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Review

The BiOS mechanism: History, theory, implications

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ABSTRACT

Over the past four decades, the understanding of Mediterranean oceanography has evolved considerably. From a purely stationary view, there has been a shift to a concept that considers the Mediterranean as a highly dynamic sea in which ocean-typical processes occur on smaller spatial and temporal scales. The recent discovery of the mechanism called BiOS (Adriatic-Ionian Bimodal Oscillating System) has further highlighted the highly variable nature of Mediterranean oceanography and the interconnectedness of its sub-basins.

The BiOS is a mechanism by which the deep thermohaline cell of the eastern Mediterranean, originating in the southern Adriatic, is connected to the upper circulation of the Northern Ionian Gyre via positive feedback, causing a decadal circulation change that leads to a redistribution of salt throughout the Mediterranean.

The effects of this variability are manifold: decadal modulations of the intensity of winter convection in the southern Adriatic, with variations in the volume and thermohaline properties of the dense water produced; variations in preconditioning in the eastern Mediterranean, affecting the salinity of the intermediate Levantine waters; influence on biodiversity in the Adriatic due to the import of Lessepsian organisms or those of western Mediterranean and Atlantic origin; variations of the trophic regime in the Ionian Sea due to the different vertical dynamics of the nutricline during the cyclonic or anticyclonic circulation of the Northern Ionian Gyre; significant contribution to the preconditioning of the northwestern Mediterranean Sea by the salinity variability of the Levantine Intermediate Water.

In this study, the BiOS mechanism, the underlying theory, and the implications for the oceanographic features of the Mediterranean Sea are presented, based on the extensive literature published in the last three decades and some new analyses.

1. Prologue

The recent discovery of the Adriatic-Ionian Bimodal Oscillating System mechanism (BiOS; Gačić et al., 2010) has once again demonstrated the high-level variability of the Mediterranean Sea and the strong interconnection of its sub-basins.

The decadal reversals of the Ionian Sea circulation, which is the most prominent expression of the BiOS, affect the pathways of the saltier Levantine Intermediate Water (LIW), the Levantine Surface Water (LSW), and the fresher Atlantic Water (AW), leading to decadal variations in the thermohaline cells of the Mediterranean Sea. Thus, the effects of BiOS at the basin scale are likely to be remarkable.

A conceptual diagram of the relationships between the circulation of the North Ionian Gyre (NIG) and the resulting processes in the Mediterranean Sea is shown in Fig. 1, which should help the reader understand the many closely related aspects that characterize the BiOS mechanism.

Table 1 shows the list of acronyms used in the text.

2. Introduction

The Mediterranean Sea is a relatively small body of water (Fig. 2). It accounts for 0.7% and 0.3% of the global ocean surface and volume, respectively. It is characterized by atmospheric forcing and fundamental oceanic processes such as surface wind stress, buoyancy fluxes, deep convection, mesoscale variability, and basin scale conveyor belt that

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also occur in the World Ocean but on shorter spatial and temporal scales. Attention to the Mediterranean Sea has recently increased as it is considered one of the most important climate hotspots (Giorgi, 2006).

In Fig. 2 some features of the general circulation in the Mediterranean Sea are depicted.

Undoubtedly, a crucial event in the oceanographic history of the Mediterranean Sea was the discovery of the Eastern Mediterranean Transient (EMT; Roether et al., 1996), which can be summarized as the abrupt change in the configuration of the intermediate/deep thermohaline cell of the Eastern Mediterranean (EMed). One of the most important (and almost neglected) questions regarding the EMT was related to the fact that it was essentially a switch between the two potential sources of Eastern Mediterranean (EMed) deep water, one in the Southern Adriatic (SA), the other in the Cretan Sea (CS). The questions were: *why did SA stop (or largely reduce) its winter convective activity just when very dense water was accumulating in CS? Was this a simple coincidence or the result of a complex process involving both areas?*

Theocharis et al. (2002) presented observational data on the condition of the EMT during 1997–1999. They found that due to the reversal of the anticyclonic circulation to cyclonic in the Ionian Sea (IS), the AW did not spread into the Northern Ionian, but passed through the Cretan Passage and then entered the Levantine Basin (LB) and the Aegean Sea (AeS). This implied a remarkable change in the salinity balance between the Adriatic Sea (AS) and the AeS, with changes in the properties of the water masses formed there.

Tsimplis et al. (2006) wrote: "*Curiously, the recently observed initiation of dense water formation in the Aegean Sea was accompanied by diminution of deep water formation in the Adriatic.*" The authors added that the formation of dense water could be influenced by the alternating supply of saline Levantine water (surface and intermediate) to the two sites.

Pisacane et al. (2006), using empirical orthogonal functional analysis (EOF) of the results of general oceanic circulation models, found that the prevalence of dense water of Aegean origin (during the EMT) was related to the reduced formation rate in the SA. In addition, they emphasized the potential importance of internal variability and reconsidered the role of atmospheric forcing in determining the state of the Mediterranean basin and phenomena such as the EMT. In summary, the authors were first to argue that internal variability likely modifies the preconditioning (salt and heat) at the two sites in an anticorrelated manner, and that atmospheric forcing then produces the final effect (deep water formation).

Comparative studies in the SA, CS, and IS over the past 30 years shed light on the oceanographic processes in these areas and the mechanisms that link their behavior (see Cardin et al., 2015, and references therein).

Table 1
List of acronyms.

AdDW	Adriatic Deep Water
ADT	Absolute Dynamic Topography
AeS	Aegean Sea
AS	Adriatic Sea
AW	Atlantic Water
BiOS	Adriatic-Ionian Bimodal Oscillating System
CS	Cretan Sea
CSOW	Cretan Sea Outflow Water
CDW	Cretan Deep Water (formerly CSOW)
DOC	Dissolved Organic Carbon
EMed	Eastern Mediterranean Sea
EMDW	Eastern Mediterranean Deep Water
EMT	Eastern Mediterranean Transient
ICI	Ionian Circulation Index (as defined in Lavigne et al., 2018)
IS	Ionian Sea
LB	Levantine Basin
LIW	Levantine Intermediate Water
LSW	Levantine Surface Water
MA	Middle Adriatic
NAdDW	North Adriatic Dense Water
NA	Northern Adriatic
NIG	North Ionian Gyre
NML	Nutrient Maximum Layer
SA	Southern Adriatic
SC	Sicily Channel
WMDW	Western Mediterranean Deep Water
WMed	Western Mediterranean Sea
WMT	Western Mediterranean Transition
WSC	Wind Stress Curl

In the following sections, we will highlight the fundamental role of the Northern Ionian circulation in linking the variability of thermohaline and biogeochemical properties of different areas in the Mediterranean Sea.

3. The BiOS mechanism

3.1. Circulation in the central Mediterranean

In the central Mediterranean, consisting of the Ionian and Adriatic Seas, the IS represents the crossroads of the main Mediterranean waters, i.e. the AW and the LIW, characterized by a salinity contrast and occupying the surface and intermediate layers, respectively.

The first detailed description of the central Mediterranean circulation (Fig. 3) was presented by Robinson et al. (1991), where, based on hydrographic data from POEM (Physical Oceanography of the Eastern

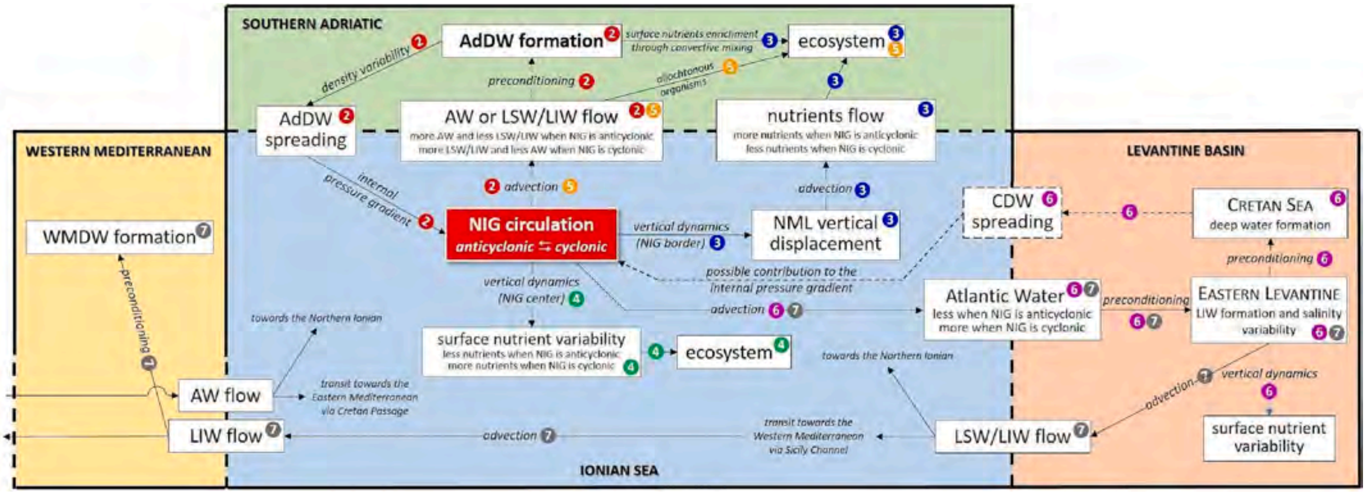

Fig. 1. Schematic representation of the relationships between the circulation of the North Ionian Gyre and various processes in the Mediterranean Sea. The colored numbers refer to the corresponding sections in the text.

Mediterranean) project for 1986 and 1987, they showed the large anticyclonic meander of the Atlantic-Ionian Stream (see also Malanotte-Rizzoli, 1997).

The surface circulation shows the inflow of the prominent Atlantic-Ionian Stream (AIS, or MAWJ, i.e., Modified Atlantic Water Jet, according to the old terminology) from the Sicily Channel (SC) as a continuation of the North African Current. It then passes through the Cretan Passage and eventually enters the LB becoming the Mid-Mediterranean Jet (MMJ). The presence of the permanent Pelops Gyre as well as of the Syrta Gyre was evidenced by Robinson et al. (1991), Malanotte-Rizzoli et al. (1997), and Pinardi et al. (2015). Pressed along the western Ionian coast, the wind-induced Messina Rise Vortex is a recurrent feature, but it varies in form and intensity (Pinardi et al., 2015; Menna et al., 2019a,b; Reyes-Suarez et al., 2019). In the early 1990 s, the prevailing idea was that the average Mediterranean circulation was very well approximated by the steady motion. However, altimetry data after 1992 indicated that the anticyclonic meander persisted only until 1997 (Criado-Aldeanueva et al., 2008), and then the entire area of the Northern Ionian was occupied by a large cyclone. Remarkably, the Pelops Gyre disappeared during the period between 1992 and 1997, as described by Menna et al. (2019a,b), i.e., during the time when CS was the main source of EMDW. According to Menna et al. (2019a,b), the presence of the Pelops Gyre in 1986 and 1987 was an indication that the Adriatic was the main source of the Eastern Mediterranean Deep Water (EMDW). Only its disappearance after 1991 indicates the overwhelming influence of the CS as a deep water source. The explanation for the absence of the Pelops Gyre after 1991, i.e., during the EMT, is that the Cretan Deep Water (CDW) exited through the Cretan Straits and spread northward along the eastern Ionian flank, incorporating the area of the Pelops Gyre. The dense water flow generated the cyclonic vorticity in the surface layer, which overwhelmed the anticyclonic wind curl forcing of the Pelops Gyre. The mechanism of cyclonic vorticity generation was explained in terms of the water column stretching due to the sinking of dense water along its path on the continental slope (Menna et al., 2019a, b; Rubino et al., 2020; Gačić et al., 2021).

The third water mass in the central Mediterranean is the EMDW, which, as mentioned above, is formed in the IS mainly by the contribution of the Adriatic Deep Water (AdDW) and, only under certain climatic and oceanographic conditions, the CDW. From the Adriatic Sea (AS), the AdDW leaves the Strait of Otranto and spreads along the western continental slope, where it slowly sinks into the Ionian abyss. There is evidence that the AdDW also propagates along the eastern continental slope during the cyclonic circulation of the NIG, which is due to the vertical flow shear and the two-layer structure of the Ionian circulation (Malanotte-Rizzoli et al., 1997). When CS was the main source, the dense water flowed across the Cretan Straits (mainly east of Crete), spread into LB, migrated westward, and then turned northward along the eastern Ionian continental slope.

3.2. Adriatic Sea circulation and deep water formation

The surface circulation of the AS is characterized by a large basin-wide cyclonic gyre in which sub-basin scale gyres are embedded (Fig. 4): Northern Adriatic Gyre, Middle Adriatic Gyre and Southern Adriatic Gyre (see Cushman-Roisin et al., 2001, and references cited therein). The precipitation prevails over evaporation implying that the AS is a freshwater source for the IS.

The same basin-wide cyclonic pattern is found in the intermediate layer, where the LIW enters the AS on the east side of the Strait of Otranto, while on the west side the cold and relatively fresh AdDW exits, which then represents the main component of the EMDW. Due to its geographical position and particular climatic conditions (northernmost area of the Mediterranean and strong continental air outbreaks in winter, i.e. the Bora wind), AS is an important place for the formation of dense water.

The formation of dense water occurs in the AS both in the shallow shelf area of the Northern Adriatic (NA) and in the southern Adriatic Pit, where the three necessary conditions for triggering the process are present: cyclonic circulation (Fig. 4), strong heat losses associated with the bora wind, and the presence of salty water of Ionian origin brought by the EAC, in the subsurface or in the intermediate layer, namely LSW and LIW. (Malanotte-Rizzoli, 1991; Bergamasco et al., 1996).

After its formation, the North Adriatic Dense Water (NAdDW) spreads southward along the continental slope of the west coast in the form of a vein (Malanotte-Rizzoli, 1977; Artegiani and Salusti, 1987), driven by the basin-wide cyclonic circulation (Fig. 4). Some of this water

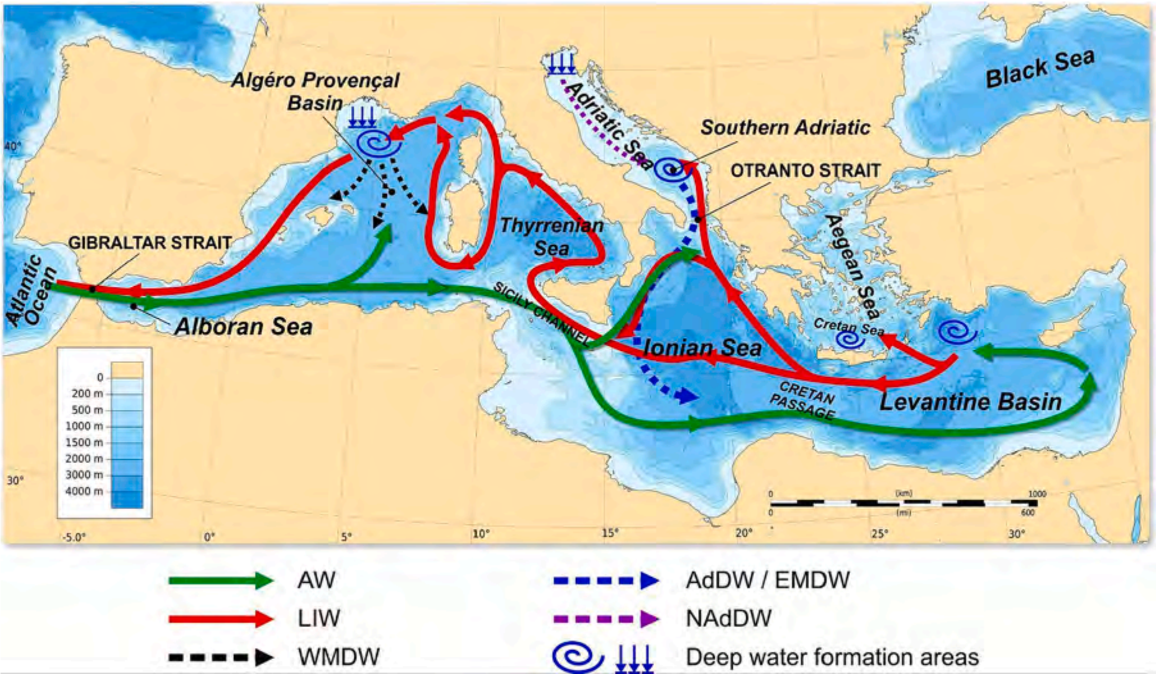

Fig. 2. The Mediterranean basin and its circulation. See Tab. 1 for the acronyms.

