: Oceanographic properties of the Adriatic Sea. Oceanogr. Mar. Biol. Annu. Rev., 14, 11–98, 1976.

Byrne, M., Przeslawski, R.: Multistressor impacts of warming and acidification of the ocean on marine invertebrates' life histories. Integr. Comp. Biol., 53, 582–596, https://doi.org/10.1093/icb/ict049, 2013.

Cantoni, C., De Vittor, C., Faganeli, J., Giani, M., Kovač, N., Malej, A.: Carbonate system and acidification of the Adriatic Sea. Mar. Chem., 267, 104462, https://doi.org/10.1016/j.marchem.2024.104462, 2024.

Capriotti, M., Bracchetti, L., Cocci, P., Mazzocchi, V., Fazzini, M., Corvaro, F., et al.: In situ investigation of ecological and molecular stress mechanisms triggered by marine heat waves in Adriatic populations of the Mediterranean mussel. Diversity, 17, 385, https://doi.org/10.3390/d17060385, 2025.

Carlot, J., Galobart, C., Gómez-Gras, D., Santamaría, J., Golo, R., Siniet, M., et al.: Vulnerability of benthic trait diversity across the Mediterranean Sea following mass mortality events. Nat. Commun., 16, 1571, https://doi.org/10.1038/s41467-025-55949-0, 2025.

Cavraro, F., Anelli Monti, M., Matić-Skoko, S., Caccin, A., Pranovi, F.: Vulnerability of the small-scale fishery to climate changes in the northern-central Adriatic Sea (Mediterranean Sea). Fishes, 8, 9, https://doi.org/10.3390/fishes8010009, 2023.

Cetinić, A. B.: Shellfisheries in Croatia: From manual collection to contemporary practices. Naše More, 71, 154–165, https://doi.org/10.17818/NM/2024/3.8, 2023.

© Author(s) 2026. CC BY 4.0 License.

Chatzimentor, A., Doxa, A., Katsanevakis, S., Mazaris, A. D.: Are Mediterranean marine threatened species at high risk by climate change?. Glob. Change Biol., 29, 1809–1821, https://doi.org/10.1111/gcb.16577, 2022.

Chiarini, M., Guicciardi, S., Zacchetti, L., Domenichetti, F., Canduci, G., Angelini, S., et al.: Short-term evaluation of changes in fisheries management measures in the Pomo/Jabuka Pits area. Sustainability, 14, 7742, https://doi.org/10.3390/su14137742, 2022.

Chimienti, G., De Padova, D., Adamo, M., Mossa, M., Bottalico, A., Lisco, A., et al.: Effects of global warming on Mediterranean coral forests. Sci. Rep., 11, 20703, https://doi.org/10.1038/s41598-021-00162-4, 2021.

Cibic, T., Baldassarre, L., Auriemma, R., et al.: Effects of the mobile gates (MOSE) closure on the ecosystem functioning of the Venice lagoon. Front. Mar. Sci., 12, 1675001, https://doi.org/10.3389/fmars.2025.1675001, 2025.

Civitarese, G., Gačić, M., Lipizer, M., Borzelli, G. L. E.: On the impact of the BiOS on the Adriatic and Ionian Seas. Biogeosciences, 7, 3987–3997, https://doi.org/10.5194/bg-7-3987-2010, 2010.

Civitarese, G., Gačić, M., Batistić, M., et al.: The BiOS mechanism: History, theory, implications. Prog. Oceanogr., 216, 103056, https://doi.org/10.1016/j.pocean.2023.103056, 2023.

Cossarini, G., Querin, S., Solidoro, C.: The continental shelf carbon pump in the northern Adriatic Sea. Ecol. Modell., 314, 118–134, https://doi.org/10.1016/j.ecolmodel.2015.07.024, 2015.

Darmaraki, S., et al.: Future evolution of Marine Heatwaves in the Mediterranean Sea. Clim. Dyn., 53, 1371–1392, https://doi.org/10.1007/s00382-019-04661-z, 2019.

Davolio, S., Henin, R., Stocchi, P., Buzzi, A.: Bora wind and heavy persistent precipitation. Q. J. R. Meteorol. Soc., 143, 1165–1177, https://doi.org/10.1002/qj.3002, 2017.

da Costa, V. S., Alessandri, J., Verri, G., Mentaschi, L., Guerra, R., Pinardi, N.: Marine climate indicators in the Adriatic Sea. Front. Clim., 6, 1449633, https://doi.org/10.3389/fclim.2024.1449633, 2024.

Degobbis, D., Gilmartin, M.: Nitrogen, phosphorus, and biogenic silicon budgets for the northern Adriatic Sea. Oceanol. Acta, 13, 31–45, 1990.

Degobbis, D., et al.: Long-term changes in the northern Adriatic ecosystem related to anthropogenic eutrophication. Int. J. Environ. Pollut., 13, 495–533, 2000.

Denamiel, C.: Far-future climate projection of the Adriatic marine heatwaves. Ocean Sci., 21, 1909–1931, https://doi.org/10.5194/os-21-1909-2025, 2025.

Denamiel, C., Pranić, P., Quentin, F., Mihanović, H., and Vilibić, I.: Pseudo-global warming projections of extreme wave storms in complex coastal regions: The case of the Adriatic Sea, Clim. Dynam., 55, 2483–2509, https://doi.org/10.1007/s00382-020-05397-x, 2020.

Dragičević, B., Matić-Skoko, S., and Dulčić, J.: Fish and fisheries of the eastern Adriatic Sea in the light of climate change, in: Trends in Fisheries and Aquatic Animal Health, edited by: Berillis, P., Bentham Science Publishers, 1–22, https://doi.org/10.2174/9781681085807117010004, 2017.

© Author(s) 2026. CC BY 4.0 License.

Cushman-Roisin, B. and Korotenko, K. A.: Mesoscale-resolving simulations of summer and winter bora events in the Adriatic Sea, J. Geophys. Res.-Oceans, 112, C11S91, https://doi.org/10.1029/2006JC003516, 2007.

Gačić, M., Civitarese, G., Miserocchi, S., Cardin, V., Crise, A., and Mauri, E.: The open-ocean convection in the Southern Adriatic: a controlling mechanism of the spring phytoplankton bloom, Cont. Shelf Res., 22, 1897–1908, https://doi.org/10.1016/S0278-4343(02)00050-X, 2002.

Gačić, M., Borzelli, G. L. E., Civitarese, G., Cardin, V., and Yari, S.: Can internal processes sustain reversals of the ocean upper circulation? The Ionian Sea example, Geophys. Res. Lett., 37, L09608, https://doi.org/10.1029/2010GL043216, 2010.