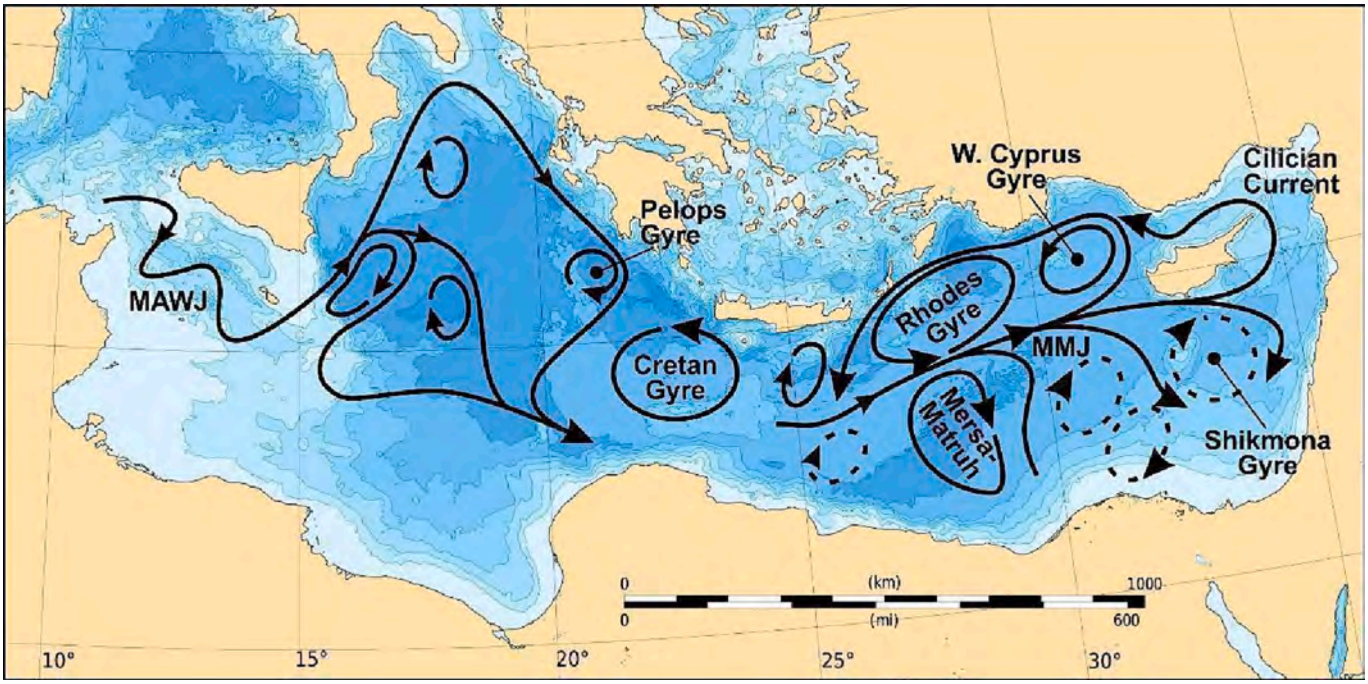

Fig. 3. Eastern Mediterranean circulation according to data from POEM 1986 and 1987 (adapted from Malanotte-Rizzoli et al., 1997). AIS: Atlantic Ionian Stream; MAWJ: Modified Atlantic Water Jet; MMJ: Mid Mediterranean Jet.

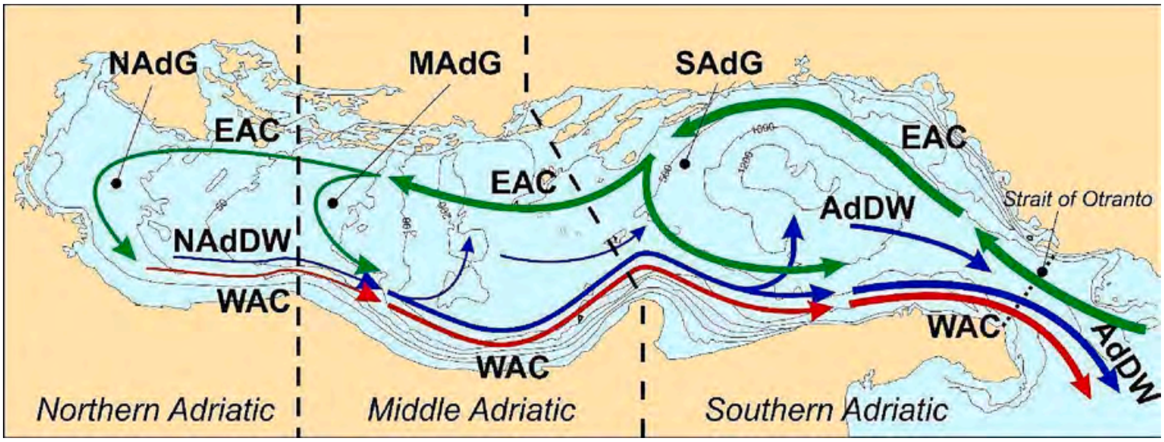

Fig. 4. Circulation in the Adriatic Sea (adapted from Tomobe03, 2012). AdDW: Adriatic Deep Water; EAC: Eastern Adriatic Current; MAdG: Middle Adriatic Gyre; NAdG: North Adriatic Gyre; NAdDW: North Adriatic Dense Water; SAdG: South Adriatic Gyre; WAC: Western Adriatic Current.

sinks into the bottom layer of the southern Adriatic Pit and contributes about 25% to the formation of the AdDW (Mantziafou and Lascaratos, 2004). The rest of the water column is renewed by the local winter open-ocean convection at the center of the SA cyclonic gyre (Fig. 4), reaching 700–800 m depth. The depth of mixing and the amount of dense water formed depend on winter climatic conditions and on the haline pre-conditioning. The AdDW flux across the Strait of Otranto can reach about 0.5 Sv (Vilibić and Orlić, 2002).

In summary, the AdDW is a mixture of dense water formed at the northern shelf by vertical mixing and deep water formed in the center of the South Adriatic Gyre by the open-ocean convection. The AdDW formation rate is variable on the interannual time scale (Lascaratos, 1993; Manca et al., 2001).

3.3. Variability in the Adriatic Sea: The Adriatic ingression theory

It is well known that salinity in the AS shows considerable decadal variability. This phenomenon has been called Adriatic Ingression, a term coined by Buljan (1953) after a detailed analysis of the results of oceanographic surveys conducted in the first half of the 20th century in the AS. The Adriatic Ingression refers to the cyclic increase of salinity in the Southern and Middle Adriatic, which, according to the original explanation, was due to the intensification of the flow of salty intermediate water (LIW) from IS through the Strait of Otranto (Buljan, 1953; Zore-Armanda, 1971). Zore-Armanda and Pucher-Petković (1976) correlated Adriatic Ingression events with changes in meteorological factors in the southern Mediterranean, such as the average annual pressure difference between Trieste and Athens.

In the ingression phase, the Adriatic Ingression implies a sudden increase of salty LIW in the AS (salinity up to 39), followed by a period of decreasing salinity (regression; S up to 38.48) when both the inflow through the Strait of Otranto and the salinity of the LIW decrease.

Buljan noted that during the ingressions, the increase of water inflow through the Strait of Otranto was accompanied by an increase in salinity and that the thickness of the layer with the highest salinity also increased and reached the surface. Obviously, in this case, there was a large influx of more saline intermediate and surface water from the LB. Buljan explained that the ingressions were the result of an intensification of the cyclonic circulation in the IS, which was related to a certain degree to the pressure patterns over the Mediterranean Sea. The view of a stationary circulation in the Mediterranean Sea still held, but unlike the variations in the amount of water entering the AS, the variations in salinity were more difficult to explain. Buljan discussed three hypotheses: (i) variability of the AW flux through the Strait of Gibraltar; (ii) variability of the inflowing AW salinity; (iii) oscillation of the E-P factor (evaporation-precipitation) in the Mediterranean Sea. Buljan suggested that all these three sources of variability could contribute to the salinity oscillations in the Mediterranean Sea. However, due to the lack of continuous observations over longer time periods, Buljan was unable to provide conclusive answers to the question regarding decadal variability, which is the true scale of the Adriatic Ingression.

Interestingly, at the time of his work Buljan was waiting for the publication of data collected by the R/V Atlantis in 1948 during the Mediterranean expedition to confirm his expectation of an increase in salinity in accordance with the decadal fluctuation already assumed. From the Mediterranean Medatlas time series elaborated by Rixen et al. (2005) and presented by Gačić et al. (2013), we know that salinity did indeed increase in 1948 as Buljan expected in IS.

It was clear from Buljan's work that his attempts to correlate the variability of salinity in the Mediterranean Sea with the variability of salinity and flux of AW in the Strait of Gibraltar, the so-called Atlantic transgressions (Le Danois, 1934), were not satisfactory and retained their hypothetical character.

The other part of the story of salinity in the AS that needed to be explained was the regression, that is, the return of the AS to "normal" salinity conditions after the ingression event. Unlike the increase in salinity, Buljan did not assert an extra-Adriatic mechanism in this case. A gradual decrease in salinity in the AS was the result of the prevailing inflow of freshwater from northern rivers and its progressive advection and mixing to the south. In other words, after the influence of extra-Adriatic forcing, the increase in salinity weakened and finally stopped, then the dilution operated by rivers re-established the "normal" salinity conditions (Buljan, 1953).

Another aspect of the Adriatic Ingression mechanism concerns the nutrient dynamics. Buljan (1964) and Buljan and Zore-Armanda (1976) compared phosphate and total P concentrations in the intermediate layer of the AS and found higher phosphate levels in the SA than in the Jabuka Pit (Middle Adriatic). They argued that the IS was an important source of phosphorus compounds for the AS, especially at the time of ingressions.

In summary, according to the Adriatic Ingression theory, the decadal variability of salinity and nutrient content in the southern and Middle Adriatic was explained by the variability of the inflow of Ionian waters, with the more saline and nutrient-rich LIW being the main component. The cause of the Adriatic Ingression was associated with the meridional atmospheric pressure gradient over the AS.

3.4. The reversals of the Ionian circulation

Circulation in the upper layer of IS is subject to reversals on a decadal scale (Fig. 5).

Starting from the first observed reversal in 1997, Theocharis et al. (1999), Manca et al. (2003), and Borzelli et al. (2009) explained the change in circulation with the spreading of CDW (formerly CSOW) in the Ionian abyssal layer during the second phase of the EMT. During 1995–1997, CDW occupied mainly the eastern and northeastern flanks of the Ionian basin, resulting in a bottom pressure gradient toward the center of the basin. This gradient supported the anticyclonic circulation in the upper thermocline layer. After 1997, CDW increasingly mixed into the central abyssal part of the Ionian (Roether et al., 2007), leading to a reversal of the bottom pressure gradient, with the flank of the basin occupied by AdDW, which was less dense than the CDW. This led to a reversal of circulation in the upper layer as well, which changed from anticyclonic to cyclonic. Absolute Dynamic Topography (ADT) maps show the sudden change in sea surface structure (Fig. 5).

Reversals occurred again in 2006, 2011, and 2018, as indicated by the altimetry data recorded to date (Fig. 5), suggesting that this phenomenon generally occurred with a time scale of about five years and was not necessarily related to the EMT. The circulation pattern has been termed the NIG by Gačić et al. (2011).

The first consequence of the reversal of the Ionian circulation is the changing pathway of AW, which flows more easily northward into the Ionian interior during the anticyclonic phase, while during the cyclonic phase it is preferentially directed eastward toward LB (Fig. 6). The path of the LIW is also influenced by the Ionian circulation, but in the opposite way: when NIG is anticyclonic, the LIW moves eastward directly toward the SC; on the other hand, the cyclonic NIG favors the LIW path northward along the eastern boundary of the IS (Fig. 6).

The resulting salinity in the IS is affected by the circulation regime: lower salinity during the anticyclonic phase and higher salinity during the cyclonic phase.

Finally, the variability of salinity in the IS is the source of the salinity changes in AS.

3.5. The Adriatic-Ionian Bimodal Oscillating System

The first evidence of the specific behavior of the IS came from studies addressing the sea level trends in the Mediterranean from the altimetric data (Cazenave et al., 2001; Vigo et al., 2005). They noted the negative trend of sea level of about −10 mm/year in the IS between January 1993 and December 1999, in contrast to what was observed in the rest of the Mediterranean, without giving a clear explanation (see the revised trend 1993–1999 in Fig. 7, obtained from ADT data). The negative trend was observed because the sea level time series was relatively short with respect to the temporal variability associated with the decadal inversions of the NIG circulation.

In the first attempts to calculate the sea level trend in the Mediterranean, there was no knowledge of the pronounced decadal circulation variations in the IS, so no reliable explanation could be offered at that time. It was not until Gačić et al. (2010) that the phenomenon of cyclic NIG inversions found its full explanation in the form of the mechanism called the BiOS.

In conjunction with the anticyclonic/cyclonic circulation mode in the IS, less salty AW/saltier (LIW/LSW) is advected into the AS (Fig. 6). This water then participates in the winter convection, which is responsible for the variations in volume and density of the water formed. In the post-convection period, the AdDW spreads into the IS with a higher or lower density than the ambient Ionian deep water, changing the orientation of the horizontal pressure gradient. During the cyclonic mode of the NIG, the AdDW propagates with progressively higher density into the IS, mainly following its preferred path along the Italian continental slope and, in some cases, along the eastern continental slope (Malanotte-Rizzoli et al., 1997). This leads to a lowering of sea level along the AdDW path, creating the density gradient toward the coast and the resulting surface geostrophic flow toward the north (transition to anticyclonic mode). Therefore, the cyclonic circulation weakens, and after a certain time the anticyclonic flow takes its place. Conversely, during the anticyclonic phase of the NIG relatively fresh AW enters the AS, leading to a decrease in AdDW density. The latter penetrates into the IS along the western side, creating a condition where sea level is higher than in the center of the gyre, producing a sea surface pressure gradient responsible for the southward geostrophic flow that eventually overwhelms the northward branch of the Ionian anticyclone, again creating the cyclonic basin-wide gyre. In the layer above the AdDW vein, the northward geostrophic flow is generated by the surface layer pressure gradient in the opposite direction. As shown in laboratory experiments (Rubino

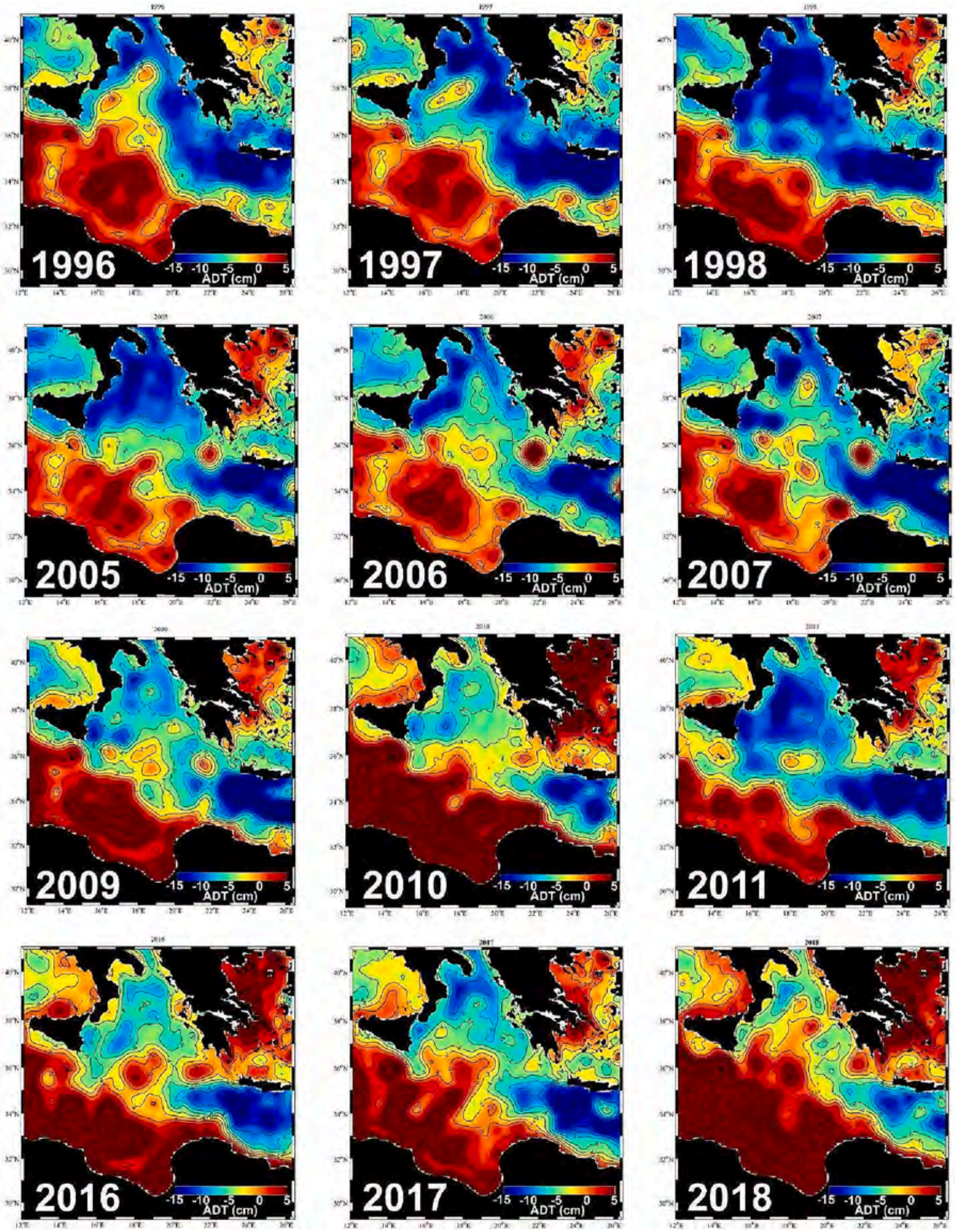

Fig. 5. Four reversals of the North Ionian Gyre circulation in the period 1996–2018. Maps created from Copernicus Marine Services Absolute Dynamic Topography (ADT) data using the method of Rio et al. (2014).

et al. 2020; Gačić et al., 2021), the IS behaves asa two-layer system.

3.6. *The inversions of the NIG: Internal or wind driven process?*

3.6.1. *Vorticity considerations: Theoretical and experimental explanations*

The vorticity balance of the upper layer is governed by the equation (see, e.g., Pedlosky, 1986):

$$\frac{\partial \zeta}{\partial t} = \frac{(\nabla p \times \nabla \rho)_z}{\rho^2} + f\frac{\partial w}{\partial z} + \frac{1}{\rho H}[curl\tau]_z$$

where ζ =(∂v/∂x)-(∂u/∂y) is the vertically averaged flow vorticity, w is the vertical component of the velocity, H is the thickness of the upper layer, ρ and p are density and pressure, respectively, and τ is the wind stress. Using dimensional considerations, Gačić et al. (2010) showed that the wind torque (third term in the above equation) is of secondary importance in generating the NIG inversions and supporting the basin-

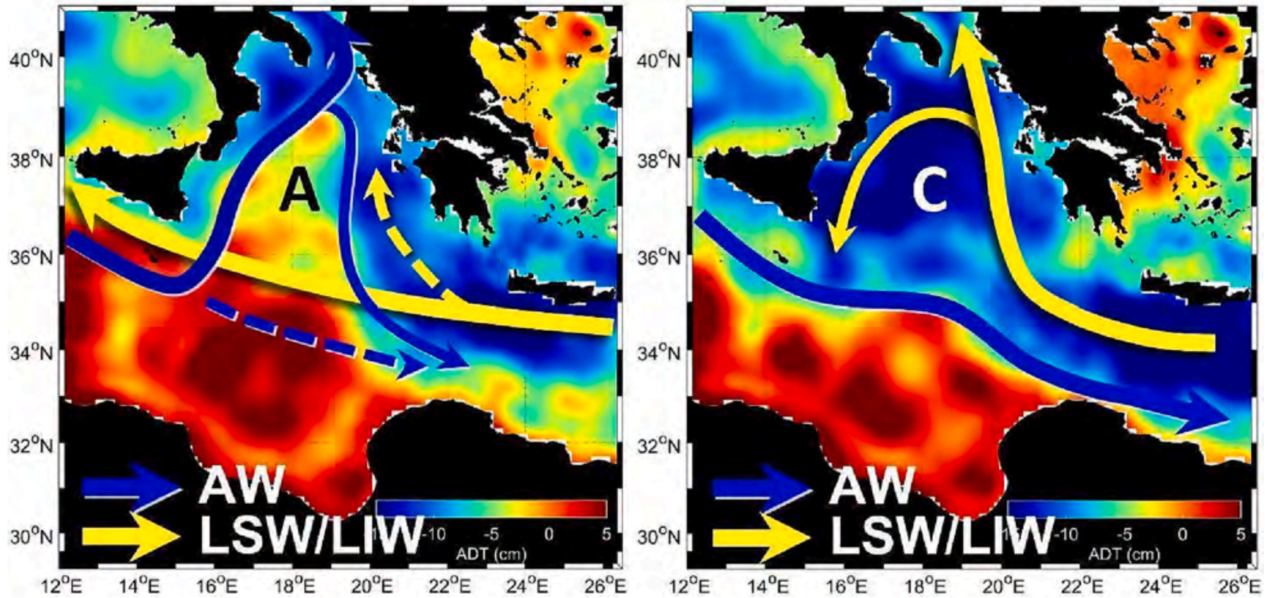

Fig. 6. Schematic representation of the two circulation modes in the Ionian Sea. A: anticyclonic circulation (left); C: cyclonic circulation (right). The effects of circulation reversal are the variation of AW and LIW paths. Annual mean ADT distributions in 1995 (left) and 1999 (right) are shown in the background.

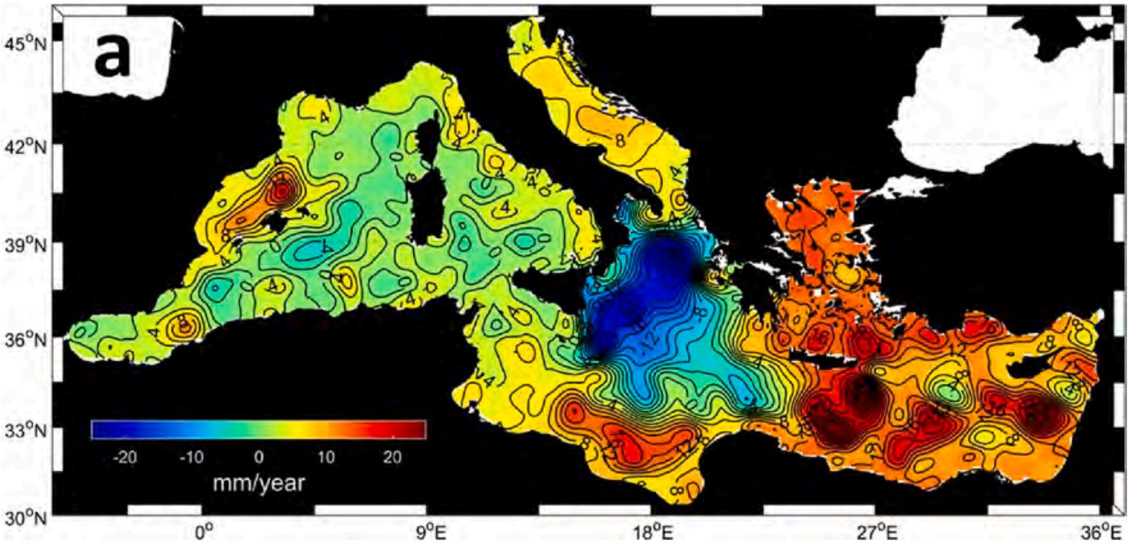

Fig. 7. Average sea level trend from ADT data in the Mediterranean for the period 1993–1999. Original ADT data from Copernicus Marine Services.

wide circulation, being almost one order of magnitude smaller than the baroclinic and the tube stretching terms (first and second terms in the above equation, respectively). In this way, it was shown that internal oceanic processes such as the tube stretching could be of central importance in determining circulation in the upper layer of the NIG.

On the other hand, Nagy et al. (2019) and Pinardi et al. (2015) have proposed, based mainly on numerical modeling, that wind is the main driving force for such pronounced variations in the circulation. Borzelli and Carniel (2023) have recently proposed a new possible energy source to trigger the BiOS mechanism using a two-layer analytical model. According to these authors, an internal Kelvin-like wave forced by a uniformly rotating wind can change the shape of the free surface, as result of the competing effects of wind and internal fluid pressure fields, and periodically generate the anticyclonic and cyclonic modes.

The vorticity equation for small Rossby number for the flat bottom and the Absolute Dynamic Topography (ADT) was qualitatively compared with the wind stress curl (WSC) for the entire central Mediterranean (Fig. 8a, b).

Similar patterns, where a negative wind stress curl corresponds to positive ADT values (negative geostrophic flow vorticity) and vice versa, are found in most of the areas considered: the southern part of the IS, the Cretan Passage, the SC, and the southern Tyrrhenian Sea. There is also evidence that the Pelops Gyre is a wind-driven phenomenon, since the negative WSC area and the local ADT maximum coincide. In the northern Ionian, however, the similarity between the two fields is completely absent: the ADT field is negative throughout the area (Fig. 8a), while the WSC field is negative in the west and positive in the east (Fig. 8b), suggesting a different influence of the wind field on the Ionian flanks. The northern Ionian is the only part of the central Mediterranean where the two fields are physically independent. In addition, the variability of the WSC was compared with the temporal variations of the second EOF ADT mode, PC2 (Fig. 8d), to find possible relationships between the wind curl forcing and the ADT pattern on the decadal (BiOS) scale. Note that the ADT PC2 contains the pattern mainly related

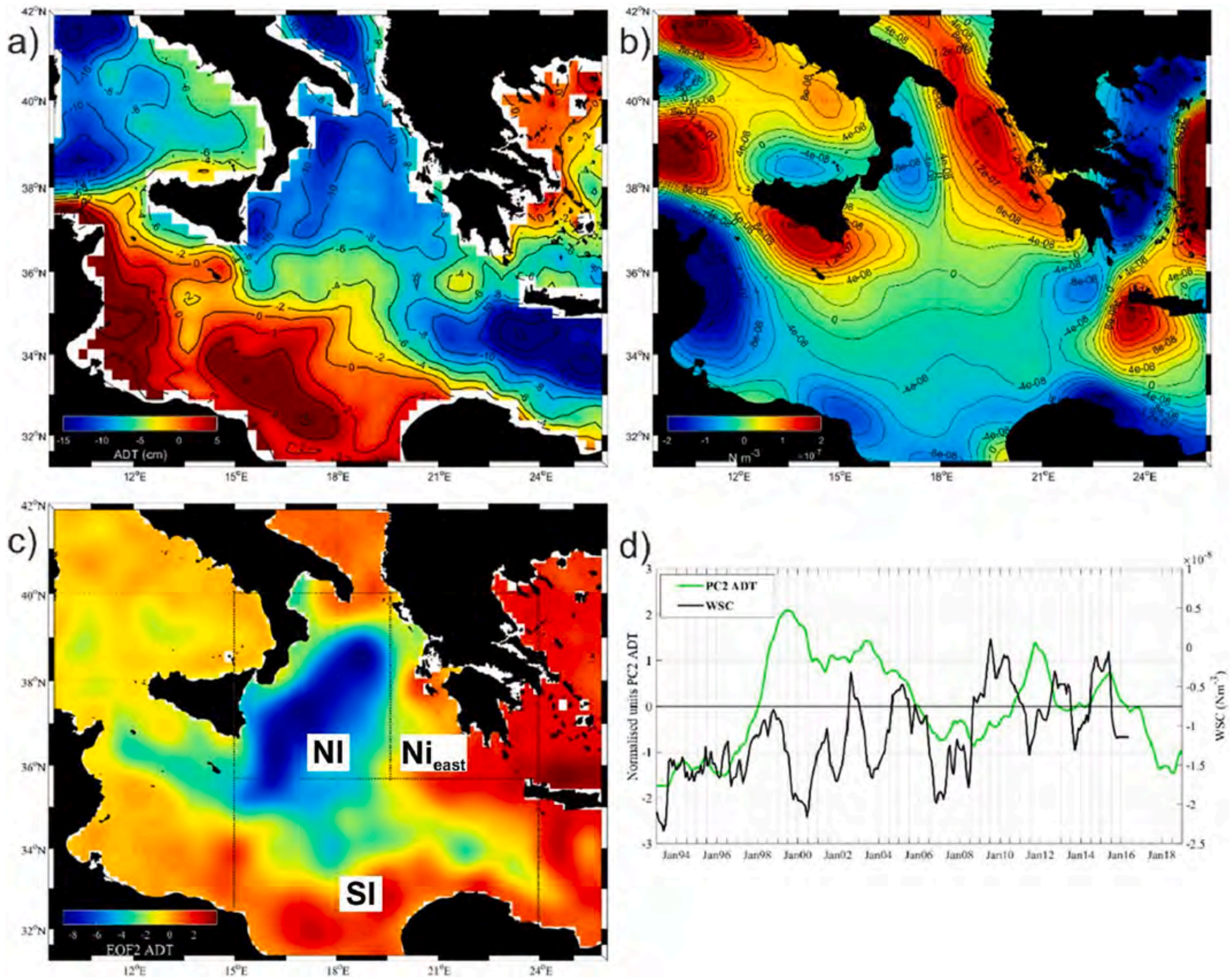

Fig. 8. Maps of ADT (a) and wind stress curl (b) averaged over the period 1993–2016. Spatial distribution of ADT EOF2 (exp. variance of 17.5%) (c), and temporal variations in amplitude of ADT PC2 and wind stress curl filtered by 13-month moving average (d). NI: northern Ionian; SI: southern Ionian; NIe: northern Ionian east. Wind stress curl (WSC) derived from the Cross-Calibrated Multi-Platform (CCMC) winds. To account for the low Rossby number dynamics, all high-frequency variability were filtered with timescales shorter than a seasonal time scale, applying a 13-month moving average to the ADT and wind curve time series.

to the BiOS-induced decadal variability of sea level. It is evident that the main amplitude of the ADT EOF2 (Fig. 8c) is concentrated in the northwestern part of the IS, as it was already shown by Gačić et al. (2011). There is also significant interannual variability in the Gulf of Sirte, probably related to the varying position of the mean Mediterranean jet caused by the cyclonic/anticyclonic BiOS mode (Fig. 8a). The spatial pattern of the WSC (Fig. 8b) is characterized by different structures than that of the ADT (Fig. 8a), and the core of the large variability is located south of Crete, east of the Greek coast, and south of Sicily (Fig. 8b), features that are probably related to the orography of the coast. The temporal evolution of the ADT PC2 (Fig. 8d) shows the pronounced decadal variability related to the BiOS mechanism, while the WSC shows an interannual variability not related to the decadal inversion of the NIG. As for the correlation between the ADT EOF2 variability and the WSC amplitudes over the whole central Mediterranean area, a weak positive correlation (0.18) is shown (Table 2). It is important to emphasize that the two variables can be considered physically related when the sign of the correlation is negative.

Positive correlation values indicate that the wind vorticity acts “against” the surface current vorticity field. Looking at different parts of the central Mediterranean (see Fig. 8c for area definitions), it can be seen that only regions with a negative correlation, i.e., the southern Ionian (SI) and the eastern part of the northern Ionian (NI east), could be affected by the wind stress, but the correlation coefficients are rather small. On the other hand, the northern Ionian (NI), i.e., the BiOS area, shows a small positive correlation coefficient, indicating that there is no physical link between the WSC and the sea level and consequently the surface circulation pattern.

Table 2
Correlation coefficients and relative p-values (correlation is significant if the p-value less than 0.05) between the ADT PC2 in the subregions defined in Fig. 8c and the WSC averaged over the entire Central Mediterranean region.

	R	p-value
Central Med	0.18	0.0023
Northern Ionian (NI)	0.18	0.0021
Northern Ionian east (NI$_{east}$)	−0.14	0.015
Southern Ionian (SI)	−0.24	6e^{-5}

The analysis of wind and relative current vorticity proposed also by Borzelli and Carniel (2023) in the NI also led to the conclusion that the wind cannot be considered the dominant source of changes in the ocean circulation.

3.6.2. The winter 2012 case study and the CRoPEx laboratory experiments

An unexpected natural test of the effectiveness of the horizontal pressure gradient in determining the reversal of the NIG circulation was provided by the extremely severe winter of 2012 in the AS, when a very cold and dense AdDW formed (max. density anomaly of 30.59 kg m^{-3} in the Gulf of Trieste) and later exported across the Strait of Otranto (max. density anomaly of 29.26 kg m^{-3}), as reported by e.g. Bensi et al. (2016), Mihanović et al. (2013), Gačić et al. (2014), and Chiggiato et al. (2016). In this case, the increase in density was due to the decrease in AdDW temperature caused mainly by the air-sea fluxes, as the thermal forcing outweighed the haline one. The outflow of this very dense AdDW, much denser than the ambient water in IS, caused a temporary inversion of the NIG circulation: the cyclonic surface NIG changed to anticyclonic for only a few months.

Recently, basin-wide circulation inversions on decadal scales of the NIG have also been studied under laboratory conditions (CRoPEx - Coriolis Rotating Platform Experiments; see Rubino et al., 2020; Gačić et al., 2021).

In particular, the role of varying internal forcing induced by changes in the horizontal pressure gradient associated with density variations of AdDW was investigated. A series of laboratory experiments were performed with a two-layer ambient fluid in a circular rotating tank, with densities of 1.000 and 1.015 kg m^{-3} characterizing the upper and lower layers, respectively. The discharge rate and density of the inflowing water varied from one experiment to another. At high density (1.020 kg m^{-3}) and large discharge, the mean flow was relatively stable, i.e., the kinetic energy of the mean flow was stronger than the eddy kinetic energy. Conversely, at a lower density (1.010 kg m^{-3}) and discharge, the vortices were more energetic than the mean flow. The vorticity behaved in a two-layer fashion over the slope region, being cyclonic in the upper layer and anticyclonic in the lower layer. At the same time, a large-scale anticyclonic eddy formed over the central flat-bottom part of the basin in the upper layer, extending partly toward the downslope margin.

The relatively reduced horizontal dimensions of the anticyclonic gyre were shown by the experimental data of Mihanović et al. (2015), who demonstrated that the cyclonic gyre had spatial scale larger than the anticyclonic one. The authors referred to the asymmetry between the two modes of the Ionian surface circulation. In the laboratory experiments, it was shown from the density records that the pycnocline rose due to the sinking of the dense water. It was shown that the rate of increase of the anticyclonic potential vorticity was proportional to the rate of the interface rise. The comparison of laboratory experiments with the real IS was also performed for the situation when the sudden change from cyclonic to anticyclonic circulation occurred after the severe winter of 2012 due to the extreme AdDW overflow. The similarity between the temporal evolution and the vertical structure in the laboratory and under oceanic conditions supported the claim that the wind-stress curl is not of paramount importance with respect to the internal forcing.

3.6.3. Vertical circulation structure

Several studies based on in situ observations, numerical modeling, and laboratory simulation results investigated the vertical extent of the circulation, which in some cases appeared to be coherent throughout the water column (see, e.g., Lazar et al., 2007 in idealized basins), but in experimental conditions and laboratory experiments had an opposite sign in the deep layer compared to the upper one (see, e.g., Kovačević et al., 1999; Rubino et al. 2020; Gačić et al. 2021).

Here we relate in a more detailed manner the internal field of mass to the horizontal sea surface slope, and compare the variations of the sea level gradient with the density gradient calculated from the MEDSEA_REANALYSIS_ PHYS _006_004 dataset (Fig. 9). Consequently, sea level differences between the two points along the north–south line (Fig. 9a) and sea water density differences at the same points (Lavigne et al., 2018) are calculated. The zonal component of the surface geostrophic velocity is proportional to the north–south gradient of sea level, i.e., the velocity of the northern branch of the cyclonic/anticyclonic NIG. On the other hand, the horizontal density gradient provides the vertical shear via the thermal wind relation.