Grbec, B., Morović, M., Matić, F., Ninčević-Gladan, Ž., Marasović, I., Vidjak, O., et al.: Climate regime shifts and multi-decadal variability of the Adriatic Sea pelagic ecosystem, Acta Adriat., 56, 47–66, 2015.

Grisogono, B. and Belušić, D.: A review of recent advances in understanding the meso- and microscale properties of the severe Bora wind, Tellus A, 61, 1–16, https://doi.org/10.1111/j.1600-0870.2008.00369.x, 2009.

Ercegović, A.: La flore sous-marine de l'îlot de Jabuka, Acta Adriat., 8, 1–130, 1956–1958.

Fach, B. A., Orek, H., Yilmaz, E., Tezcan, D., Salihoglu, I., Salihoglu, B., et al.: Water mass variability and Levantine Intermediate Water formation in the Eastern Mediterranean between 2015 and 2017, J. Geophys. Res.-Oceans, 126, e2020JC016472, https://doi.org/10.1029/2020JC016472, 2021.

Escudier, R., Clementi, E., Cipollone, A., Pistoia, J., Drudi, M., Grandi, A., et al.: A high resolution reanalysis for the Mediterranean Sea. Front. Earth Sci., 9, 702285, https://doi.org/10.3389/feart.2021.702285, 2021.

Favaretto, C., Ruol, P., and Martinelli, L.: Analysis of the vulnerability of the lagoon levees of the Po Delta to coastal flooding in a changing climate, Estuar. Coast. Shelf Sci., 313, 109089, https://doi.org/10.1016/j.ecss.2024.109089, 2025.

Fedele, G., Mauri, E., Notarstefano, G., and Poulain, P. M.: Characterization of the Atlantic Water and Levantine Intermediate Water in the Mediterranean Sea using 20 years of Argo data, Ocean Sci., 18, 129–142, https://doi.org/10.5194/os-18-129-2022, 2022.

Fedele, G., Manco, I., Barbato, G., Verri, G., and Mercogliano, P.: Evaluation of atmospheric indicators in the Adriatic coastal areas: a multi-hazards approach for a better awareness of the current and future climate, Front. Clim., 6, 1330299, https://doi.org/10.3389/fclim.2024.1330299, 2024.

Fortibuoni, T., Libralato, S., Arneri, E., Giovanardi, O., Solidoro, C., and Raicevich, S.: Fish and fishery historical data since the 19th century in the Adriatic Sea, Mediterranean, Sci. Data, 4, 170104, https://doi.org/10.1038/sdata.2017.104, 2017.

Franco, P. and Michelato, A.: Northern Adriatic Sea: oceanography of the basin proper and of the western coastal zone, in: Marine Coastal Eutrophication, edited by: Vollenweider, R. A., Marchetti, R., and Viviani, R., Elsevier, Amsterdam, 35–62, https://doi.org/10.1016/B978-0-444-89990-3.50013-4, 1992.

Funari, E. and Ade, P.: Human health implications associated with mucilage in the northern Adriatic Sea, Ann. Ist. Super. Sanita, 35, 421–425, 1999.

Gačić, M., Civitarese, G., Kovačević, V., Ursella, L., Bensi, M., Menna, M., et al.: Extreme winter 2012 in the Adriatic: an example of climatic effect on the BiOS rhythm. Ocean Sci. 10, 513–522. https://doi.org/10.5194/os-10-513-2014, 2014.

© Author(s) 2026. CC BY 4.0 License.

Gao, S., Schwinger, J., Tjiputra, J., Bethke, I., Hartmann, J., Mayorga, E., et al.: Riverine impact on future projections of marine primary production and carbon uptake, Biogeosciences, 20, 93–119, https://doi.org/10.5194/bg-20-93-2023, 2023.

Gerace, S. D., Yu, J., Moore, J. K., and Martiny, A. C.: Observed declines in upper ocean phosphate-to-nitrate availability. Proc. Nat. Acad. Sci., 122, e241183512, https://doi.org/10.1073/pnas.2411835122, 2025.

Giani, M., Rinaldi, A., and Degobbis, D.: Mucilages in the Adriatic and Tyrrhenian Sea: an introduction, Sci. Total Environ., 353, 3–9, https://doi.org/10.1016/j.scitotenv.2005.09.006, 2005.

Giani, M., Djakovac, T., Degobbis, D., Cozzi, S., Solidoro, C., and Umani, S. F.: Recent changes in the marine ecosystems of the northern Adriatic Sea, Estuar. Coast. Shelf Sci., 115, 1–13, https://doi.org/10.1016/j.ecss.2012.08.023, 2012.

Granata, A., Bergamasco, A., Celentano, P., Guglielmo, L., Minutoli, R., Vanucci, S., et al.: Decapod crustacean larval communities in the South Adriatic: spring composition, horizontal and vertical distribution patterns, Water, 16, 3482, https://doi.org/10.3390/w16233482, 2024.

Guillam, M., Bessin, C., Blanchet-Aurigny, A., Cugier, P., Nicolle, A., Thiébaut, É., et al.: Vertical distribution of brittle star larvae in two contrasting coastal embayments: implications for larval transport, Sci. Rep., 10, 12033, https://doi.org/10.1038/s41598-020-68750-4, 2020.

Haberle, I., Hackenberger, D. K., Djerdj, T., Bavčević, L., Geček, S., Hackenberger, B. K., et al.: Effects of climate change on gilthead seabream aquaculture in the Mediterranean, Aquaculture, 578, 740052, https://doi.org/10.1016/j.aquaculture.2023.740052, 2024.

Hassoun, A. E. R., Bantelman, A., Canu, D., Comeau, S., Galdies, C., Gattuso, J.-P., et al.: Ocean acidification research in the Mediterranean Sea: status, trends and next steps, Front. Mar. Sci., 9, 892670, https://doi.org/10.3389/fmars.2022.892670, 2022.

Hassoun, A. E. R., Mojtahid, M., Merheb, M., Lionello, P., Gattuso, J.-P., and Cramer, W.: Climate change risks on key open marine and coastal Mediterranean ecosystems, Sci. Rep., 15, 24907, https://doi.org/10.1038/s41598-025-07858-x, 2025.

He, H. L., Hamdi, R., Luo, G. P., Cai, P., Yuan, X. L., Zhang, M., et al.: The summer cooling effect under the projected restoration of Aral Sea in Central Asia, Climatic Change, 174, 13, https://doi.org/10.1007/s10584-022-03434-8, 2022.