As expected, when the sea level gradient is negative, the density gradient ρS1-ρS2 is positive and vice versa (Fig. 9b, c). Thus, the anticyclonic flow (eastward geostrophic velocity) is associated with the southward density gradient. The westward geostrophic current (cyclonic BiOS mode) is associated with the northward density gradient. According to the thermal wind relationship, both the eastward and westward flow reduce with depth. Thus, considering the calculated average horizontal density gradient, we can estimate that the zero-crossing of the geostrophic flow occurs at a depth of 600–800 m, and thus the IS behaves like a two-layer ocean. It is important to note the long-term decrease in the eastward geostrophic flow (i.e., the amplitude of the anticyclonic BiOS mode) since the 1990s, which can be explained by the long-term decrease in the strength of the anticyclonic BiOS mode. Another explanation could be that the dense water flow reached its

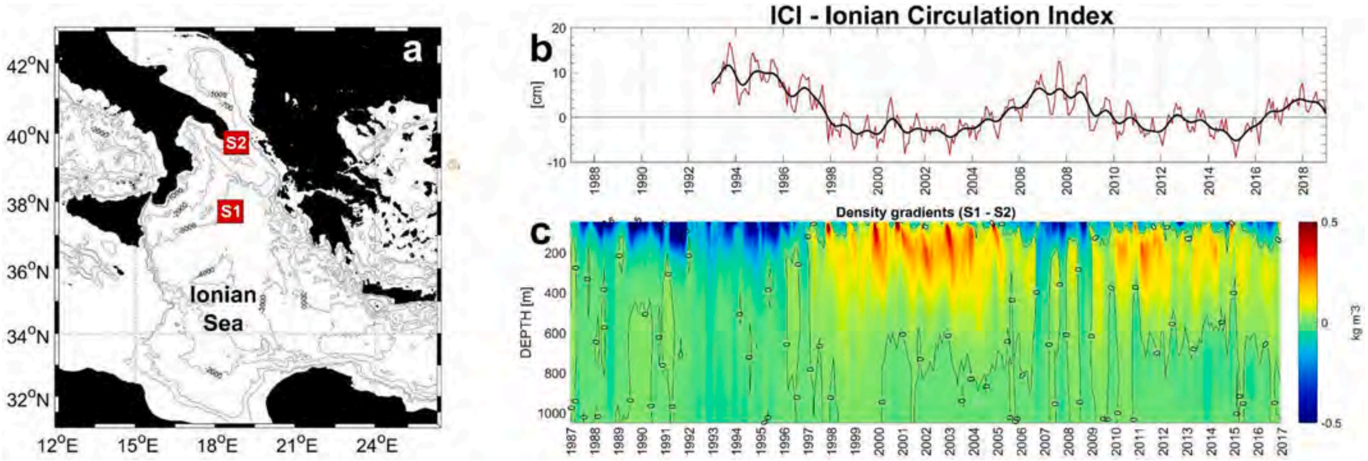

Fig. 9. Comparison between variations of the ICI (b) and density gradients (c) in the NIG. ICI is the sea level difference between the ADT at S1 and ADT at S2. Water column density structure obtained from the MEDSEA_REANALYSIS_ PHYS _006_004 dataset (3D - monthly averages for the entire Mediterranean Sea) for the period from 1987 to 2017. The physical reanalysis component of the Mediterranean Forecasting System is a hydrodynamic model provided by the Nucleus for European Modeling of the Ocean (NEMO), with a variable data assimilation scheme (OceanVAR) for vertical temperature and salinity profiles and satellite-derived sea level anomalies along the track data. The horizontal grid resolution of the model is 1/16° (about 6–7 km) and the unevenly distributed vertical levels are 72 (Simoncelli et al., 2019).

maximum when the CS was its source (EMT phase), i.e., in the 1990s. Thereafter, when the Adriatic recovers as the only source of dense water, its water production is almost an order of magnitude lower than that of the CS, and the amplitude of the induced anticyclonic flow is correspondingly lower.

4. Effects of NIG circulation on biogeochemical and biological dynamics in the Adriatic Sea

4.1. Nutrient variability in the Adriatic Sea

The behavior of nutrient concentration in the SA was one of the features that inspired the formulation of the BiOS mechanism. Analyzing the updated time series of the average nitrate concentration and salinity in the center of the SA Pit in the layer from 200 to 800 m depth[1], Civitarese et al. (2010) evidenced an oscillatory, out-of-phase variation between the two properties (Fig. 10). This result was in contrast to the Adriatic Ingression mechanism (Buljan, 1953), where a covariance of salinity and nutrient concentration was assumed.

Since the northeastern Ionian is the source area for the AS, similarities or differences in the behavior of nutrient distribution should reflect the processes that occur after Ionian water enters the AS. Nutrients in the SA are mainly controlled by the influx of nutrient-rich LIW from the IS across the Otranto sill (about 800 m deep) and by the consumption of autotrophs during the spring bloom. In Fig. 10, nitrate concentrations in SA and the northeastern Ionian appear to be approximately in phase, although absolute values sometimes differ significantly between the two areas.

The increase in nitrate concentration in the IS during the first half of the 1990 s was described by Klein et al. (1999) as the result of the upward shift of the nutricline and the nutrient maximum layer due to the massive spreading of the new CSOW dense water during the second phase of the EMT.

Civitarese et al. (2010) analyzed the horizontal distributions of the nitracline depth (defined as the depth at which the nitrate concentration is 3 μM) in IS in 1987, 1991, 1995, and 1999 (Fig. 11) and showed that the nitracline shoaling at the northeasternmost part occurred as early as 1991, when the CSOW was not yet present in this area. On the other hand, a deeper nitracline was clearly visible in both 1987 and 1999. Thus, it appears that the vertical shift of nitracline was not necessarily related to the spreading of the CSOW. The authors assumed that the vertical position of the nitracline as well as the nutrient maximum layer, should be dynamically maintained by the horizontal circulation.

Comparing the horizontal distribution of nitracline depths in the IS with the circulation regimes of the NIG, Civitarese et al. (2010) found that in 1991 and 1995 nitracline shoaling occurred at the border of the anticyclone, while in 1987 and 1999 the nitracline deepening was remarkable at the border of the cyclone. It became clear that the dynamics associated with the circulation affected the vertical positioning of the nitracline and the maximum nitrate level. In this way, the amount of nitrate (nutrients) inflowing the AS over the Otranto sill was modulated according to the circulation regime of the NIG: more nutrients during anticyclones and less nutrients during cyclones.

4.2. Effects of NIG circulation on ecosystem dynamics in the southern Adriatic

The results presented previously show that the NIG circulation has two effects on the SA: the first effect is the modulation of the salt input to the Adriatic, depending on the amount of fresher AW or saltier LSW/LIW advected, which is due to the anticyclonic or cyclonic circulation of the NIG; the second effect is the regulation of the amount of nutrients supplied to the AS, depending on the vertical shift of the nutrient interfaces at the border of the NIG (upwelled when the circulation is anticyclonic, i.e. more nutrients are supplied, downwelled when the circulation is cyclonic, i.e. less nutrients are supplied).

The SA is an oligotrophic basin characterized by remarkable seasonal variability in phytoplankton abundance and biomass, reaching a maximum in spring (Antoine et al., 1995). Phytoplankton abundance and biomass are generally dominated by low and smaller species (Cerino et al., 2012; Batistić et al., 2019; Jasprica et al., 2022). Sometimes meteorological and oceanographic conditions are favorable for a shift from nano- to micro-phytoplankton, such as recently observed by Cerino et al. (2012) and Ljubimir et al. (2017). Using chlorophyll-a satellite imagery, Gačić et al. (2002) showed that increased biomass production and resulting vertical carbon export were related to the intensity and number of winter convective mixing events that resulted in nutrient inputs to the illuminated layer. The authors therefore concluded that the open ocean convection is the controlling mechanism for the spring phytoplankton bloom at the SA. Batistić et al. (2019) also emphasized the importance of winter meteorological and oceanographic conditions for phytoplankton dynamics at the SA.

Winter bloom in the SA can occur in relation to both circulation regimes of the NIG (Batistić et al., 2019), but it should be noted that nutrients level and haline preconditioning are in counterphase. The anticyclonic NIG increases the buoyancy of the SA, making vertical convection more difficult. On the other hand, the nutricline is shallower and the nutrient content is higher, so even moderate vertical mixing could be sufficient to fertilize the surface layer. This was the case, for example, in 1995 (Fig. 10), when the average salinity in SA was at minimum (about 38.65) but the average nitrate content was maximum (more than 5.5 μmol/L) and the nitracline was relatively shallow (Batistić et al., 2019), less than 100 m deep at the Strait of Otranto (Fig. 11). Conversely, during the cyclonic NIG, surface fertilization of the SA could have been limited by the depth of the nutricline, although the higher salt preconditioning favored a deeper vertical mixing in SA.

Although the data for the northeastern Ionian are insufficient to draw a clear conclusion, it appears that nitrate concentrations in SA are more similar to those in the northeastern Ionian during periods of nutrient maximum and salinity minimum (Fig. 10). These are periods of reduced winter convection, and autotrophic consumption is limited by weak surface nutrient fertilization. In other words, the lack of vertical convection in the SA results in nutrient concentrations approaching those observed in the NE Ionian. This aspect was already noted by Civitarese and Gačić (2001), who used the differences between nitrate concentrations to roughly estimate new production and its interannual variability. Civitarese et al. (2010) hypothesized that there is a possible opposite effect between the magnitude of the haline preconditioning (stronger after the cyclonic phase) and the amount of nutrients present in the basin interior (lower during the same phase) potentially available for new production.

4.3. What about the rest of the Adriatic Sea?

To test the relevance of the impact of the BiOS mechanism on the interior of the AS at least for the Middle Adriatic, oceanographic data between 1960 and 2010 were analyzed at the Palagruža Sill transect by Vilibić et al. (2012). The Palagruža Sill (about 140 m deep) delimits the southern Adriatic to the north and acts as a bathymetric filter for the water flowing northward on the eastern side of the Adriatic (Fig. 4). The time series of de-seasoned temperature, salinity, dissolved oxygen, and nutrients concentration showed decadal variability, similar to the values previously reported by Civitarese et al. (2010) for the SA. In contrast to the latter, Vilibić et al. (2012) hypothesized for the 1991–1998 period that a significant amount of WMed water lying below the AW entered via

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[1] The 200–800 m layer is the part of the water column where the averaged concentrations of nutrients and salinity are considered. This layer is partially separated from the influence of surface variability and reaches the depth of the Otranto sill, over which the exchange between SA and the Ionian Sea takes place.

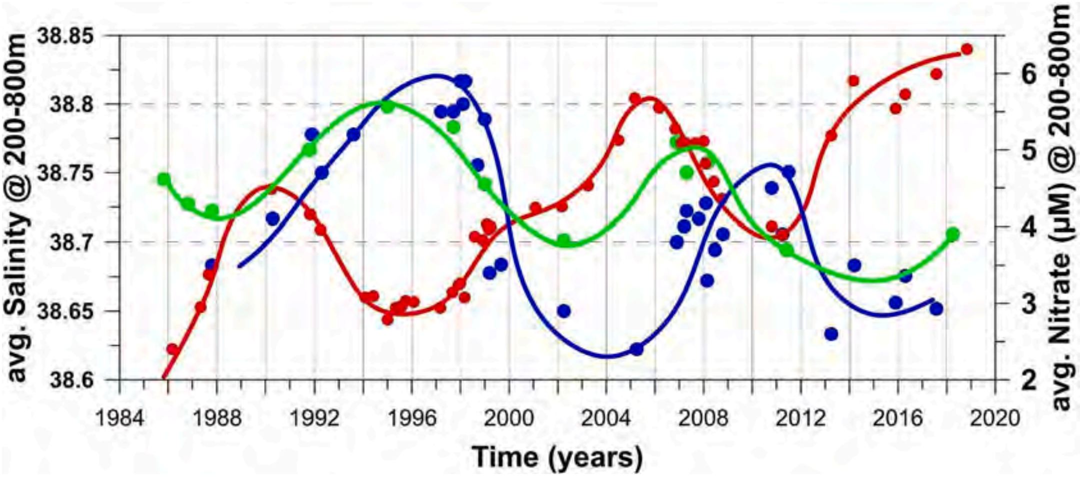


Fig. 10. Averaged nitrate concentrations in SA (blue line), in northeastern Ionian (green line), and salinity in SA (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

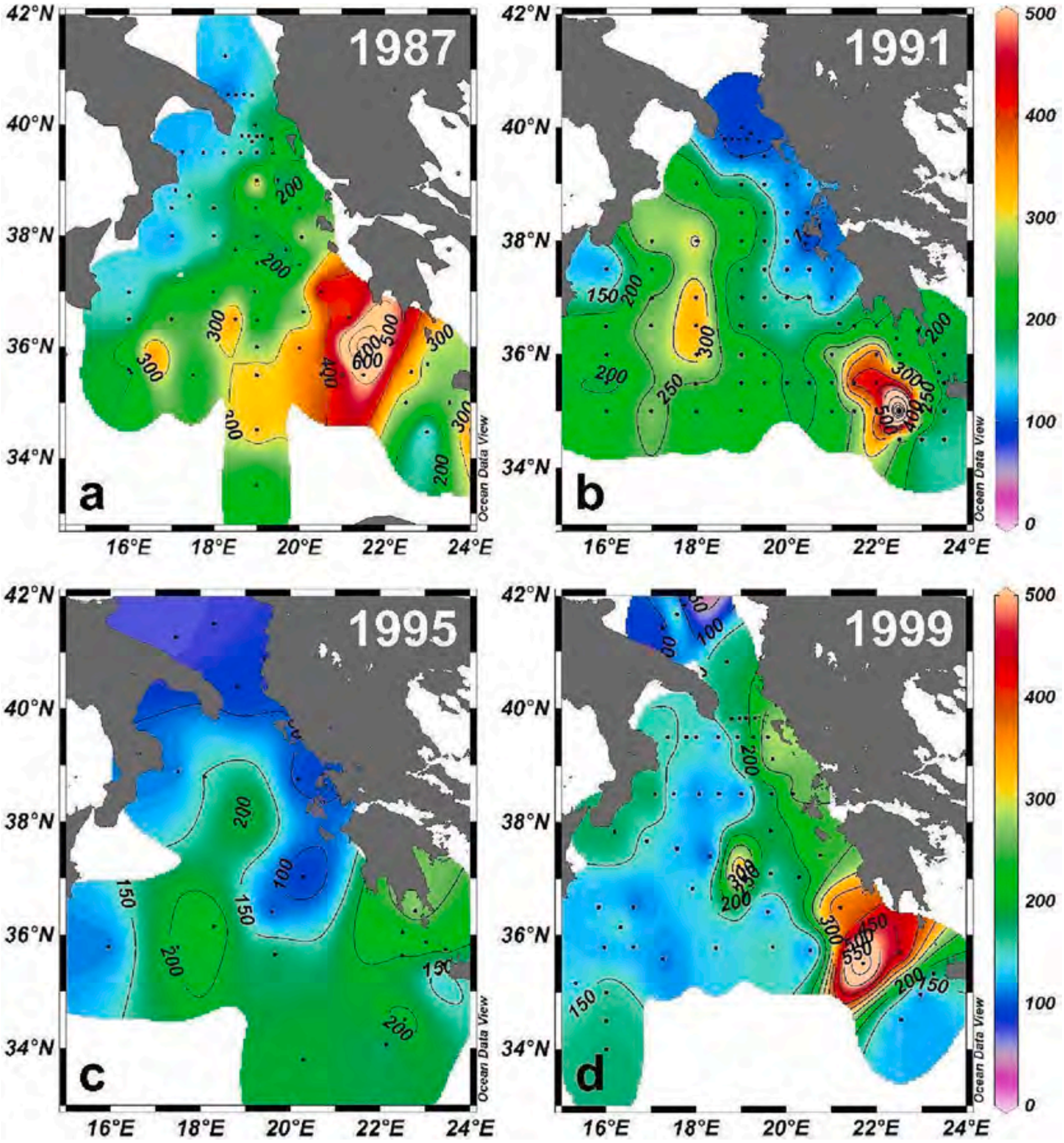


Fig. 11. Nutricline (depth of [nitrate] = 3 μM) horizontal distributions in the Ionian (Modified from Civitarese et al, 2010).

SC, with characteristics typical of the western basin: nitrate and phosphate about twice higher than in EMed, lower N:P (16 vs. 25), and lower pH. The time period considered by the authors was the period of the EMT, which produced a larger than usual discharge to the EMed via the SC (Vilibić et al., 2012). This resulted in increased compensatory flow of WMed water into the EMed, which consists of surface AW and some water below. In the first half of the 1990 s, the circulation in the northern Ionian was strongly anticyclonic, allowing advection of WMed water into the AS, whose subsurface component shaped the characteristics of the deep layer at stations north of the Palagruža Sill (Vilibić et al., 2012). However, after 2010, oscillations in nutrient levels in the SA appear to have continued (Fig. 9), i.e., far beyond a possible effect of the EMT.

Apart from various hypotheses about the origin of nutrient variability, one might wonder whether the nutrient increase in the Middle Adriatic in the 1990 s influenced primary production. Grbec et al. (2009), analyzing the time series of primary production for the period 1961–2002 at the Stončica station (open Middle Adriatic), reported higher-than-average production rates in the period 1980–1996. The increase in the period 1988–1996 seems to be consistent with an increase in nutrient availability also detected in the SA. On the other hand, the previous increase in primary production in 1980–1988 does not seem to be justified by the BiOS dynamics. As mentioned by Vilibić et al. (2012), other local factors, such as an increase in vertical mixing and fertilization of the euphotic zone after the harsh winters of 1981–83 (Josey, 2003), may have influenced the ecosystem dynamics.

The consistency between the variability of thermohaline properties in the Middle Adriatic and the NIG circulation regimes (i.e., the BiOS phases) was confirmed by the work of Mihanović et al. (2015), who used the Self-Organizing Maps (SOM) method over the Palagruža Sill and northern Ionian areas. Their results classified the BiOS as the dominant generator (forcing) of the Adriatic-wide decadal variability, which allows predictions of hydrographic conditions in the AS by monitoring the ADT in the IS.

At this point, the question arises whether the influence of BiOS extends to the entire AS, including the NA (Fig. 4).

Due to its physiographic characteristics and geographic location, the NA is strongly affected by local forcing. Large heat losses in winter during bora wind outbreaks activate the formation of dense water, while considerable river discharge determines thermohaline conditions and maintains strong stratification during warm months (Vilibić et al., 2020).

Nevertheless, some authors have shown significant correlations between BiOS phases and biogeochemical time series, linking, for example, the Ionian circulation and Dissolved Organic Carbon (DOC) distribution variability in the NA (Dautović et al., 2017). DOC fluctuations have been shown to correlate with NIG circulation modes, so DOC variability was considered a good proxy for BiOS (Dautović et al., 2017).

Strong correlations between BiOS phases and annual growth of bivalve shells of Glycymeris pilosa along the coast of Istria in the NA were shown by Peharda et al. (2018). Their results suggest that the remote forcing of BiOS is particularly strong and more important than local freshwater input processes.

In light of this growing biogeochemical and biological evidence, Vilibić et al. (2020) further investigated possible drivers of thermohaline variability in the NA. Their analysis showed that among the various possible drivers examined (North Atlantic Oscillation index, Mediterranean Oscillation index, East Atlantic index, and others), BiOS had the strongest impact on year-scale salinity variability and that, on average, a change in circulation in the IS led to variations in salinity in the North Adriatic after about 2–4 years. Recently, Ciglenečki et al. (2020) analyzed a time- series (1998–2017) of various organic matter compounds in the NA and their variability in relation to local and remote environmental drivers. They found that for the surfactants component, the largest correlations with BiOS mode were obtained with a phase lag of 3 to 4 years. The phase lags was about one year larger than the phase lags between salinity and the BiOS mode (as found by Vilibić et al., 2020), which is due to the time required for biogeochemical processes to cause changes in organic matter variables (Ciglenečki et al., 2020).

Therefore, a growing number of studies show that BiOS affects the thermohaline and biogeochemical properties of the entire AS, even its northernmost sub-basin.

5. Effects of NIG circulation on phytoplankton dynamics in the Ionian Sea

The most important factor for phytoplankton growth in oligotrophic environments is the availability of nutrients. Nutrient distribution is in turn determined by external sources and by biogeochemical and physical processes. Circulation patterns (cyclonic and anticyclonic) alter the depth of the nutricline (Williams and Follows, 2003), which, when it intercepts the base of the euphotic layer, causes an increase in primary production (Salihoglu et al., 1990).

The objective of this section is to review the effects of circulation variability driven by the BiOS mechanism on plankton dynamics in the IS.

The effects of circulation on nutrient distribution in the IS were previously addressed by Civitarese et al. (1996). For the first time, the distribution of nutrients was studied with sufficient spatial resolution in two different seasonal situations: in October 1991 and in April 1992 (Fig. 12). In 1991, the upper layer was characterized by a general anticyclonic circulation, so that the nitrate concentration at 100 m depth was negligible, the nitracline being depressed at more than 200 m depth. In 1992, the situation was more complicated because there was a broad anticyclonic circulation in which small mesoscale cyclonic eddies were embedded. Horizontal nitrate distributions at 100 m depth showed that there was significant enrichment of new nitrate in the productive layer (up to more than 2.5 μM) in the central cyclonic eddies and at the edges of the broader anticyclone. Subsequently, it was shown that the general oligotrophy of the IS could be challenged by local fertilization of the illuminated layer due to mesoscale dynamics and not only to the basin-wide flow.

More recently, as mentioned in Section 3, Civitarese et al. (2010) qualitatively demonstrated the relationship between basin scale circulation and the depth of the nutricline (Fig. 11).

Information on the interannual biogeochemical variability of the Ionian basin is scarce, but even more scarce is the information on the interannual ecosystem dynamics associated with circulation variations. D’Ortenzio et al. (2003) investigated the possible effects of changing circulation during the EMT on the general pattern of biomass in the EMed by comparing satellite images of ocean colors during the pre-EMT (1975–1985) and post-EMT (1998–2000) periods. Their results showed that surface Chl-*a* fields were essentially similar during the two periods, suggesting that biological activity remained unchanged. On the other hand, recurrent patches of Chl-*a* fields were consistently detected in the northwestern Ionian during the post-EMT period when the circulation regime of the NIG was strongly anticyclonic (1998–2000).

The possible effects of the sudden change in NIG circulation (from anticyclonic to cyclonic) in 1997–98 on ecosystem dynamics have attracted the attention of some other authors.

An interesting study was published by Mazzocchi et al. (2003), dealing with mesozooplankton communities and aiming to assess the impact of EMT-induced circulation change in the IS during 1998–99. They found a general spatial homogeneity in the distribution of trophic groups in spring 1992. In 1999, however, a classic food web (phytoplankton-cephalopods-predators) prevailed in the more productive northwestern part of the IS, while the eastern part was characterized by microbial links, typical of more oligotrophic areas. The authors attributed these significant differences in the functioning of the pelagic system on opposite sides of the basin to the cyclonic circulation during the post-EMT phase and the consequent nutricline uprise.

The analysis of Casotti et al. (2003) on the effects of water masses on

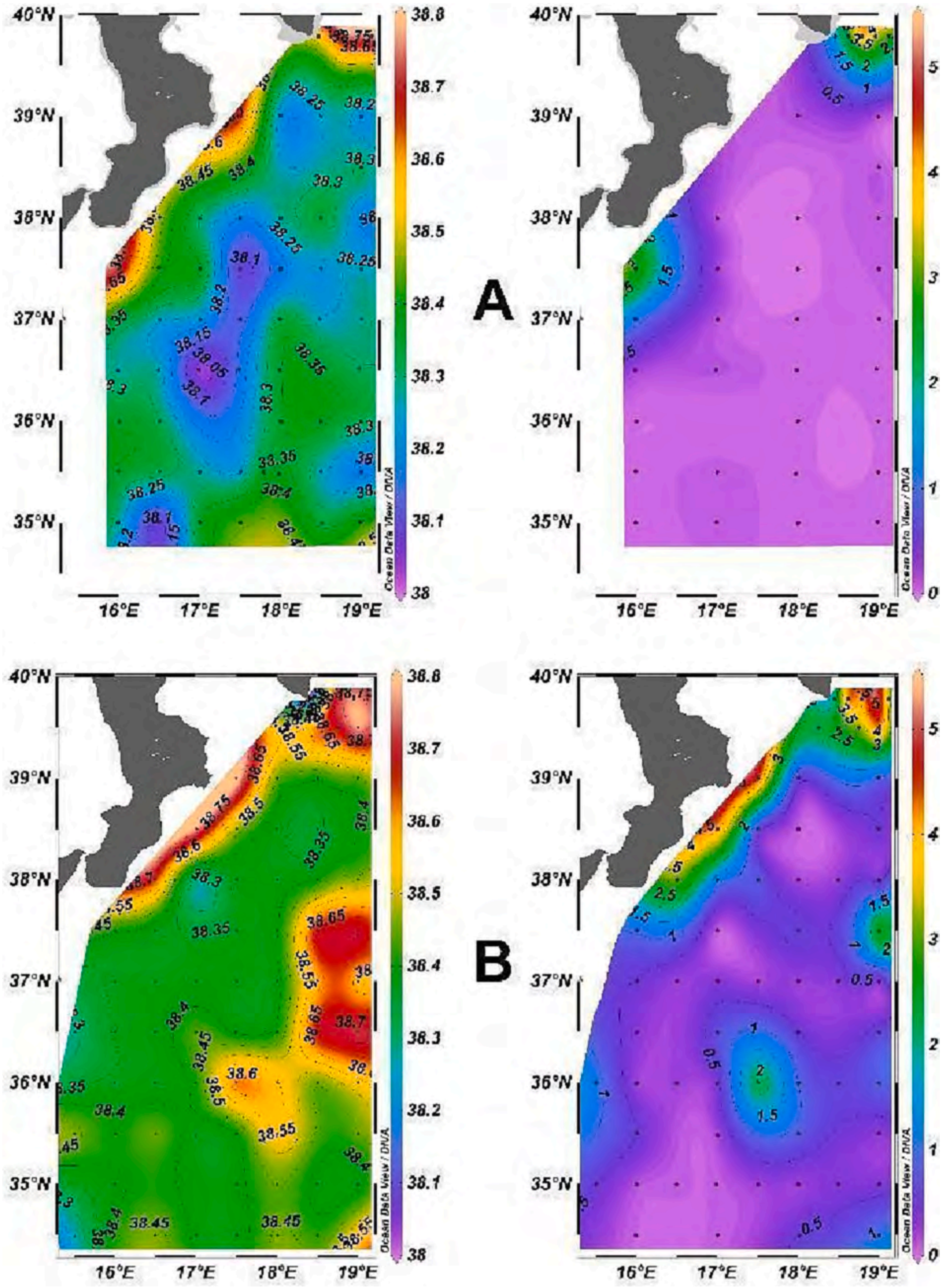


Fig. 12. Horizontal distribution at 100 m depth of salinity (left) and nitrate (μM, right): A) POEM-BC-O91 (October 1991); B) POEM-BC-A92 (April 1992).

the distribution and dynamics of phytoplankton agreed with the results of Mazzocchi et al. (2003), according to which the eastern part of the IS was more oligotrophic than the western part, although the higher Chl-*a* concentrations in the latter were probably due to local accumulation from Adriatic waters rather than active growth. The relative increase in oligotrophy in the eastern part of the IS was reflected in the dominance of ultraphytoplankton and may be related to the low availability of orthophosphate.

Changes in subsurface nutrient distribution are also likely to affect phytoplankton phenology, i.e., the timing of periodic events in the seasonal cycle of phytoplankton (Ji et al., 2010), which in turn may have major implications at higher trophic levels (Edwards and Richardson, 2004). The lack of data in the open ocean can be addressed by monitoring ocean Chl-*a* color, which provides a synoptic view of surface phytoplankton biomass dynamics on a global scale (Platt et al., 2010).

Along these lines, a more detailed investigation of the relationship between circulation and ecosystem dynamics was conducted by Lavigne et al. (2018), who analyzed some critical phenological metrics to examine the impact of NIG reversals on the seasonal cycle of phytoplankton between 1993 and 2013. The main conclusion of the authors was that two trophic regimes coexist in the center of the northern Ionian. During the cyclonic phases, the spring peak of Chl-*a* concentration was observed in March, indicating typical spring bloom dynamics. On the other hand, no peak was observed during the anticyclonic periods, indicating the absence of a distinct seasonal bloom. The annual cycle of Chl-*a* concentration was also influenced by the mixed layer depth (MLD), which in turn is determined by winter buoyancy loss. Only during the cyclonic phases did MLD exceed the depth of the fall nitracline, indicating possible nutrient enrichment. Finally, Lavigne et al. (2018) concluded that phytoplankton phenology resulted from the interplay between circulation and atmospheric conditions. The authors emphasized that phytoplankton dynamics in the northern Ionian are linked to the properties and variability of the semi-closed deep thermohaline cell of the EMed. Therefore, the dense water generated at the SA as a result of local air-sea flow and BiOS-driven haline preconditioning exerts a significant influence on and remotely controls the trophic web in the northern Ionian.

6. Changes in plankton and fish communities in the Adriatic Sea due to the NIG circulation regime

In this chapter, the terms “ingression” and “regression” are used according to Buljan (1953; see par. 2.3), following historical terminology prior to BiOS discovery. Essentially, the terms “ingression” and “regression” are considered here as synonyms for “S-increase” and “S-decrease” phases, respectively, due to the different circulation regime of the NIG (cyclonic and anticyclonic, respectively) according to the BiOS mechanism (Gačić et al., 2010).

6.1. Changes in plankton communities

It is well known that the Mediterranean Sea is one of the marine biomes sensitive to global warming and particularly susceptible to biological invasions (Coll et al., 2010). In addition to the potential influx of species through the Strait of Gibraltar, the construction of the Suez Canal led to the introduction of a number of tropical and subtropical species from the Red Sea (Por, 1978; Pancucci-Papadopoulou et al., 2005; Pancucci-Papadopoulou et al. 2012). Many of these Indo-Pacific species were already established in the EMed and their dispersal coincided with significant hydrographic changes associated with warming of Mediterranean waters (Occhipinti-Ambrogi and Galil, 2010).

The variability of water advected to the AS according to the BiOS mechanism refers to plankton species, because it is known that their presence is primarily determined by water transport. Evidence of the arrival of new plankton species in the AS has been reported since about 120 years ago, showing that in certain years species from the EMed (LB /Indo-Pacific origin) or from the WMed/Atlantic Ocean entered the AS. These historical data contributed significantly to the understanding of past conditions of the marine environment in the Mediterranean Sea, when human impact was different than today. In the past, introduction vectors such as aquaculture, tourism and maritime transport (for commercial and tourist reasons) were absent or greatly reduced. Therefore, we were able to use data from new plankton species introduced to AS early in the last century as cases of natural dispersal by currents. Data in the last few decades are mainly from the eastern part of the MA and SA (Croatian side). This part of the AS is particularly exposed to incoming currents from the IS (EMed or AW), so it is the catchment area for the new plankton species. It should be noted that here we considered open ocean stations that are generally not exposed to coastal influences. Moreover, Croatian ports are mainly import ports, so the volume of ballast water (a possible vector for alien species) is not significant (David and Jakomin, 2003).

Throughout this section, reference is made to Fig. 13, which indicates the occurrence of plankton taxa and/or their unusual abundance and biomass associated with the NIG circulation regime.

The compilation of Fig. 13 originates from the pioneering work of Buljan (1953), who for the first time comprehensively reported biological observations from the end of the 19th century to the first half of the last century and related them in the context of the theory of the Adriatic Ingression.

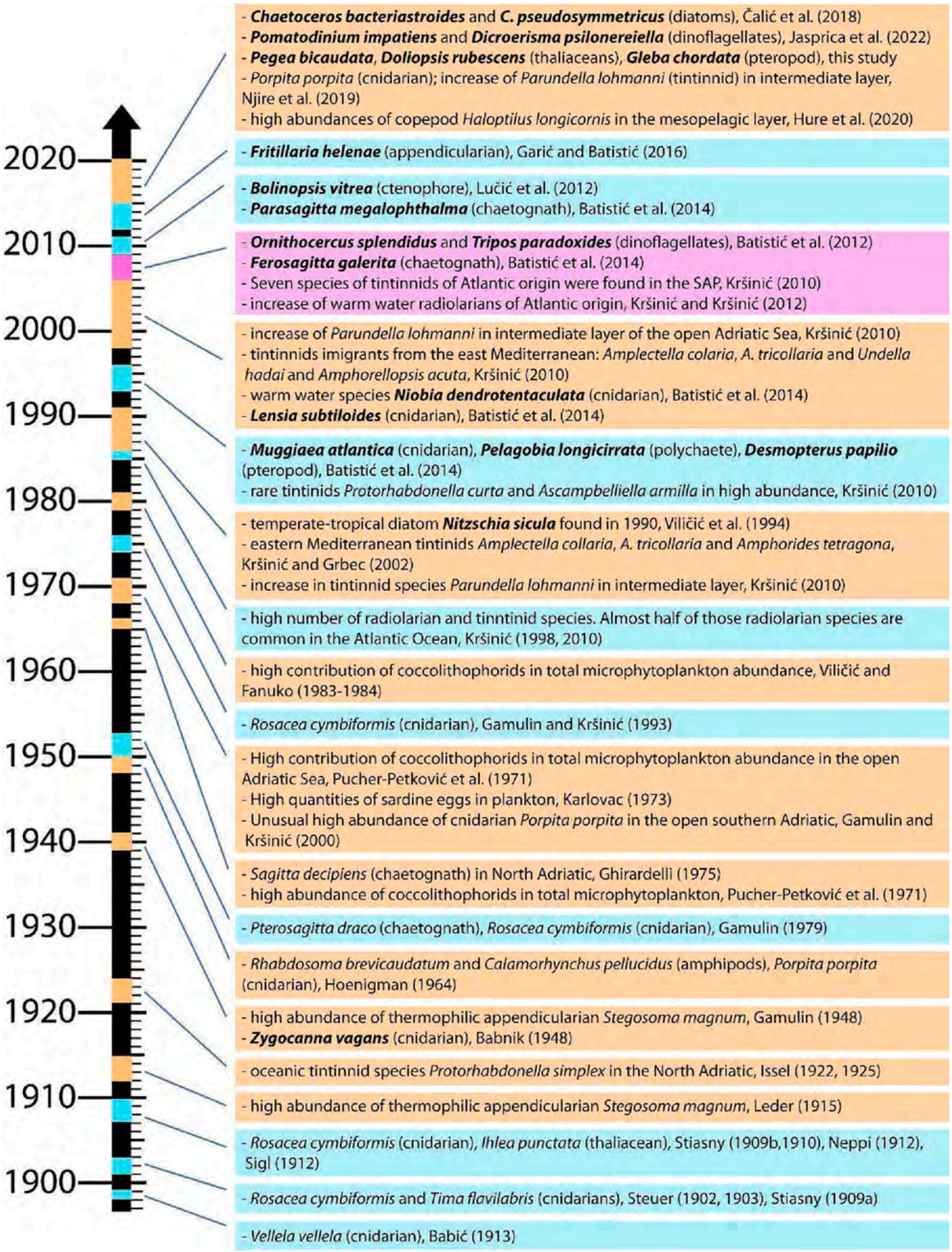
Between the end of the 19th and the beginning of the 20th century, relatively intensive biological research was carried out on AS, mainly limited to the northern part. According to these data, zooplankton species common in the Atlantic/WMed (Fig. 13) were found in the NA in 1898, 1901–1902, and 1907–1909. These findings could probably indicate a regression period. It should be noted that the Atlantic calycophora *R. cymbifromis* is a mesopelagic species that is very rarely found in the AS (Gamulin and Kršinić, 2000). The NA is not a favorable environment for oceanic species, especially those that live in deeper waters, so they cannot establish long-term populations and their presence in the NA may be related only to water transport (Batistić et al., 2014). Floating polymorphic colonies of the hydrozoan *Vellela vellela*, which live in open waters in tropical and temperate latitudes (Betti et al., 2019), were unusually found in the NA. It is likely that this species originated in the WMed where it has been observed in dense swarms recently and in the past (Betti et al., 2019). Oceanographic information from the past in the AS is very sparse. Buljan (1953), citing the work of Wolf & Luksch (1878), reported a possible ingression during the campaign of the vessel Deli in the summer of 1876, followed by a decrease in salinity in the following years until a possible minimum in the summer of 1880 (Wolf & Luksch, 1881). Assuming a periodicity of about 10 years between 1875 and 1912, i.e., between the years in which the ingressions were observed, we can assume three other intermediate ingressions (1885, 1895, and 1905) and as many regressions (1890, 1900, and 1910).

In the years 1912 to 1914, an unusually large number of thermophilic appendicularian species *Stegosoma magnum* were found in the MA. This finding could be an indicator of the ingression period, i.e., the influx of warm and saline LIW into the AS (due to the NIG cyclonic circulation in the BiOS view). According to Steuer’s (1915) data from the “Najade” expedition (March 1913), zooplankton organisms like heteropoda from the genus Pterotrachea, which had not been recorded before, appeared in the NA.