Holt, J., Katavouta, A., Hopkins, J., Amoudry, L. O., Appendini, C. M., Arneborg, L., et al.: Future climate projections in the global coastal ocean, Prog. Oceanogr., 235, 103497, https://doi.org/10.1016/j.pocean.2025.103497, 2025.

Iakunin, M., Abreu, E. F. M., Canhoto, P., Pereira, S., and Salgado, R.: Impact of a large artificial lake on regional climate: a typical meteorological year Meso-NH simulation results, Int. J. Climatol., 42, 1231–1252, https://doi.org/10.1002/joc.7299, 2021.

Ingrosso, G., Bensi, M., Cardin, V., and Giani, M.: Anthropogenic CO2 in a dense water formation area of the Mediterranean Sea, Deep-Sea Res. Part I, 123, 118–128, https://doi.org/10.1016/j.dsr.2017.04.004, 2017.

Iona, A., Theodorou, A., Sofianos, S., Watelet, S., Troupin, C., and Beckers, J. M.: Mediterranean Sea climatic indices: monitoring long-term variability and climate changes, Earth Syst. Sci. Data, 10, 1829–1842, https://doi.org/10.5194/essd-10-1829-2018, 2018.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

Ivatek-Šahdan, S., Stanešić, A., Tudor, M., Odak Plenković, I., and Janeković, I.: Impact of SST on heavy rainfall events on eastern Adriatic during SOP1 of HyMeX, Atmos. Res., 200, 36–59, https://doi.org/10.1016/j.atmosres.2017.09.019, 2018.

Ivušić, S., Güttler, I., and Horvath, K.: Overview of mean and extreme precipitation climate changes across the Dinaric Alps in the latest EURO-CORDEX ensemble, Clim. Dynam., 62, 10785–10815, https://doi.org/10.1007/s00382-024-07476-9, 2024.

Jacox, M. G. and Edwards, C. A.: Effects of stratification and shelf slope on nutrient supply in coastal upwelling regions, J. Geophys. Res.-Oceans, 116, C03019, https://doi.org/10.1029/2010JC006547, 2011.

Janeković, I., Mihanović, H., Vilibić, I., and Tudor, M.: Extreme cooling and dense water formation estimates in open and coastal regions of the Adriatic Sea during the winter of 2012, J. Geophys. Res.-Oceans, 119, 3200–3218, https://doi.org/10.1002/2014JC009865, 2014.

Jordà, G., Von Schuckmann, K., Josey, S. A., Caniaux, G., García-Lafuente, J., and Sammartino, S.: The Mediterranean Sea heat and mass budgets: estimates, uncertainties and perspectives, Prog. Oceanogr., 156, 174–208, https://doi.org/10.1016/j.pocean.2017.07.001, 2017.

Jordà, G., Marbà, N., Bennett, S., Santana-Garcon, J., Agusti, S., and Duarte, C. M.: Ocean warming compresses the three-dimensional habitat of marine life, Nat. Ecol. Evol., 4, 109–114, https://doi.org/10.1038/s41559-019-1058-0, 2020.

Juza, M., Fernández-Mora, À., Tintoré, J.: Sub-regional marine heat waves in the Mediterranean Sea from observations: long-term surface changes, sub-surface and coastal responses, Front. Mar. Sci., 9, 785771, https://doi.org/10.3389/fmars.2022.785771, 2022.

Kamberi, E., Hala, E., and Möllmann, C.: Evidence of climate-driven regime shifts in Adriatic Sea fisheries, Sci. Mar., 89, e108, https://doi.org/10.3989/scimar.05566.108, 2025.

Kamberi, E., Hala, E., and Möllmann, C.: Impact of large-scale oceanic variability on Adriatic fisheries evidenced through the 'mean temperature of the catch' approach, Front. Mar. Sci., 12, 1719738, https://doi.org/10.3389/fmars.2025.1719738, 2025.

Kassis, D. and Korres, G.: Hydrography of the Eastern Mediterranean basin derived from Argo floats profile data, Deep-Sea Res. Part II, 171, 104712, https://doi.org/10.1016/j.dsr2.2019.104712, 2020.

Khodayar, S. and Hoerner, J.: An idealized model sensitivity study on Dead Sea desertification with a focus on the impact on convection, Atmos. Chem. Phys., 20, 12011–12031, https://doi.org/10.5194/acp-20-12011-2020, 2020.

Khodayar, S., Kushta, J., Catto, J. L., Dafis, S., Davolio, S., and Ferrarin, C.: Mediterranean cyclones in a changing climate: a review on their socio-economic impacts, Rev. Geophys., 63, e2024RG000853, https://doi.org/10.1029/2024RG000853, 2025.

Kokkini, Z., Mauri, E., Gerin, R., Poulain, P. M., Simoncelli, S., and Notarstefano, G.: On the salinity structure in the South Adriatic as derived from float and glider observations in 2013–2016, Deep-Sea Res. Part II, 171, 104625, https://doi.org/10.1016/j.dsr2.2019.07.013, 2020.

Kourafalou, V. H.: Process studies on the Po River plume, North Adriatic Sea, J. Geophys. Res.-Oceans, 104, 29963–29985, https://doi.org/10.1029/1999JC900217, 1999.