During the two world wars and the period in between, data are sparse.

Between 1921 and 1923, the tintinnid *Protorhabdonella simplex* (Kršinić, 2010), a rare oceanic species with sporadic occurrence in the open SA, was found in the NA, most likely due to the strong ingression of LIW.

The changes in zooplankton abundance observed in 1939 and 1940 (Fig. 13) indicate that AS was under the predominant influence of EMed water (ingression period), which is confirmed by the influx of warm



- ***Chaetoceros bacteriastroides*** and ***C. pseudosymmetricus*** (diatoms), Čalić et al. (2018)
- ***Pomatodinium impatiens*** and ***Dicroerisma psilonereiella*** (dinoflagellates), Jasprica et al. (2022)
- ***Pegea bicaudata***, ***Doliopsis rubescens*** (thaliaceans), ***Gleba chordata*** (pteropod), this study
- *Porpita porpita* (cnidarian); increase of *Parundella lohmanni* (tintinnid) in intermediate layer, Njire et al. (2019)
- high abundances of copepod *Haloptilus longicornis* in the mesopelagic layer, Hure et al. (2020)

- ***Fritillaria helenae*** (appendicularian), Garić and Batistić (2016)

- ***Bolinopsis vitrea*** (ctenophore), Lučić et al. (2012)
- ***Parasagitta megalophthalma*** (chaetognath), Batistić et al. (2014)

- ***Ornithocercus splendidus*** and ***Tripos paradoxides*** (dinoflagellates), Batistić et al. (2012)
- ***Ferosagitta galerita*** (chaetognath), Batistić et al. (2014)
- Seven species of tintinnids of Atlantic origin were found in the SAP, Kršinić (2010)
- increase of warm water radiolarians of Atlantic origin, Kršinić and Kršinić (2012)

- increase of *Parundella lohmanni* in intermediate layer of the open Adriatic Sea, Kršinić (2010)
- tintinnids imigrants from the east Mediterranean: *Amplectella colaria*, *A. tricollaria* and *Undella hadai* and *Amphorellopsis acuta*, Kršinić (2010)
- warm water species ***Niobia dendrotentaculata*** (cnidarian), Batistić et al. (2014)
- ***Lensia subtiloides*** (cnidarian), Batistić et al. (2014)

- ***Muggiaea atlantica*** (cnidarian), ***Pelagobia longicirrata*** (polychaete), ***Desmopterus papilio*** (pteropod), Batistić et al. (2014)
- rare tintinids *Protorhabdonella curta* and *Ascampbelliella armilla* in high abundance, Kršinić (2010)

- temperate-tropical diatom ***Nitzschia sicula*** found in 1990, Viličić et al. (1994)
- eastern Mediterranean tintinids *Amplectella collaria*, *A. tricollaria* and *Amphorides tetragona*, Kršinić and Grbec (2002)
- increase in tintinnid species *Parundella lohmanni* in intermediate layer, Kršinić (2010)

- high number of radiolarian and tinntinid species. Almost half of those radiolarian species are common in the Atlantic Ocean, Kršinić (1998, 2010)

- high contribution of coccolithophorids in total microphytoplankton abundance, Viličić and Fanuko (1983-1984)

- *Rosacea cymbiformis* (cnidarian), Gamulin and Kršinić (1993)

- High contribution of coccolithophorids in total microphytoplankton abundance in the open Adriatic Sea, Pucher-Petković et al. (1971)
- High quantities of sardine eggs in plankton, Karlovac (1973)
- Unusual high abundance of cnidarian *Porpita porpita* in the open southern Adriatic, Gamulin and Kršinić (2000)

- *Sagitta decipiens* (chaetognath) in North Adriatic, Ghirardelli (1975)
- high abundance of coccolithophorids in total microphytoplankton, Pucher-Petković et al. (1971)

- *Pterosagitta draco* (chaetognath), *Rosacea cymbiformis* (cnidarian), Gamulin (1979)

- *Rhabdosoma brevicaudatum* and *Calamorhynchus pellucidus* (amphipods), *Porpita porpita* (cnidarian), Hoenigman (1964)

- high abundance of thermophilic appendicularian *Stegosoma magnum*, Gamulin (1948)
- ***Zygocanna vagans*** (cnidarian), Babnik (1948)

- oceanic tintinnid species *Protorhabdonella simplex* in the North Adriatic, Issel (1922, 1925)

- high abundance of thermophilic appendicularian *Stegosoma magnum*, Leder (1915)

- *Rosacea cymbiformis* (cnidarian), *Ihlea punctata* (thaliacean), Stiasny (1909b,1910), Neppi (1912), Sigl (1912)

- *Rosacea cymbiformis* and *Tima flavilabris* (cnidarians), Steuer (1902, 1903), Stiasny (1909a)

- *Vellela vellela* (cnidarian), Babić (1913)

Fig. 13. Timeline of the occurrence of plankton taxa and/or their unusual abundance and biomass associated with the NIG circulation regime (blue: anticyclonic; orange: cyclonic; pink: transition). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) (See above-mentioned references for further information.)

(greater than14.5 °C) and highly saline (38.9) water in the AS (Gamulin, 1948). Under these hydrographic conditions, a bloom of thaliacean *Salpa maxima* was recorded in the open sea of the SA (Babnik, 1948). In addition, the tropical hydromedusa *Zygocanna vagans* was found for the first time in AS (as *Zygocanna* sp.; Babnik, 1948), which is also a first finding of this species in the Mediterranean. It is possible that *Z. vagans* entered the EMed from the Indian Ocean through the Suez Canal (Babnik, 1948) and then entered the AS within the LIW.

Thermophilic species such as floating polymorphic colonies of the hydrozoan *Porpita porpita* collected in the late 1940 s (1948–1949) during the Croatian expedition “Hvar” (Fig. 13) confirmed the presumed cyclonic NIG circulation, a period of strong ingression of LIW, as suggested by Buljan (1953).

As in the early 20th century (associated with the regression period), Atlantic species were found in the SA from 1951 to 1952 (Fig. 13). In addition, the recorded species of *Pterosagitta. draco* are well known in the parts of the WMed under the influence of AW (Furnestin 1963).

Plankton data have been collected more regularly since the mid-1960 s, but there are still gaps in some periods. In the late 1960 s, thermophilic species and the important contribution of coccolithophorides to the total microphytoplankton abundance in the open SA were observed (Fig. 13). It seems that in this period, SA was influenced by warmer and saltier water (LIW) coming from IS. A rich coccolithophorid community was found in IS and in LIW-influenced areas (Fonda-Umani, 1996; Malinverno, 2003).

From 1975 to 1990, according to fito- and zooplankton data (Fig. 13) periods of regression and ingression alternated.

In the 1990 s, during the EMT, there was a large influx of AW into the AS (Civitarese et al., 2010). Accordingly, changes in the zooplankton community were recorded in the AS from 1993 to 1995. Calycophoran *Muggiaea atlantica* (Fig. 13) was first found in the AS in 1995, while the pelagic polychaeta *Pelagobia longicirrata* reappeared in 1993 after more than two decades (Batistić et al., 2014). Both species are widely distributed in the Atlantic Ocean and have also been found in the WMed (Pleijel & Dales, 1991; Pinca and Dallot, 1995; Licandro et al., 2012). Changes also occurred in the microzooplankton community: the occurrence of oceanic species very rare in the Atlantic, the tintinnids *Protorhabdonella curta* and *Ascampbelliella armilla*, was recorded in relatively high abundance in the open waters of the SA (Kršinić, 2010). An opposite pattern was observed in the period from 1998 to 2006, when species from warmer waters appeared. For example, tintinnid *Undella hadai* and the calycophora *Lensia subtiloides*, both of Indo-Pacific origin (Abboud-Abi Saab, 2012; Pugh, 1999) and most likely Lessepsian migrants, benefited from the strong shift to cyclonic circulation of the NIG and consequently from the influx of warmer and saltier Levantine waters into the AS.

From 2006 to 2008 (Fig. 13), the circulation of NIG reversed from anticyclonic to cyclonic, and thus species from both the Atlantic/WMed and Indo-Pacific/EMed were recorded simultaneously. Chaetognath species *Ferosagitta galerita* of Indian Ocean origin (Madagascar waters) was observed for the first time in the AS in 2007, while it was recorded in LB as early as 2003, likely being a Lessepsian species (Terbiyik et al., 2007). At the same time, tintinnid species of Atlantic origin were found. From 2009 to 2011, an anticyclonic circulation prevailed in the NIG. In accordance with the increased influx of AW, Atlantic/Mediterranean species were detected in the AS. During this period, chaetognatha *Sagitta megalophthalma* was recorded for the first time in the AS. This species is very rare, and it has only been reported in the deeper waters of the WMed and Atlantic (Dallot & Ducret, 1969; Michel, 1984). The reversal to NIG cyclonic circulation occurred again in 2010. However, an episode of short inversion from cyclonic to anticyclonic circulation was observed in 2012 (Gačić et al., 2014). This could probably explain the presence of appendicularian species *Fritillaria helenae* at AS in 2012–2014 (Garić and Batistić, 2016), which was previously observed only in the Atlantic.

From 2015 to 2020, warm-water organisms (Fig. 13), such as the phytoplankton species *Chaetoceros bacteriastroides* and *C. pseudosymmetricus* and the zooplankton species thaliacean *Pegea bicaudata*, *Doliopsis rubescens* and the pteropod *Gleba cordata* appeared for the first time in the AS. According to the high salinity and temperature (greater than38.8 and greater than 14 °C, respectively) in the intermediate layer of SA, these species were most likely advected with the EMed water due to the cyclonic circulation of the NIG. Both phytoplankton species have an Indo-Pacific origin (Hernández-Becerril, 1993, 2000) and can therefore be considered Lessepsian migrants. Three zooplankton species are thermophilic and globally distributed (Van Soest, 1974, 1975; Godeaux, 2003; Sunwoo et al., 2017; WoRMS, 2021) and could also be Lessepsian migrants already established in the EMed. Due to increasing seawater temperatures in the EMed (Belkin, 2009), Indo-Pacific or warmer-water Atlantic species have found optimal conditions for establishment in the EMed, which is not the case for colder water species, i.e., circumboreal and North Atlantic species (Zenetos, 2010). Given projected climate change (IPCC 2018), we can also expect the northeast Atlantic to be a more common source of warm-temperate than cold-temperate species for the Mediterranean Sea as well as for AS.

Despite the gaps in studies in the AS over the past 120 years, the biological record appears to be consistent with the timing of advection of different water masses, AW or EMW (LSW/LIW), into the AS and suggests that the prevailing circulation in the IS is a driving force for newly arriving plankton species. This is consistent with previous studies from 1993 to 2011 in the AS (Batistić et al., 2014). Hydrographic dynamics also influence the probability of establishment and population dynamics of newcomers.

In summary, the BiOS mechanism appears to have a significant impact on plankton distribution and abundance in the AS. The BiOS effect is to perturbate the population patterns by introducing invasive species, which can both increase and decrease biodiversity. Recent studies (Batistić et al., 2014) and constant monitoring of the open Adriatic waters (unpublished data, Fig. 13) suggest that the BiOS may act as a repopulation mechanism for those species that, according to the circulation regime NIG, do not find favorable conditions for the development of a stable population.

6.2. *Changes in fish communities*

The year of discovery (occurrence) of a fish species is not necessarily synonymous with the actual year of its entry into an area. In general, the early developmental stages of fishes and juveniles can be associated with currents, meaning that they are directly associated with or dependent on currents. This is not the case for adult fish; they can move independently. However, the fact is that adults are also indirectly associated with currents that can affect the state of primary and secondary production, i.e., potential food.

The presence of thermophilic, rare, and non-indigenous (alien) species in the AS was usually attributed to the Adriatic ingressions (Pallaoro, 1988). However, according to Civitarese et al. (2010), more complex dynamics of SA and IS, linked by the BiOS mechanism, may provide a more plausible explanation for the occurrence of such species. While according to BiOS, the occurrence of Lessepsian and other eastern Mediterranean migrants could be attributed to the cyclonic circulation of the NIG (such as *Siganus rivulatus*, *Sphyraena chrysotaenia*, *Equulites klunzingeri*, *Fistularia commersoni*, etc.), the anticyclonic circulation could favor the influx of marine species from regions of the central Mediterranean (Lobotes surinamensis) (Fig. 14). This thermophilic species inhabits tropical and subtropical waters of all oceans. However, it seems that *L. surinamensis* has recently become widespread in the nearshore waters of Malta, as numerous specimens have been recorded in this area (Deidun et al., 2010) arriving probably from the tropical waters of the Atlantic Ocean. Characteristic of *L. surinamensis* specimens is that they float on its side near the surface staying close to floating objects (Myers, 1999; Massutí and Reñones, 1994), so it is likely that specimens of this fish have reached the AS from the Maltese area by incoming currents due to the anticyclonic circulation of the NIG.

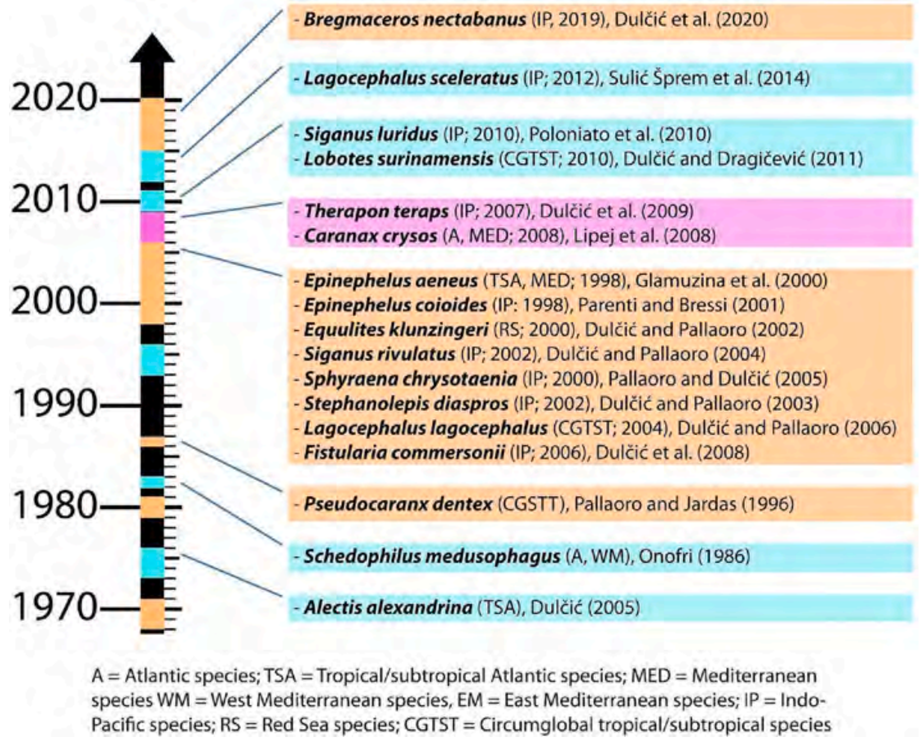


Fig. 14. Timeline of the first records of incoming fish species associated with the NIG circulation regime (blue: anticyclonic; orange: cyclonic; pink: transition). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) (See above-mentioned references for further information.)

The first record of the Lessepsian migrant *Siganus luridus* was in the NA (Trieste Bay) in the 2010 (anticyclonic circulation, Fig. 14), and it is possible that the entry of this species occurred earlier during the reversal period, as it takes time to reach NA (we exclude here the possibility of ship transport). This assumption can be supported by the finding of this species in the WMed in 2008 (Daniel et al., 2009).

Earlier evidence of the new incoming Atlantic fish species in the Adriatic dates from 1973 (*Alectis alexandrina*) and 1982 (*Schedophilus medusophagus*) during the anticyclonic circulation of NIG, when AW entered the AS (Fig. 14).

6.3. *Final remarks*

We have seen that the historical observations on the occurrence of different plankton taxa and their abundance and biomass, as well as some first records of incoming fish species of different origins in the AS are in reasonable agreement with the alternation of the circulation regime of the NIG. Thus, the BiOS mechanism appears to have a profound influence on the distribution of primary and higher organisms in the AS and ultimately to be a natural regulator of biodiversity.

All this confirms and extends to the present day what was already stated in 1953 by Buljan, from whom we quote the following:

> *"If we want to have a thorough knowledge of the zoogeographic distribution of single organisms in the Adriatic, or if we want to make a general study of the biology of that sea, it will not be out of place to know when, in which years, were the catches and research carried out, as it seems that the ingressions leave a marked impression on both the quantitative and qualitative composition of populations".*

7. Effects of NIG circulation and preconditioning in the Cretan and Levantine Seas: salinity, LIW formation, and nutrients availability

7.1. *Salt redistribution within the eastern Mediterranean*

The pervasive effect of the NIG circulation is a direct consequence of the characteristics of the Mediterranean open thermohaline cell. The reversals of the NIG change the route of the AW, affecting the salt preconditioning not only in the AS, but also in the LB (Gačić et al., 2011; Theocharis et al., 2014; Velaoras et al., 2014; Cardin et al., 2015; Bensi et al., 2016), where the decadal variability of the AW advection impacts the quantity of LIW produced as well as its thermohaline properties. Therefore, the ability of the Aegean and Adriatic Seas to alternate the dense water production is directly affected by the reversal of the NIG, apart from the influence of air-sea interaction and local dynamics (Cardin et al. 2015).

Sea level differences between the center and north of the NIG were used by Lavigne et al. (2018) to determine the cyclonic/anticyclonic character of the NIG circulation (Fig. 15), referred to as the Ionian Circulation Index (ICI). During the NIG cyclonic pattern (negative ICI), the zonal surface geostrophic current reaches its maximum over the Cretan Passage (i.e., the maximum of AW eastward flow), while during the anticyclonic phase it reaches its minimum remaining however always eastward (Fig. 15).

Spatiotemporal variability of sea level (ADT), sea surface temperature (SST), sea surface salinity (SSS), and freshwater flux in Mediterranean Sea was estimated by Menna et al. (2022) for 27 years (1993–2019). Using empirical orthogonal function analysis, the authors found that the decadal signal associated with the reversals of NIG was evident in SST, SSS, and ADT. The decadal NIG-associated variability was present in EMed and was related to the intensity of the AW spreading, and it was also evident in the intermediate layer characterized by the westward flow of the LIW, which is the preconditioning for

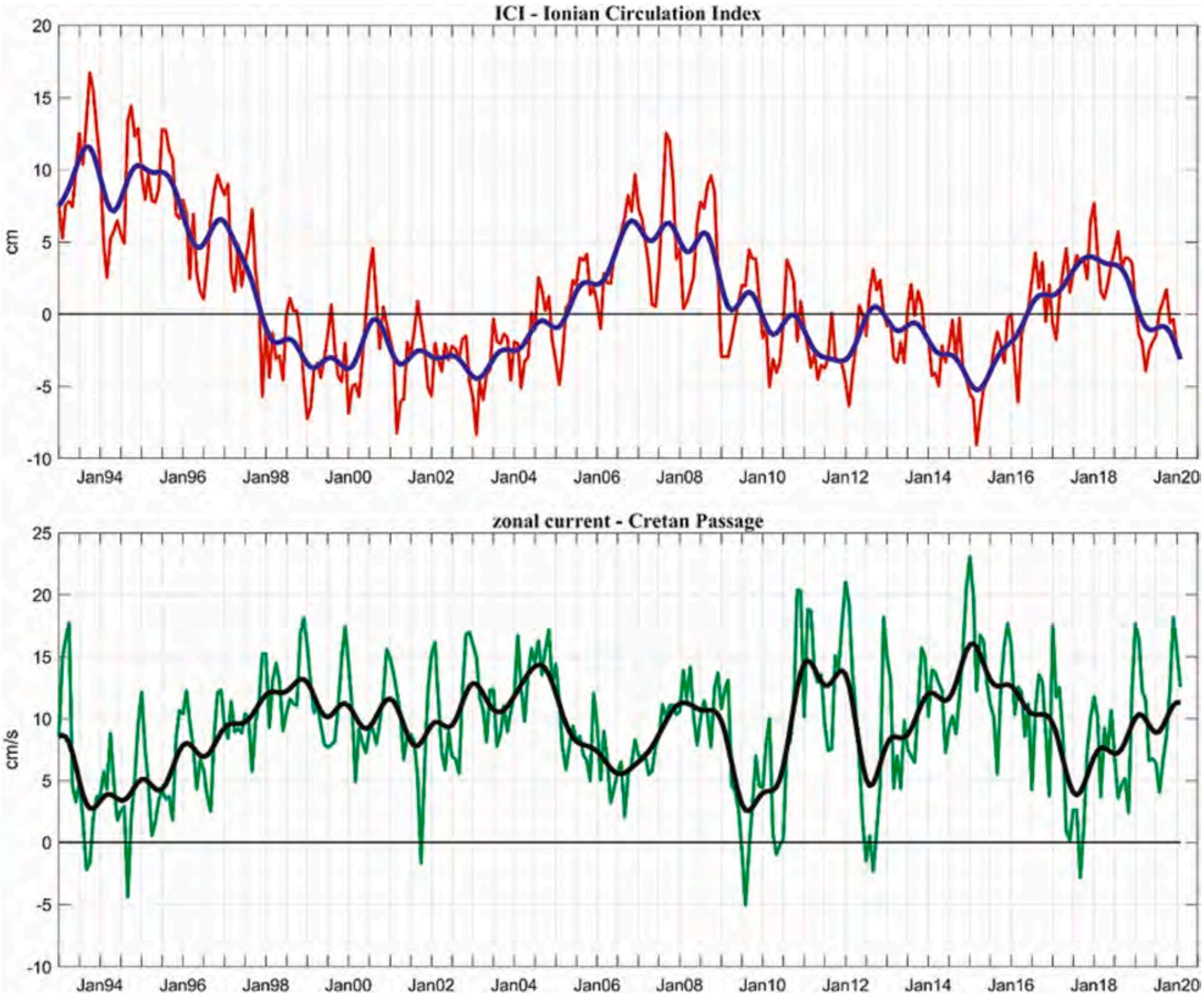


Fig. 15. Ionian Circulation Index (ICI, upper panel; modified from Lavigne et al., 2018) and zonal surface geostrophic flow across the Cretan Passage (lower panel; see Fig. 6 of Menna et al., 2019a,b). The red and green lines indicate the monthly data of the ICI and the Cretan Passage flow, respectively, while the blue and black lines represent their 13-month moving averages. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the deep water formation in CS, SA, and WMed (for the latter, see Section 7).

Evidence of the change in circulation and internal redistribution of salt in the Ionian and Levantine basins was already mentioned by Malanotte-Rizzoli et al. (1999), who pointed out the increase of salinity in the surface and intermediate layers between 1987 and 1991 in LB, while the surface salinity in the IS was contextually decreasing. They hypothesized that the decrease in surface salinity in the IS was related to the increased presence of AW in the area in 1991, which coincided with the anticyclonic circulation of the NIG that was already in act in the area. “*In that year, the upper thermohaline cell connecting the Levantine and the Ionian Sea was already disrupted, and the two basins were more separated than in 1987*…” the researchers wrote. The increase in salinity in the LB and consequently in the adjacent AeS played the main role as a preconditioning factor that favored enhanced winter convection and the occurrence of the EMT in the following years.

Manca et al. (2003) reported salinity fluctuations in the Ionian and Levantine basins and in the Cretan Passage during the 1987–1995 and 1995–1998 periods from CTD measurements made in the area. These data showed a redistribution of salt between the two basins, especially in the 0–22 m and 200–800 m layers. It was clear that the IS experienced a loss of salt during the 1987–1995 period, especially in the upper 200 m depth. In contrast, during the second period (1995–1998), there was a significant salt gain in the IS and a salt loss in the LB, related to the cyclonic phase of the NIG and the resulting increase in the AW flux in the LB.

By 1997, the Ionian circulation changed from anticyclonic to cyclonic. Theocharis et al. (2002), based on the basin-wide survey conducted in 1998 and 1999 in the EMed, reported the intrusion of AW through the Cretan Passage and into the LB with a much stronger signal with salinity less than 38.8, compared to the values observed in 1991 by Malanotte-Rizzoli et al. (1999). Therefore, the presence of AW in the northern Ionian was probably limited and reached the Cretan Passage directly from the SC. As expected from the cyclonic phase of the NIG, this situation affected the salt balance between the two basins: an increase in salinity in the northern Ionian and a simultaneous decrease in both the LB and the AeS.

The variability of salinity on a multiyear and near-decadal time scale in the upper layer of the LB during the last 30 years is shown in Fig. 16, based on the work of Cardin et al. (2015) and Hainbucher et al. (2020). The alternation of increasing and decreasing salinity in the upper layer of LB during the last decades is evident. The salinity distributions shown in 1987 and 1995 (Fig. 16a, b) represent the time window of the anticyclonic circulation of the NIG, a period of increasing salinity in the Levantine. At the time of the 1999 cruise (Fig. 16c), the circulation in the IS reversed to a cyclonic circulation, facilitating the entry of low salinity

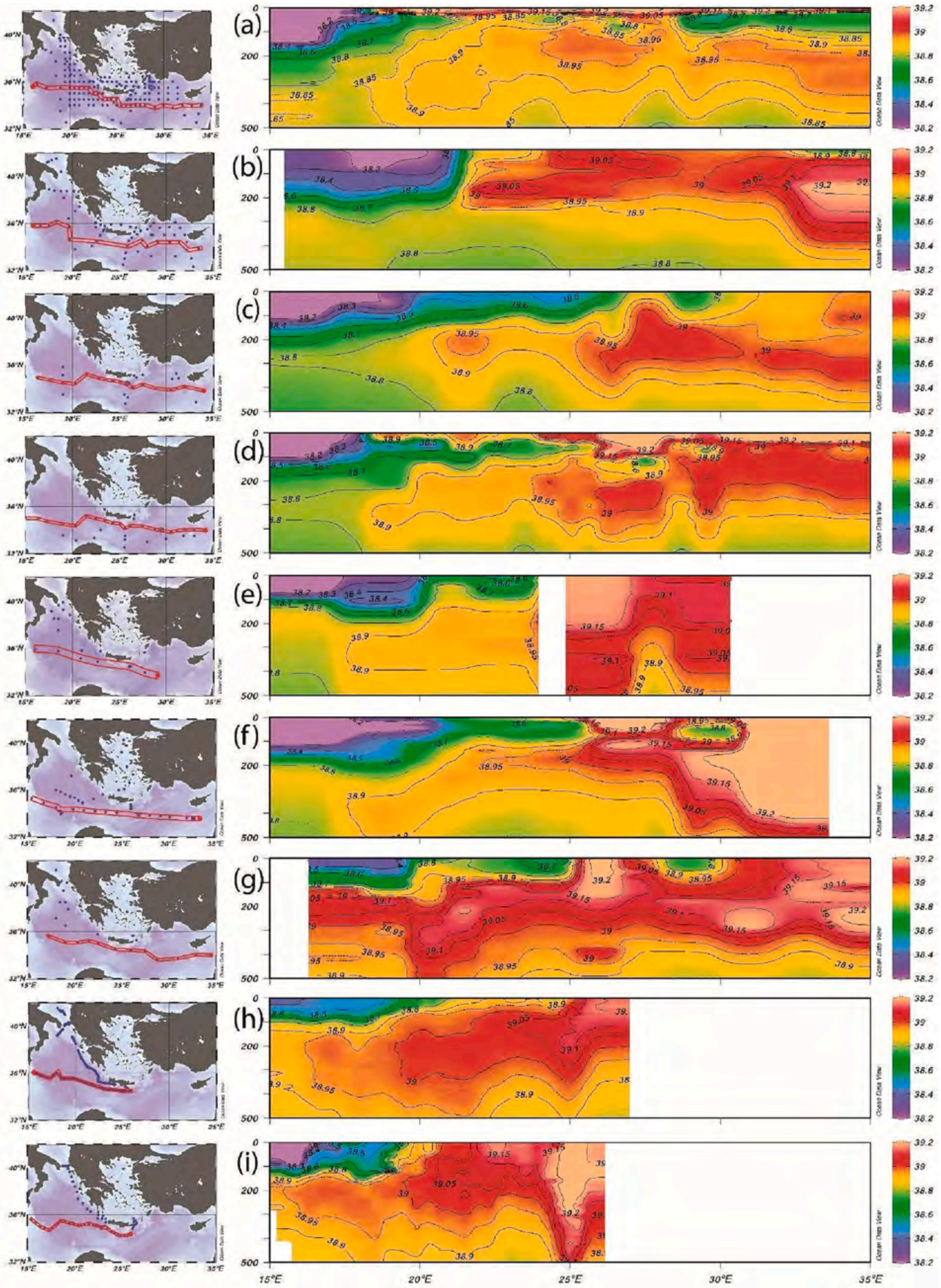


Fig. 16. Vertical distribution of salinity in the upper layer of the eastern Mediterranean in the period 1987–2018 (modified from Cardin et al., 2015): (a) M5/6–1987, (b) M31-1995, (c) M44/1999, (d) M51-2001, (e) M71/3–2007 (Christiansen et al., 2015), (f) BOUM-2008, (g) M84/3–2011, (h) POS468-2014 (Hainbucher et al., 2015), (i) MSM72-2018 (Hainbucher et al., 2020).

water into the surface layer of the Levantine. The LIW core deepened and advanced westward to 22.5°E. Oceanographic conditions in 2008 (Fig. 16f) showed minimal salinity in the IS and a significant increase in salinity in the upper layer (0–500 m depth) in the LB, probably as a result of the anticyclonic circulation in the IS that occurred from 2006 to 2010. The intermediate layer in the IS was replenished by LIW with high salinity.

Data collected during an oceanographic cruise in spring 2011 (Fig. 16g) show a not yet well-defined change in salinity due to the reversal of NIG circulation from anticyclonic to cyclonic that occurred in 2010. By 2014, the presence of high salinity water in the IS decreased (Fig. 16h, i; Hainbucher et al., 2015, 2020). In 2018 (Fig. 16i), the salinity pattern reflected the anticyclonic regime of the NIG, with a notable core of high salinity LIW south of Crete (25°E).

Salinity variations on a decadal scale (about 9 years) were also found in the easternmost Levantine by Ozer et al. (2017) based on a 30-year time-series. Two maxima of salinity, the first in 1992 and the second in 2008, were found for the LSW (39.55 and 39.70) and the LIW (39.32 and 39.30). These two maxima were attributed to the anticyclonic circulation regime of the NIG.

In recent years, numerous papers have shown pronounced changes in the salinity of the SA (Kokkini et al., 2020; Mihanović et al., 2021; Matić et al., 2022), with record values in the surface and intermediate layers in 2017 and 2020 (Mihanović et al., 2021; Menna et al., 2022b). These values are the result of a decadal salification process, showing a steep increase from 2017, and are indicative of changes in the zonal overturning circulation of the central Mediterranean. The positive ICI values associated with the anticyclonic NIG modes decreased with time, showing lower values in 2017–2018 than in the 1990 s (Fig. 15). Reduced ICI indicates a weakening of the anticyclonic mode of the NIG, resulting in the reduced transport of AW toward SA (Gačić et al., 2011). Meanwhile, the reduced strength of the surface current in the anticyclonic NIG of 2017–2018 favored the transport of the highly saline Levantine or Aegean waters toward the SA. The coastal current along the eastern Ionian generally shows decadal fluctuations correlated with the NIG reversals, with southward transports during the anticyclonic mode (negative values of volume transport) and northward transports during the cyclonic mode (see Fig. 10c of Mihanović et al., 2021; Fig. 40.7.1e of Menna et al., 2022b). In 2017–2018, the reduced strength of the surface current compared to the previous NIG anticyclonic phases led to a temporary weakening of the northward transport, but not to its reversal (Mihanović et al., 2021; Menna et al., 2022b). In summary, the variability of thermohaline properties in the upper thermocline at LB and SA, in conjunction with the NIG reversals, confirms the statements of Gačić et al. (2011, 2013) and Theocharis et al. (2014), which indicate the predominance of internal mechanisms over the atmospheric forcing in shaping the salinity distribution in the EMed.

7.2. *Biogeochemical variability*

Only recently have the relationships between interannual variations of the LIW core properties and corresponding biochemical variations in LB been studied in more detail (Ozer et al., 2017, 2022). Ozer et al. (2017) observed that the surface salinity in the IS was out of phase with that in LB and derived a direct dependence on BiOS mode. The peaks of salinity in the LSW and LIW in 2008–2010, 2014–2015, and 2018–2019 were associated with periods of anticyclonic mode of NIG (Ozer et al., 2022). The observed increase in nutrient supply in the euphotic zone (and consequently a significantly higher average level of integrated primary production and bacterial abundances) was the result of the prolonged residence time of the LIW due to reduced outflow from the LB, which caused positive buoyancy flux and thus deeper winter convection. These dynamics explain the out-of-phase relationship between salinity and nutrient content (along with integrated Chl-*a*) observed in the LIW (Ozer et al., 2017). Moreover, Ozer et al. (2022) indicated that nutrient fertilization of the euphotic layer was also promoted by the average uplift of the LIW core due to global warming. Therefore, the authors concluded that the combined effects of the BiOS mechanism and global warming, and thus the increase in LIW residence time and buoyancy, may affect the biomass of primary producers in the photic zone.

7.3. *CMEMS model output*

A more detailed analysis of the relationship between salinities in the IS and the LB in two layers (AW, surface-150 m and LIW, 200–450 m depth), in the period 1986–2017 is proposed here (Fig. 17), using the Copernicus Marine Environment Monitoring Service (CMEMS, https://marine.copernicus.eu/about) physical reanalysis dataset.

We have previously shown that salinity in LB exhibits variations associated with NIG inversions: periods of anticyclonic circulation are characterized by high salinity (i.e., 1987–1997, 2005–2011), while the cyclonic mode coincides with periods of low salinity (i.e., 1998–2005, 2011–2017; see Fig. 16).

The time series of salinity in the LB is out of phase compared to that recorded in the Ionian basin (Ozer et al., 2017; Menna et al., 2022), just as the zonal transport of the Mid Ionian Jet (part of the MAWJ shown in Fig. 3) at the Cretan Passage is out of phase compared to that in the northern Ionian (Menna et al., 2019). The AW during the cyclonic NIG phase crosses the IS in its southern part and therefore not only has a smaller impact on the salinity of the northern Ionian, but reaches the Levantine directly with a larger volume and lower salinity, where it thus causes a greater reduction in salinity. In contrast, the salinity in the upper layer of the Levantine is greater during the anticyclonic phase of the NIG, as AW remains longer in the IS before reaching the LB, and thus has a smaller effect on the dilution of the upper layer in the easternmost part of the Mediterranean Sea. In addition to decadal variations, the upper layer (AW) in the Ionian Basin showed a positive trend in salinity, which was more pronounced than in the Levantine, especially after the mid-1990 s. On the other hand, long-term salinity variations in the LIW layer (200–450 m) show a trend of increase of similar magnitude in both IS and LB.

7.4. *The EMT preconditioned by the BiOS mechanism*

The AS has always been recognized as the main source of deep water of the Ionian and Levantine basins. Nevertheless, the AeS has also been mentioned as a possible secondary source of dense water reaching the intermediate and/or deep layers (Nielsen, 1912; Miller, 1963; Schlitzer et al., 1991), mainly affecting the area adjacent to the Cretan Arc in the EMed.

As mentioned earlier, the propensity of the Adriatic or Aegean Seas to produce dense water depends on how much salt is available in these seas to trigger the preconditioning phase and, consequently, the subsequent events of dense water formation.