Kovač, Ž., Platt, T., Ninčević Gladan, Ž., Morović, M., Sathyendranath, S., Raitsos, D. E., et al.: A 55-year time series station for primary production in the Adriatic Sea: data correction, extraction of photosynthesis parameters and regime shifts, Remote Sens., 10, 1460, https://doi.org/10.3390/rs10091460, 2018.
Kraus, R., Grilli, F., Supić, N., Janeković, I., Brailo, M., Cara, M., et al.: Oceanographic characteristics of the Adriatic Sea – support to secondary HAOP spread through natural dispersal, Mar. Pollut. Bull., 147, 59–85, https://doi.org/10.1016/j.marpolbul.2018.10.062, 2019.
Kružić, P., Rodić, P., Popijač, A., and Sertić, M.: Impacts of temperature anomalies on mortality of benthic organisms in the Adriatic Sea, Mar. Ecol., 37, 1190–1209, https://doi.org/10.1111/maec.12293, 2016.
Kružić, P., Guić, R., Lipej, L., Mavrič, B., Gračan, R., and Ankon, P.: A Cladocora caespitosa bank (National Park Mljet, Adriatic Sea) under climate and anthropogenic impacts: a 20-year survey, Mediterr. Mar. Sci., 26, 156–174, https://doi.org/10.12681/mms.37029, 2025.
Krvavica, N. and Ružić, I.: Assessment of sea-level rise impacts on salt-wedge intrusion in idealized and Neretva River Estuary, Estuar. Coast. Shelf Sci., 234, 106638, https://doi.org/10.1016/j.ecss.2020.106638, 2020.
Kubin, E., Poulain, P.-M., Mauri, E., Menna, M., and Notarstefano, G.: Levantine intermediate and Levantine deep water formation: an Argo float study from 2001 to 2017, Water, 11, 1781, https://doi.org/10.3390/w11091781, 2019.
Kubin, E., Menna, M., Mauri, E., Notarstefano, G., Mieruch, S., and Poulain, P.-M.: Heat content and temperature trends in the Mediterranean Sea as derived from Argo float data, Front. Mar. Sci., 10, 1271638, https://doi.org/10.3389/fmars.2023.1271638, 2023.
Kunkel, K. E., Westcott, N. E., and Kristovich, D. A. R.: Assessment of potential effects of climate change on heavy lake-effect snowstorms near Lake Erie, J. Great Lakes Res., 28, 521–536, https://doi.org/10.1016/S0380-1330(02)70603-5, 2002.
Kurkin, A., Kurkina, O., Rybin, A., and Talipova, T.: Comparative analysis of the first baroclinic Rossby radius in the Baltic, Black, Okhotsk, and Mediterranean seas, Russ. J. Earth Sci., 20, ES4008, https://doi.org/10.2205/2020ES000737, 2020.
Kuzmić, M., Janeković, I., Book, J. W., Martin, P. J., and Doyle, J. D.: Modeling the northern Adriatic double-gyre response to intense bora wind: a revisit, J. Geophys. Res.-Oceans, 112, C03S13, https://doi.org/10.1029/2005JC003377, 2007.
Langone, L., Conese, I., Miserocchi, S., Boldrin, A., Bonaldo, D., Carniel, S., et al.: Dynamics of particles along the western margin of the Southern Adriatic: Processes involved in transferring particulate matter to the deep basin, Mar. Geol., 375, 28–43, https://doi.org/10.1016/j.margeo.2015.09.004, 2016.
Le Meur, J., Wirth, A., de Mendoza, F. P., Miserocchi, S., and Cardin, V.: Intermittent supply of dense water to the deep South Adriatic Pit: an observational study, Front. Mar. Sci., 12, 1516780, https://doi.org/10.3389/fmars.2025.1516780, 2025.
Li, P. Y. and Tanhua, T.: Recent changes in deep ventilation of the Mediterranean Sea: evidence from long-term transient tracer observations, Front. Mar. Sci., 7, 594, https://doi.org/10.3389/fmars.2020.00594, 2020.
Lipizer, M., Partescano, E., Rabitti, A., Giorgetti, A., and Crise, A.: Qualified temperature, salinity and dissolved oxygen climatologies in a changing Adriatic Sea, Ocean Sci., 10, 771–797, https://doi.org/10.5194/os-10-771-2014, 2014.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

Liu, C., Liang, X., and Yu, L.: Salinity trends and mass balances in the Mediterranean Sea: revisit the role of air–sea freshwater fluxes and oceanic exchange, Ocean Sci., 21, 2069–2083, https://doi.org/10.5194/os-21-2069-2025, 2025.

Liu, G. S., Yu, X., Zhang, J. H., Wang, X. P., Xu, N., and Ali, S.: Reconstruction of the three-dimensional dissolved oxygen and its spatio-temporal variations in the Mediterranean Sea using machine learning, J. Environ. Sci., 157, 710–728, https://doi.org/10.1016/j.jes.2025.01.010, 2025.

Lučić, D., Ljubešić, Z., Babić, I., Bosak, S., Cetinić, I., and Vilibić, I.: Unusual winter zooplankton bloom in the open southern Adriatic Sea, Turk. J. Zool., 41, 1024–1035, https://doi.org/10.3906/zoo-1702-17, 2017.

Ljubimir, S., Jasprica, N., Čalić, M., Hrustić, E., Radić, I. D., and Car, A.: Interannual (2009–2013) variability of winter–spring phytoplankton in the open South Adriatic Sea: Effects of deep convection and lateral advection, Cont. Shelf Res., 143, 311–321, https://doi.org/10.1016/j.csr.2017.05.007, 2017.

Macias, D., Garcia-Gorriz, E., and Stips, A.: Understanding the causes of recent warming of Mediterranean waters: How much could be attributed to climate change?, PLoS ONE, 8, e81591, https://doi.org/10.1371/journal.pone.0081591, 2013.

Malanotte-Rizzoli, P., Manca, B. B., Marullo, S., Ribera d'Alcala, M., Roether, W., Theocharis, A., et al.: The Levantine Intermediate Water Experiment (LIWEX) Group: Levantine basin—A laboratory for multiple water mass formation processes, J. Geophys. Res.-Oceans, 108, C9, 8101, https://doi.org/10.1029/2002JC001643, 2003.

Malanotte-Rizzoli, P., Artale, V., Borzelli, G. L. E., Brenner, S., Crise, A., Gačić, M., et al.: Physical forcing and physical/biochemical variability of the Mediterranean Sea: a review of unresolved issues and directions for future research, Ocean Sci., 10, 281–322, https://doi.org/10.5194/os-10-281-2014, 2014.

Mallil, K., Testor, P., Bosse, A., Margirier, F., Houpert, L., Le Goff, H., et al.: The Levantine Intermediate Water in the western Mediterranean and its interactions with the Algerian Gyres: insights from 60 years of observation, Ocean Sci., 18, 937–952, https://doi.org/10.5194/os-18-937-2022, 2022.

Mamoutos, I. G., Potiris, E., Androulidakis, Y., Tragou, E., and Zervakis, V.: Evidence for reduced Black Sea Water outflow to the North Aegean, Earth Space Sci., 11, e2024EA003674, https://doi.org/10.1029/2024EA003674, 2024.

Manca, B. B., Burca, M., Giorgetti, A., Coatanoan, C., Garcia, M. J., and Iona, A.: Physical and biochemical averaged vertical profiles in the Mediterranean regions: an important tool to trace the climatology of water masses and to validate incoming data from operational oceanography, J. Mar. Syst., 48, 83–116, https://doi.org/10.1016/j.jmarsys.2003.11.025, 2004.

Marasović, I., Grbec, B., and Morović, M.: Long-term production changes in the Adriatic, Neth. J. Sea Res., 34, 267–273, https://doi.org/10.1016/0077-7579(95)90037-3, 1995.

Marcos, M. and Tsimplis, M. N.: Coastal sea level trends in Southern Europe, Geophys. J. Int., 175, 70–82, https://doi.org/10.1111/j.1365-246X.2008.03892.x, 2008.

Marguš, D. and Teskeredžić, E.: Settlement of mussels (Mytilus galloprovincialis Lamarck) on rope collectors in the estuary of the river Krka, Yugoslavia, Aquaculture, 55, 285–296, https://doi.org/10.1016/0044-8486(86)90169-9, 1986.

Marini, M., Russo, A., Paschini, E., Grilli, F., and Campanelli, A.: Short-term physical and chemical variations in the bottom water of middle Adriatic depressions, Clim. Res., 31, 227–237, https://doi.org/10.3354/cr031227, 2006.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

Mariotti, A. and Dell'Aquila, A.: Decadal climate variability in the Mediterranean region: roles of large-scale forcings and regional processes, Clim. Dynam., 38, 1129–1145, https://doi.org/10.1007/s00382-011-1056-7, 2012.

Martellucci, R., de Mendoza, F. P., Menna, M., Pirro, A., Reale, M., Gačić, M., et al.: A multiobservation analysis of the 2017 dense water formation events: Climate change, bottom density currents, and Adriatic–Ionian Sea circulation (Mediterranean Sea), J. Geophys. Res.-Oceans, 130, e2024JC022306, https://doi.org/10.1029/2024JC022306, 2025a.

Martellucci, R., Dentico, C., Coppola, L., Skjelvan, I., Giani, M., Pensieri, S., et al.: Air–sea CO2 exchange in the Eastern Atlantic and the Mediterranean Sea based on autonomous surface measurements, Front. Mar. Sci., 12, 1633617, https://doi.org/10.3389/fmars.2025.1633617, 2025b.

Martinelli, M., Zacchetti, L., Belardinelli, A., Domenichetti, F., Scarpini, P., Penna, P., et al.: Changes in abundance and distribution of the sea pen, Funiculina quadrangularis, in the central Adriatic Sea (Mediterranean basin) in response to variations in trawling intensity, Fishes, 8, 347, https://doi.org/10.3390/fishes8070347, 2023.

Mattei, G., Vacchi, M., Rizzo, A., and Aucelli, P. P. C.: Past coastal evolution indicates low resilience of Mediterranean coastal plains to ongoing climate change, Climatic Change, 178, 161, https://doi.org/10.1007/s10584-025-03985-6, 2025.

Matić-Skoko, S., Pavičić, M., Šepić, J., Janeković, I., Vrdoljak, D., Vilibić, I., et al.: Impacts of sea bottom temperature on CPUE of European lobster Homarus gammarus (Linnaeus, 1758; Decapoda, Nephropidae) in the Eastern Adriatic Sea, Front. Mar. Sci., 9, 891197, https://doi.org/10.3389/fmars.2022.891197, 2022.

Mentaschi, L., Lovato, T., Butenschön, M., Alessandri, J., Aragão, L., Verri, G., et al.: Projected climate oligotrophication of the Adriatic marine ecosystems, Front. Clim., 6, 1338374, https://doi.org/10.3389/fclim.2024.1338374, 2024.

Mihanović, H., Vilibić, I., Carniel, S., Tudor, M., Russo, A., Bergamasco, A., et al.: Exceptional dense water formation on the Adriatic shelf in the winter of 2012, Ocean Sci., 9, 561–572, https://doi.org/10.5194/os-9-561-2013, 2013.

Mihanović, H., Vilibić, I., Dunić, N. and Šepić, J.: Mapping of decadal middle Adriatic oceanographic variability and its relation to the BiOS regime, J. Geophys. Res. Oceans, 120, 5615–5630, https://doi.org/10.1002/2015JC010725, 2015.

Mihanović, H., Janeković, I., Vilibić, I., Kovačević, V., and Bensi, M.: Modelling interannual changes in dense water formation on the northern Adriatic shelf, Pure Appl. Geophys., 175, 4065–4081, https://doi.org/10.1007/s00024-018-1935-5, 2018.

Mihanović, H., Vilibić, I., Šepić, J., Matić, F., Ljubešić, Z., Mauri, E., et al.: Observation, preconditioning and recurrence of exceptionally high salinities in the Adriatic Sea, Front. Mar. Sci., 8, 672210, https://doi.org/10.3389/fmars.2021.672210, 2021.

Montanari, A., Nguyen, H., Rubinetti, S., Ceola, S., Galelli, S., and Rubino, A.: Why the 2022 Po River drought is the worst in the past two centuries, Sci. Adv., 9, eadg8304, https://doi.org/10.1126/sciadv.adg8304, 2023.

Moraitis, M.-L., Valavanis, V. D., and Karakassis, I.: Modelling the effects of climate change on the distribution of benthic indicator species in the Eastern Mediterranean Sea, Sci. Total Environ., 667, 16–24, https://doi.org/10.1016/j.scitotenv.2019.02.338, 2019.

Morović, M. and Domijan, N.: Light attenuation changes in the middle and southern Adriatic, Acta Adriat., 32, 621–635, 1991.

Moulin, A., Mentaschi, L., Clementi, E., Verri, G., and Mercogliano, P.: Projections of the Adriatic wave conditions under climate changes, Front. Clim., 6, 1409237, https://doi.org/10.3389/fclim.2024.1409237, 2024.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

Neri, F., Garzia, A., Ubaldi, M., Romagnoli, T., Accoroni, S., Coluccelli, A., et al.: Ocean warming, marine heatwaves and phytoplankton biomass: long-term trends in the Northern Adriatic Sea, Estuar. Coast. Shelf Sci., 322, 109282, https://doi.org/10.1016/j.ecss.2025.109282, 2025.

Nof, D.: The translation of isolated cold eddies along a sloping bottom, Deep-Sea Res., 30, 171–182, https://doi.org/10.1016/0198-0149(83)90067-5, 1983.

Ojeda, M. G. V., Di Sante, F., Coppola, E., Fantini, A., Nogherotto, R., Raffaele, F., et al.: Climate change impact on flood hazard over Italy, J. Hydrol., 615, 128628, https://doi.org/10.1016/j.jhydrol.2022.128628, 2022.

Olschewski, P., Dieng, M. D. B., Moutahir, H., Böker, B., Haas, E., Kunstmann, H., et al.: Amplified potential for vegetation stress under climate-change-induced intensifying compound extreme events in the Greater Mediterranean Region, Nat. Hazards Earth Syst. Sci., 24, 1099–1134, https://doi.org/10.5194/nhess-24-1099-2024, 2024.

Orlić, M., Gačić, M., and La Violette, P. E.: The currents and circulation of the Adriatic Sea, Oceanol. Acta, 15, 109–124, 1982.