The ability of the Levantine and consequently the Aegean basins to gain salt, especially at the surface and at the LIW horizon (ca. 200–300 m depth), can be considered a precondition that could trigger the “EMT-like” events. Velaoras et al. (2014) identified some of these events based on the revised Medar/Medatlas database for the Levantine Sea (Rixen et al., 2005). The authors listed four EMT-like events in which the AeS contributed with water denser than the intermediate water but not dense enough to reach the bottom of the EMed (except in the case of the actual EMT). The first event was in the 1970 s and was also observed in the Levantine at depths of 150–300 m (S = 39.03), the second occurred between 1987 and 1991 (the well-known EMT event), the third between 1998 and 2000 (recognizable by the dense water exported from the AeS), and the last between 2007 and 2009 (also reported for the Levantine by Ozer et al., 2017). Velaoras et al. (2014) attributed these recurrent EMT-like events to an internal oscillating thermohaline pumping mechanism (Theocharis et al., 2014) affecting the upper thermohaline conveyor belt of the EMed. In any case, the timing of salt preconditioning is consistent with the circulation regime of the NIG and

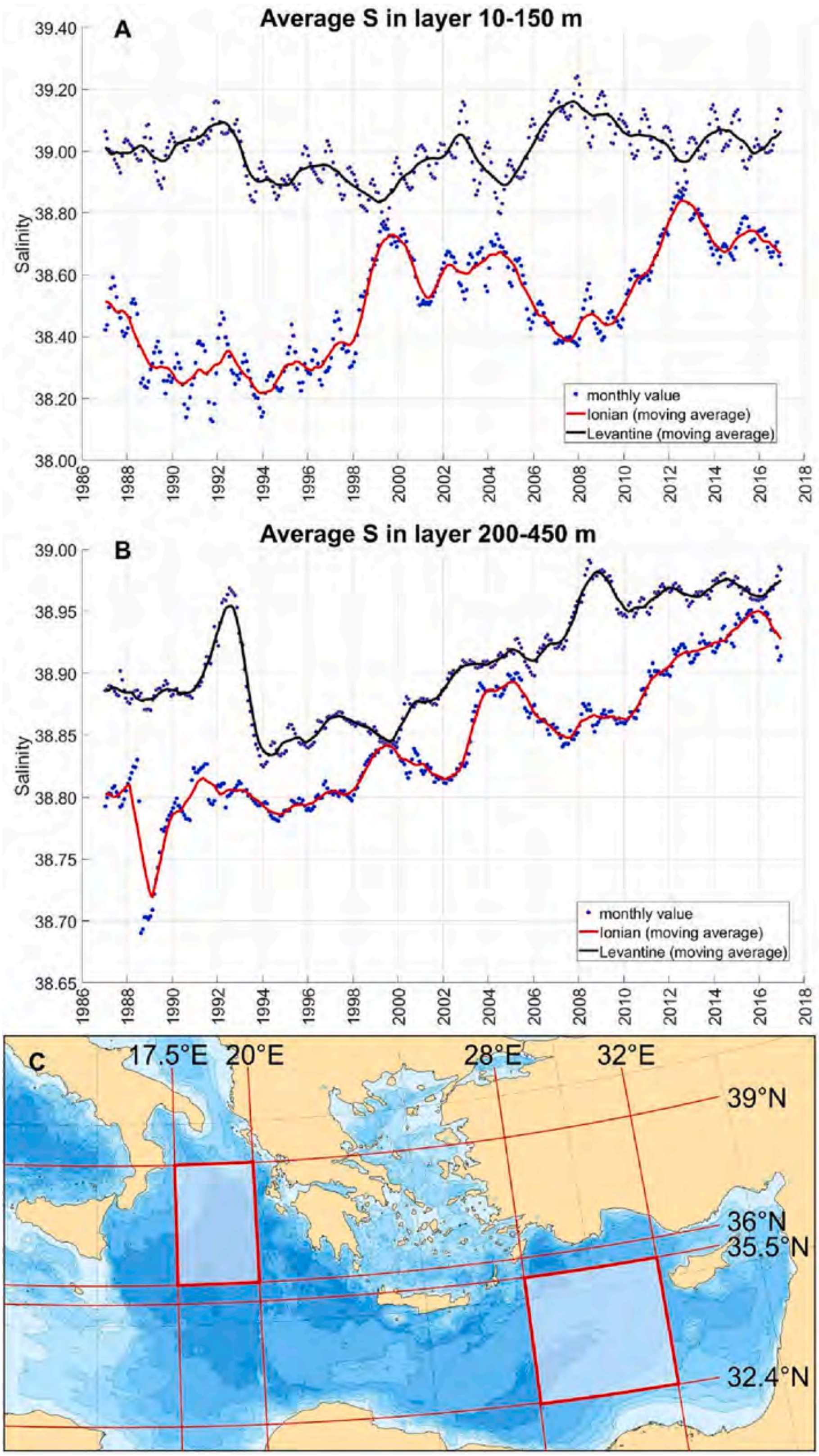


Fig. 17. Time series of average salinity in the 10–150 m (A) and 200–450 m (B) layer in the Ionian Sea and Levantine (C) subareas. Points refer to monthly data, lines to 13-month moving average. Physical reanalysis from the Copernicus Marine Environment Monitoring Service (CMEMS, https://marine.copernicus.eu/about) dataset. Mean monthly salinity was spatially averaged for the Ionian and Levantine basins in the areas defined in Gačić et al. (2011).

confirms that the formation of dense water in the AeS is preconditioned by internal mechanisms. It is worth noting that salt preconditioning does not necessarily lead to EMT events, but exceptional heat loss in the basin (Josey, 2003) should also occur to produce EMT.

8. Effects of NIG circulation and preconditioning in the western Mediterranean: Deep water formation

Beginning in the winter of 2004–05, there was an abrupt increase in temperature and salinity in the bottom waters of the WMed. This climatic event, termed the Western Mediterranean Transition (WMT, CIESM 2009), was described in great detail in a number of studies (see Schroeder et al., 2010, and articles cited therein). The hypothesis of intense heat loss and evaporation, which was put forward in an initial attempt to explain the formation mechanism, explained less than 50% of the salinity increase. Slightly more than 50% of the salinity increase was instead attributed to advective contributions. According to Gasparini et al. (2005), anticyclonic Ionian circulation during 1991–92 favored isopycnal shoaling along the border of the IS and uplifting of the warmer and saltier CSOW that eventually exited the SC. From the timing of the EMT (Roether et al., 2013), it appears that the CSOW had already entered the IS during the period under consideration, enhancing the anticyclonic circulation, but not enough to occupy the area near the SC. The open basin-wide thermohaline cell of the Mediterranean Sea can be summarized as a gradual salinification of AW as it spreads eastward, followed by its conversion to LIW, which in turn flows westward from the LB to the Gibraltar Strait through the SC. Thus, the presence of the saltier and warmer intermediate water in the SC in 1991–92 observed by Gasparini et al. (2005) can be associated with thermohaline variability of LIW rather than with water of Cretan origin (see Fig. 2 in Gačić et al., 2013).

Using a cross-correlation analysis between the salinities of LB and SC, Gačić et al. (2013) estimated a signal travel time of about 11 years for the LIW from its formation area to SC. The authors also estimated another 10 years for LIW propagation time from SC to the WMDW formation area (Gulf of Lion). In total, the LIW takes about 20 years to move from its formation area to the northwestern Mediterranean. These figures agree well with estimates by Roether et al. (2013), who used the tritium-3He dating technique (22 ± 2 years).

Thus, by comparing the salinity increase observed in SC since 1994 with the similar increase during the WMT in WMed starting in 2004 (i.e., 10 years after), Gačić et al. (2013) showed that about 60% of the salinity increase in the deep layers of WMed could be attributed to the salinity increase reported for the LIW in LB in the early 1980s (Ozer et al., 2017).

The presence of “cyclic patterns’’ in temperature and salinity of the SC, due to the effects of different circulation modes of the NIG on LIW formation, have been confirmed for more recent time series by Schroeder et al. (2017) and Placenti et al. (2022). Placenti et al. (2022) also showed out-of-phase cyclic oscillation of nutrients with salinity in intermediate water, possibly related to the NIG circulation, in agreement with Ozer et al. (2017). Further studies could reveal the possible impact of these oscillations on the dynamics of the more recent deep-water formation process in the northwestern Mediterranean.

Amitai et al. (2021) defined the signature of EMed water properties in the Gulf of Lion based on model simulations and confirmed its influence on deep and intermediate water characteristics throughout the Mediterranean Sea. Margirier et al. (2020) highlighted the role of the LIW in activating or deactivating the deep convection in the Gulf of Lion region and defined it as an essential remote forcing and constraint on a local process.

In this context, the acquisition of multi-decadal time series at key points of the Mediterranean thermohaline circulation, such as AS, LB /CS, SC, northern WMed, and Gibraltar Strait are of fundamental importance for climate studies.

9. Reproducibility of BiOS in climate models

There have been recently several attempts with different objectives to replicate the BiOS mechanism and its impact on the Adriatic and Ionian Seas.

The concept of the internal mechanism as the main driver of changes between different equilibria was first proposed before the formulation of the BiOS mechanism in the numerical study of Pisacane et al. (2006). Namely, they hypothesized for the first time that the EMed was subject to internal bimodal oscillations. More specifically, they claimed that “*although air-sea interaction remains the principal driving force of Mediterranean circulation, purely oceanic processes might prove to be crucial*”. According to their study, the eastern basin oscillates between two different patterns (weakening/strengthening of the thermohaline cell), which could be qualitatively related to the density difference of the water masses formed in the Adriatic and Aegean Seas.

Mantziafou and Lascaratos (2008) showed that the calculated deep water formation rate in the AS is subject to strong interannual variability, which depends strongly on the interannual variability of the atmospheric forcing. They sustained that advection of salty waters from the south plays an important role in determining the properties and volume of deep water formed in the Adriatic basin, but it is also the high-frequency atmospheric forcing that determines the interannual variability of deep water formation rates. According to Mantziafou and Lascaratos (2008), the rate of dense water formation was three times higher than climatology during the 1992–1993 biennium, and it was mainly associated with specific buoyancy loss events rather than mean winter buoyancy fields.

Dunić et al. (2019) proposed a performance study of seven regional hindcast simulations based on different configurations of the NEMO - Mediterranean model (Beuvier et al., 2010) during 1980–2012. These configurations differed in resolution, model physics, atmospheric forcing (forced vs. coupled models), and imposed river discharge, and aimed to quantify long-term changes in the oceanographic properties of the Adriatic-Ionian thermohaline circulation. The authors concluded that models with atmospheric coupling better reproduced AdDW formation and consequently BiOS reversal and its decadal variability.

Denamiel et al. (2022) studied the impact of the BiOS on the interannual to decadal variability of the AS thermohaline circulation during the period 1987–2017 using the numerical results of the kilometer-scale climate simulation of the Adriatic Sea and Coast (AdriSC). The results showed that the time series associated with the first five empirical orthogonal functions calculated from the monthly detrended anomalies of salinity, temperature and current velocity were correlated with the BiOS signal.

Liu et al. (2022) performed a long-term hindcast using a regional ocean circulation model run with a realistic atmospheric forcing for the period from 1901 to 2010. The objective of this work was to define the role of various forcing factors (atmospheric and large-scale patterns, strong AdDW formation events) in modulating the NIG reversals. This model reproduced the observed variability in the EMed thermohaline circulation (e.g., NIG upper layer circulation since the late 1980s and the evolution of the EMT event in the early 1990s), which allows us to investigate the unknown behavior of the NIG circulation prior to the observation period. The results suggest that sufficiently strong AdDW formation events are essential for the reversal of the NIG circulation to the anticyclonic mode. The precondition for AdDW formation was explained by the combined effects of net freshwater flux and horizontal advection of salinity. Variations in net freshwater flux were influenced by multidecadal changes in large-scale atmospheric forcing, while variations in horizontal advection of salinity were modulated by circulation patterns of the NIG. The authors found that the simulated NIG upper-layer circulation prior to the observation period was characterized by long-lasting cyclonic phases with weak variability during 1910–1940 and 1960–1985, while quasi decadal NIG circulation reversals with characteristics similar to those observed in recent decades were observed during 1940–1960. Thus, an important result of their simulation indicates that the circulation in the upper layer of the NIG tends to be cyclonic and only occasionally changes to the anticyclonic mode. The coherent variability of upper-level NIG circulation mode and of the AdDW outflow implied that an atmospheric forcing triggering strong AdDW formation was required to reverse the NIG into an anticyclonic circulation 1–2 years later. A sensitivity experiment simulating a cold winter event over AS confirmed this hypothesis (see also experimental results in Gačić et al., 2014, showing however the occurrence of the reversal only 6 months later). Their simulation showed that multi-decadal salinity variability in the AS resulted in conditions where low salinity prevented strong AdDW formation events that favored the persistence of the cyclonic NIG mode. This could explain the absence of quasi-decadal NIG reversals during 1910–1940 and 1960–1985. It should be noted, however, that the historical data examined by Buljan (1953) show that during the period when, according to Liu et al. (2022), there were no NIG reversals (1910–1940), the Adriatic ingressions occurred with decadal frequency.

Other modeling studies suggest that the decadal variability of NIG during the EMT was driven by multiple equilibria between the Ionian and Aegean Seas, extending the concept of BiOS to a coupled system including Adriatic, Ionian, and Aegean Seas (Amitai et al., 2017; Reale et al., 2016, 2017; Theocharis et al., 2014). Reale et al. (2017) concluded that "*two observed BiOS-like reversals reflect the existence of multiple equilibrium states in the thermohaline circulation in the eastern Mediterranean*" and that "*a complete characterization of observed variability needs to take into account a fully coupled Adriatic-Ionian-Aegean system*".

The good representativeness of some hindcast models for BiOS variability in the past gives hope for realistic predictions. In the context of climate change and the associated increase in temperature and stratification (Coma et al., 2009; Adloff et al., 2015), the inversions of NIG can be considered as an indicator of Mediterranean variability (Menna et al., 2019), and its behavior can be usefully interpreted as a signal of changes in the circulation and/or distribution of water masses in the basin.

10. Summary and conclusions

In this paper, based on studies published in the last three decades and some new analyses, we have outlined the history and characteristics of the BiOS and shown that the quasi decadal variability of the Ionian circulation is very pronounced and affects the thermohaline and ecosystem properties of the Mediterranean Sea. Table 3 summarizes the observed variations in the Mediterranean sub-basins as a result of the NIG circulation regime.

The review by Cushman-Roisin et al. (2001) called for a detailed study of decadal changes in the function of AS as a place of dense water production and long-term variations in water exchange between the Adriatic and Ionian Seas. The series of studies mentioned in the present study have indeed addressed this demand and have shown that the two basins are connected by the BiOS feedback mechanism, which on the one hand determines the oceanography of AS and on the other hand causes inversions of the upper circulation in IS.

Two different theories have been proposed about the driving mechanism of BiOS: wind forcing or internal mass redistribution. Here, however, we report how observations, laboratory and numerical

Table 3
Observed variations as a consequence of the NIG circulation regime.

	NIG circulation	SALINITY	BIOGEOCHEMISTRY	BIODIVERSITY and ECOSYSTEM DYNAMICS
Adriatic Sea	*anticyclonic*	$S_{(200\text{-}800m)}$ DECREASE ↘	**Nutrients**$_{(200\text{-}800m)}$ INCREASE ↗	Occurrences of organisms of Atlantic and WMed origin
	cyclonic	$S_{(200\text{-}800m)}$ INCREASE ↗	**Nutrients**$_{(200\text{-}800m)}$ DECREASE ↘	Occurrences of organisms of Lessepsian and EMed origin
Ionian Sea	*anticyclonic*	S_{250m} DECREASE ↘	**Nutrients**$_{(\text{nutricline and NML})}$ (SHOALING of interfaces along boundaries) ↗	No [Chl *a*] peak (no spring bloom)
	cyclonic	S_{250m} INCREASE ↗	**Nutrients**$_{(\text{nutricline and NML})}$ (DEEPENING of interfaces along boundaries) ↘	March [Chl *a*] peak (spring bloom)
Levantine Basin **Cretan Sea** *(~2 years time lag)*	*anticyclonic*	S_{LIW} INCREASE ↗	**Nutrients**$_{LIW}$ (1) DECREASE ↘	Primary Production ↗ (1) Bacterial Abundance ↗ (1)
	cyclonic	S_{LIW} DECREASE ↘	**Nutrients**$_{LIW}$ (1) INCREASE ↗	Primary Production ↘ (1) Bacterial Abundance ↘ (1)
Sicily Channel *(~10 years time lag)*	*anticyclonic*	S_{LIW} INCREASE ↗	**Nutrients**$_{LIW}$ DECREASE ↘	-
	cyclonic	S_{LIW} DECREASE ↘	**Nutrients**$_{LIW}$ INCREASE ↗	-
Western Mediterranean *(~20 years time lag)*	*anticyclonic*	S_{LIW} INCREASE ↗ (60% of contribution for the WMT)	-	-
	cyclonic	-	-	-

(1) For Levantine Basin only.

experiments provide clear evidence that internal forcing causing periodic NIG reversals is the mechanism. Recently, Borzelli and Carniel (2023) have proposed a reconciling view of the combined influence of internal fluid pressure fields and wind.

A second research focus related to the BiOS driving mechanism is its impact on thermohaline and biogeochemical properties and ecosystem dynamics in different sub-basins of the Mediterranean Sea. As evidenced in this review, the BiOS has been shown to influence the oceanographic properties of both the eastern and western Mediterranean by modulating the pathways of AW and LIW, thus affecting the salt distribution throughout the Mediterranean Sea. The LIW, as a carrier of decadal variability caused by the BiOS over the entire Mediterranean, influences the intensity of dense water formation and leads to variability in the deepest part of the thermohaline cells. Thus, the BiOS is an internal mechanism that has a number of effects on a large part of the Mediterranean Sea.

Although it is an internal forcing mechanism, it also depends on the preconditions and the heat exchange with the atmosphere in the dense water formation sites (Gulf of Lions, South Adriatic Pit and occasionally Cretan Sea).

Therefore, future research should address and further clarify the relationship between the climatic variations and the functioning of the BiOS that would affect air-sea heat exchange on the one hand, and preconditioning through changes in water exchange in the Adriatic-Ionian region on the other. In future studies, it will also be important to consider variations in thermohaline properties of waters of Atlantic or Levantine origin as a consequence of climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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