Ozer, T., Rahav, E., Gertman, I., Sisma-Ventura, G., Silverman, J., and Herut, B.: Relationship between thermohaline and biochemical patterns in the Levantine upper and intermediate water masses, Southeastern Mediterranean Sea (2013–2021), Front. Mar. Sci., 9, 958924, https://doi.org/10.3389/fmars.2022.958924, 2022.

Paladini de Mendoza, F., Schroeder, K., Miserocchi, S., Borghini, M., Giordano, P., and Chiggiato, J.: Sediment resuspension and transport processes during dense water cascading events along the continental margin of the southern Adriatic Sea (Mediterranean Sea), Mar. Geol., 459, 107030, https://doi.org/10.1016/j.margeo.2023.107030, 2023.

Pairaud, I. L., Bensoussan, N., Garreau, P., Faure, V., and Garrabou, J.: Impacts of climate change on coastal benthic ecosystems: assessing the current risk of mortality outbreaks associated with thermal stress in NW Mediterranean coastal areas, Ocean Dynam., 64, 103–115, https://doi.org/10.1007/s10236-013-0661-x, 2014.

Parras-Berrocal, I. M., Vázquez, R., Cabos, W., Sein, D. V., Álvarez, O., Bruno, M., et al.: Dense water formation in the eastern Mediterranean under a global warming scenario, Ocean Sci., 19, 941–952, https://doi.org/10.5194/os-19-941-2023, 2023.

Parras-Berrocal, I. M., Waldman, R., Gonzalez, N. M., Ahrens, B., Cabos, W., Jordà, G., et al.: Regionalized Mediterranean relative sea level projections under high-emission regional climate scenarios, Environ. Res. Lett., 20, 114068, https://doi.org/10.1088/1748-9326/ae15a5, 2025.

Pastor, F., Valiente, J. A., and Khodayar, S.: A warming Mediterranean: 38 years of increasing sea surface temperature, Remote Sens., 12, 2687, https://doi.org/10.3390/rs12172687, 2020.

Pertesi, V., Sarantopoulou, J., Exadactylos, A., Vafidis, D., and Gkafas, G. A.: Genetic structuring and connectivity of European squid populations in the Mediterranean Sea based on mitochondrial COI data, Fishes, 10, 394, https://doi.org/10.3390/fishes10080394, 2025.

Pisano, A., Marullo, S., Artale, V., Falcini, F., Yang, C. X., Leonelli, F. E., et al.: New evidence of Mediterranean climate change and variability from sea surface temperature observations, Remote Sens., 12, 132, https://doi.org/10.3390/rs12010132, 2020.

Pomaro, A., Cavaleri, L., Papa, A., and Lionello, P.: 39 years of directional wave recorded data and relative problems, climatological implications and use, Sci. Data, 5, 180139, https://doi.org/10.1038/sdata.2018.139, 2018.

Poulain, P.-M., Barbanti, R., Font, J., Cruzado, A., Millot, C., Gertman, I., et al.: MedArgo: a drifting profiler program in the Mediterranean Sea. Ocean Sci., 3, 379–395. https://doi.org/10.5194/os-3-379-2007, 2007.

Pranić, P., Denamiel, C., and Vilibić, I.: Performance of the Adriatic Sea and Coast (AdriSC) climate component – a COAWST V3.3-based one-way coupled atmosphere–ocean modelling suite: ocean results. Geosci. Model Dev., 14, 5927–5955, https://doi.org/10.5194/gmd-14-5927-2021, 2021.

Pranić, P., Denamiel, C., Janeković, I., and Vilibić, I.: Multi-model analysis of the Adriatic dense-water dynamics, Ocean Sci., 19, 649–670, https://doi.org/10.5194/os-19-649-2023, 2023.

Pranić, P., Denamiel, C., and Vilibić, I.: Kilometer-scale assessment of the Adriatic dense water multi-decadal dynamics, J. Geophys. Res.-Oceans, 129, e2024JC021182, https://doi.org/10.1029/2024JC021182, 2024.

Pusceddu, A., Mea, M., Canals, M., Heussner, S., Durrieu de Madron, X., Sanchez-Vidal, A., et al.: Major consequences of an intense dense shelf water cascading event on deep-sea benthic trophic conditions and meiofaunal biodiversity, Biogeosciences, 10, 2659–2670, https://doi.org/10.5194/bg-10-2659-2013, 2013.

Querin, S., Bensi, M., Cardin, V., Solidoro, C., Bacer, S., Mariotti, L., et al.: Saw-tooth modulation of the deep-water thermohaline properties in the southern Adriatic Sea, J. Geophys. Res.-Oceans, 121, 4585–4600, https://doi.org/10.1002/2015JC011522, 2016.

Raicich, F.: On the fresh water balance of the Adriatic Sea, J. Mar. Syst., 9, 305–319, https://doi.org/10.1016/S0924-7963(96)00042-5, 1999.

Raicich, F., Malačič, V., Celio, M., Giaiotti, D., Cantoni, C., Colucci, R. R., et al.: Extreme air-sea interactions in the Gulf of Trieste (north Adriatic) during the strong bora event in winter 2012, J. Geophys. Res.-Oceans, 118, 5238–5250, https://doi.org/10.1002/jgrc.20398, 2013.

Reich, T., Belkin, N., Sisma-Ventura, G., Hauzer, H., Berman-Frank, I., and Rahav, E.: Does oligotrophy favor chemoautotrophy over photoautotrophy?, Prog. Oceanogr., 241, 103633, https://doi.org/10.1016/j.pocean.2025.103633, 2026.

Reimann, L., Vafeidis, A. T., Brown, S., Hinkel, J., and Tol, R. S. J.: Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise, Nat. Commun., 9, 4161, https://doi.org/10.1038/s41467-018-06645-9, 2018.

Richardson, C. M., Peucker-Ehrenbrink, B., Wyatt, S., Bourbonnais, A., Hatje, V., Frey, C., et al.: Effects of climate change on river and groundwater nutrient inputs to the coastal ocean, Commun. Earth Environ., 6, 761, https://doi.org/10.1038/s43247-025-02594-6, 2025.

Rinaldi, A., Vollenweider, R. A., Montanari, G., Ferrari, C. R., and Ghetti, A.: Mucilages in Italian seas: the Adriatic and Tyrrhenian seas, 1988–1991, Sci. Total Environ., 165, 165–183, https://doi.org/10.1016/0048-9697(95)04550-K, 1995.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

Rivetti, I., Fraschetti, S., Lionello, P., Zambianchi, E., and Boero, F.: Global warming and mass mortalities of benthic invertebrates in the Mediterranean Sea, PLoS ONE, 9, e115655, https://doi.org/10.1371/journal.pone.0115655, 2014.

Röpke, A., Nellent, W., and Piatkowski, U.: A comparative study on the influence of the pycnocline on the vertical distribution of fish larvae and cephalopod paralarvae in three ecologically different areas of the Arabian Sea, Deep-Sea Res. Pt. II, 40, 801–819, https://doi.org/10.1016/0967-0645(93)90059-V, 1993.

Rubinetti, S., Taricco, C., Zanchettin, D., Arnone, E., Bizzarri, I., and Rubino, A.: Interannual-to-multidecadal sea-level changes in the Venice lagoon and their impact on flood frequency, Climatic Change, 174, 26, https://doi.org/10.1007/s10584-022-03448-2, 2022.

Sannino, G., Carillo, A., Iacono, R., Napolitano, E., Palma, M., Pisacane, G., et al.: Modelling present and future climate in the Mediterranean Sea: a focus on sea-level change, Clim. Dynam., 59, 357–391, https://doi.org/10.1007/s00382-021-06132-w, 2022.

Santojanni, A., Arneri, E., Bernardini, V., Cingolani, N., Di Marco, M., and Russo, A.: Effects of environmental variables on recruitment of anchovy in the Adriatic Sea, Clim. Res., 31, 181–193, https://doi.org/10.3354/cr031181, 2006.

Schlitzer, R., Roether, W., Oster, H., Junghaus, H.-G., Hausmann, M., Johannsen, H., et al.: Chlorofluoromethane and oxygen in the Eastern Mediterranean, Deep-Sea Res., 38, 1531–1551, https://doi.org/10.1016/0198-0149(91)90088-W, 1991.

Schroeder, S., Chiggiato, J., Josey, S. A., Borghini, M., Aracri, S., and Sparnocchia, S.: Rapid response to climate change in a marginal sea, Sci. Rep., 7, 4065, https://doi.org/10.1038/s41598-017-04455-5, 2017.

Schroeder, K., Ben Ismail, S., Bensi, M., Bosse, A., Chiggiato, J., Civitarese, G., et al.: A consensus-based, revised and comprehensive catalogue for Mediterranean water masses acronyms, Mediterr. Mar. Sci., 25, 783–791, https://doi.org/10.12681/mms.38736, 2024.

SeaDataNet: Data quality control procedures, version 2.0, https://www.seadatanet.org/content/download/596/file/SeaDataNet_QC_procedures_V2_%28May_2010%29.pdf, accessed 28 May 2026

Šepić, J., Pasarić, M., Međugorac, I., Vilibić, I., Karlović, M., Mlinar, M., et al.: Climatology and process-oriented analysis of the Adriatic sea level extremes, Prog. Oceanogr., 209, 102908, https://doi.org/10.1016/j.pocean.2022.102908, 2022.

Shlesinger, T., Mills, E., McFadden, C. S., and Benayahu, Y.: A dramatic northward range expansion of a Red Sea soft coral in the Mediterranean Sea, Ecosphere, 15, e4938, https://doi.org/10.1002/ecs2.4938, 2024.

Skliris, N., Zika, J. D., Herold, L., Josey, S. A., and Marsh, R.: Mediterranean Sea water budget long-term trend inferred from salinity observations, Clim. Dynam., 51, 2857–2876, https://doi.org/10.1007/s00382-017-4053-7, 2018.

Skliris, N., Marsh, R., Breedon, M., and Josey, S. A.: Accelerated warming and salinification of the Mediterranean Sea: Implications for dense water formation, J. Mar. Sci. Eng., 13, 25, https://doi.org/10.3390/jmse13010025, 2025.

Small, E. E., Giorgi, F., Sloan, L. C., and Hostetler, S.: The effects of desiccation and climatic change on the hydrology of the Aral Sea, J. Climate, 14, 300–322, https://doi.org/10.1175/1520-0442(2001)013<0300:TEODAC>2.0.CO;2, 2001.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

Smith, K. E., Burrows, M. T., Hobday, A. J., King, N. G., Moore, P. J., Gupta, A. S., et al.: Biological impacts of marine heatwaves, Annu. Rev. Mar. Sci., 15, 119–145, https://doi.org/10.1146/annurev-marine-032122-121437, 2023.

Sprintall, J., and Tomczak, M.: Evidence of the barrier layer in the surface layer of the tropics, J. Geophys. Res., 97(C5), 7305–7316, https://doi.org/10.1029/92JC00407, 1992.

Solidoro, C., Bastianini, M., Bandelj, V., Codermatz, R., Cossarini, G., Canu, D. M., et al.: Current state, scales of variability, and trends of biogeochemical properties in the northern Adriatic Sea, J. Geophys. Res.-Oceans, 114, C07S91, https://doi.org/10.1029/2008JC004838, 2009.

Somero, G. B.: The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine 'winners' and 'losers', J. Exp. Biol., 213, 912–920, https://doi.org/10.1242/jeb.037473, 2010.

Soto-Navarro, J., Jordá, G., Amores, A., Cabos, W., Somot, S., Sevault, F., et al.: Evolution of Mediterranean Sea water properties under climate change scenarios in the Med-CORDEX ensemble, Clim. Dynam., 54, 2135–2165, https://doi.org/10.1007/s00382-019-05105-4, 2020.

Stocchi, P. and Davolio, S.: Intense air-sea exchange and heavy rainfall: impact of the northern Adriatic SST, Adv. Sci. Res., 13, 7–12, https://doi.org/10.5194/asr-13-7-2016, 2016.

Supić, N., Grbec, B., Vilibić, I., and Ivančić, I.: Long-term changes in hydrographic conditions in northern Adriatic and its relationship to hydrological and atmospheric processes, Ann. Geophys., 22, 733–745, https://doi.org/10.5194/angeo-22-733-2004, 2004.

Terzić, E., Cardin, V., Le Meur, J., Dunić, N., Vodopivec, M., and Vilibić, I.: Unprecedented warming and salinization observed in the deep Adriatic, Limnol. Oceanogr. Lett., 10, 888–898, https://doi.org/10.1002/lol2.70051, 2025a.

Terzić, E., Gardiol, C., and Vilibić, I.: Surface saline lakes in the Mediterranean Sea, Ocean Sci., 21, 1441–1459, https://doi.org/10.5194/os-21-1441-2025, 2025b.

Tojčić, I., Denamiel, C., and Vilibić, I.: Kilometer-scale trends, variability, and extremes of the Adriatic far-future climate (RCP 8.5, 2070−2100), Front. Mar. Sci., 11, 1329020, https://doi.org/10.3389/fmars.2024.1329020, 2024.

Tintoré, J., Pinardi, N., Álvarez-Fanjul, E., Aguiar, E., Álvarez-Berastegui, D., Bajo, M., et al.: Challenges for sustained observing and forecasting systems in the Mediterranean Sea, Front. Mar. Sci., 6, 568, https://doi.org/10.3389/fmars.2019.00568, 2019.

Tramblay, Y., Arnaud, P., Artigue, G., Lang, M., Paquet, E., Neppel, L., et al.: Changes in Mediterranean flood processes and seasonality, Hydrol. Earth Syst. Sci., 27, 2973–2987, https://doi.org/10.5194/hess-27-2973-2023, 2023.

Tsimplis, M. N. and Baker, T. F.: Sea level drop in the Mediterranean Sea: An indicator of deep water salinity and temperature changes?, Geophys. Res. Lett., 27, 1731–1734, https://doi.org/10.1029/1999GL007004, 2000.

Vatova, A.: L'anormale regime fisico-chimico dell'Alto Adriatico nel 1929 e le sue ripercussioni sulla fauna, Thalassia, 8, 1–49, 1934.

Verri, G., Furnari, L., Gunduz, M., Senatore, A., Santos da Costa, V., De Lorenzis, A., et al.: Climate projections of the Adriatic Sea: role of river release, Front. Climate, 6, 1368413, https://doi.org/10.3389/fclim.2024.1368413, 2024.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

Vested, H. J., Berg, P., and Uhrenholdt, T.: Dense water formation in the northern Adriatic, J. Mar. Syst., 18, 135–160, https://doi.org/10.1016/S0924-7963(98)00009-8, 1998.

Vichi, M., May, W., and Navarra, A.: Response of a complex ecosystem model of the northern Adriatic Sea to a regional climate change scenario, Clim. Res., 24, 141–159, https://doi.org/10.3354/cr024141, 2003.

Vilibić, I. and Orlić, M.: Least-squares tracer analysis of water masses in the South Adriatic (1967–1990), Deep-Sea Res. Pt. I, 48, 2297–2330, https://doi.org/10.1016/S0967-0637(01)00014-0, 2001.

Vilibić, I., Matijević, S., Šepić, J. and Kušpilić, G.: Changes in the Adriatic oceanographic properties induced by the Eastern Mediterranean Transient, Biogeosci., 9, 2085–2097, https://doi.org/10.5194/bg-9-2085-2012, 2012.

Vilibić, I., Zemunik, P., Šepić, J., Dunić, N., Marzouk, O., Mihanović, H., et al.: Present-climate trends and variability in thermohaline properties of the northern Adriatic shelf, Ocean Sci., 15, 1351–1362, https://doi.org/10.5194/os-15-1351-2019, 2019.

Vilibić, I., Zemunik, P., Dunić, N. and Mihanović, H.: Local and remote drivers of the observed thermohaline variability on the northern Adriatic shelf (Mediterranean Sea), Cont. Shelf Res., 199, 104110, https://doi.org/10.1016/j.csr.2020.104110, 2020.

Vilibić, I., Pranić, P. and Denamiel, C.: North Adriatic Dense Water: lessons learned since the pioneering work of Mira Zore-Armanda 60 years ago, Acta Adriat., 64, 53–78, https://doi.org/10.32582/aa.64.1.11, 2023.

Vilibić, I., Terzić, E., Vrdoljak, I., Dominović Novković, I., Vodopivec, M., Ciglenečki, I., et al.: Extraordinary mucilage event in the northern Adriatic in 2024—a glimpse into the future climate?, Estuar. Coast. Shelf Sci., 317, 109222, https://doi.org/10.1016/j.ecss.2025.109222, 2025.

Vlašiček, I., Marić Pfannkuchen, D., Smodlaka Tanković, M., Baričević, A., Kužat, N., Knjaz, M., et al.: Cluster analysis of long-term phytoplankton data from the Northern Adriatic reveals environmental influences and disruptions in seasonal patterns, Front. Ecol. Evol., 13, 1498307, https://doi.org/10.3389/fevo.2025.1498307, 2025.

Wagawa, T., Igeta, Y. and Abe, S.: Warming and springtime freshening trend in the southeastern Sea of Japan revealed by observational data, Geophys. Res. Lett., 52, e2025GL118631, https://doi.org/10.1029/2025GL118631, 2025.

Wang, H., You, Z., Guo, H., Zhang, W., Xu, P. and Ren, K.: Quality assessment of sea surface salinity from multiple ocean reanalysis products. J. Mar. Sci. Eng., 11, 54, https://doi.org/10.3390/jmse11010054, 2023.

Wetz, M. S. and Yoskowitz, D. W.: An 'extreme' future for estuaries? Effects of extreme climatic events on estuarine water quality and ecology, Mar. Pollut. Bull., 69, 7–18, https://doi.org/10.1016/j.marpolbul.2013.01.020, 2013.

Wong, A., Keeley, R., and Carval, T., and the Argo Management Team: Argo Quality Control Manual for CTD and Trajectory Data. Version 3.7. https://doi.org/10.13155/33951, 2023.

Yang, Z., Wang, J. L., Qian, Y., Chakraborty, T. C., Xue, P. F., Pringle, W. J., et al.: Summer convective precipitation changes over the Great Lakes region under a warming scenario, J. Geophys. Res.-Atmos., 129, e2024JD041011, https://doi.org/10.1029/2024JD041011, 2024.

https://doi.org/10.5194/egusphere-2026-3080
Preprint. Discussion started: 4 June 2026
© Author(s) 2026. CC BY 4.0 License.

Zanchettin, D., Bruni, S., Raicich, F., Lionello, P., Adloff, F., Androsov, A., et al.: Sea-level rise in Venice: historic and future trends (review article), Nat. Hazards Earth Syst. Sci., 21, 2643–2678, https://doi.org/10.5194/nhess-21-2643-2021, 2021.

Zore-Armanda, M.: Les masses d'eau de la mer Adriatique, Acta Adriat., 10, 5–88, 1963.

Zore-Armanda, M.: Natural characteristics and climatic changes of the Adriatic Sea, Acta Adriat., 32(2), 567–586, 1991.

Zore-Armanda, M., Bone, M., Dadić, V., Morović, M., Ratković, D., Stojanoski, L., et al.: Hydrographic properties of the Adriatic Sea in the period from 1971 through 1983, Acta Adriat., 32(1), 1–547, 1991.