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REVIEW

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North Adriatic Dense Water: lessons learned since the pioneering work of Mira Zore-Armanda 60 years ago

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Abstract: This review first pays tribute to the famous Croatian oceanographer, Mira Zore-Armanda, and her seminal work on the Adriatic water masses in 1963, and emphasises the importance of the densest Mediterranean water mass: North Adriatic Dense Water (NAddW). This water mass is generated through substantial wintertime surface cooling and evaporation over the wide northern Adriatic and is known to (1) influence the Adriatic-Ionian thermohaline circulation, (2) bring oxygen and carbon to the deep Adriatic layers and, (3) more generally, have a substantial impact on the physics and biogeochemistry of the whole Adriatic. Second, the NAddW physics, from preconditioning, through generation and spreading, to accumulation in Adriatic depressions, is reviewed. Then, the temporal evolution of the NAddW properties influenced and connected to (1) basin-wide interannual and decadal variability and (2) trends towards warmer and saltier source characteristic due to ongoing climate change, is discussed. The importance of long-term observations and atmosphere-ocean modelling in event, decadal and climate studies is then presented. Finally, a review of the identified gaps and perspectives for future research is concluding this article.
***Keywords*:** Adriatic Sea, water masses, dense water formation, bottom density currents, observations, modelling, decadal and climate changes

Sažetak: SJEVERNOJADRANSKA VODA VISOKE GUSTOĆE: ŠTO ZNAMO 60 GODINA NAKON PIONIRSKOG RADA MIRE ZORE-ARMANDA. Ovaj rad daje počast hrvatskoj oceanografkinji Miri Zore-Armanda i njenom pionirskom radu iz 1963. godine o jadranskim vodenim masama, te detaljno opisuje Sjevernojadransku vodu, vodenu masu s najvišom gustoćom u Sredozemlju. Ova vodena masa se stvara za vrijeme izraženih zimskih prodora hladnog i suhog zraka nad sjevernim Jadranom, te je poznato da (1) pokreće jadransko-jonsku termohalinu cirkulaciju, (2) donosi kisik i ugljikove spojeve u duboke slojeve Jadrana, te (3) ima značajan utjecaj na fizička i biogeokemijska svojstva cijelog Jadrana. Rad daje pregled novijih istraživanja dinamike Sjevernojadranske vode u svim njenim fazama, od prekondicioniranja, stvaranja, širenja pa do akumuliranja u jadranskim kotlinama. Nakon toga diskutiraju se promjene u izvornim svojstvima (temperaturi i salinitetu) Sjevernojadranske vode i povezuju s (1) međugodišnjim i dekadskim oscilacijama u Jadranu, kao i s (2) trendovima termohalinih svojstava koji nastaju zbog klimatskih promjena. U pregledu se naglašava važnost provođenja dugoročnih mjerenja kao i razvoj numeričkih modela atmosphere i mora, namijenjenih kako istraživanju pojedinačnih događaja za kojih se stvara voda, tako i kvantificiranju trendova i varijabilnosti na dekadskim i klimatskim skalama. Naposljetku, dan je i pregled potencijalnih istraživačkih tema vezanih za Sjevernojadransku vodu koji bi mogao unaprijediti saznanja o oceanografskim procesima u Jadranu.
Ključne riječi: Jadransko more, vodene mase, stvaranje vode visoke gustoće, pridnene struje gustoće, mjerenja, modeliranje, dekadske varijacije i klimatske promjene

INTRODUCTION

The transfer of surface waters to deep layers is a key process for replenishment of deep ocean waters and for driving basin-wide and global thermohaline circulations, as well as for transporting oxygen and carbon from the surface to the bottom (Schmidtko *et al.*, 2017; Sun *et al.*, 2017). Such transfer may occur by means of two different processes: (1) through deep-convection over deep oceans, where the surface waters are cooled and evaporated enough to turbulently sink to deep layers, even to the bottom (Marshall and Schott, 1999), or (2) through substantial cooling and evaporation of surface waters over continental shelves and coastal shallow seas, resulting in vigorous near-bottom density currents that rapidly transport dense waters over slopes towards the deep and abyssal plains (Ivanov *et al.*, 2004; Luneva *et al.*, 2020). The former drives the global conveyor belt (Schmitz and McCartney, 1993) and the thermohaline circulation of many deep basins (e.g., the Mediterranean Sea, Skliris, 2014), transporting heat, oxygen, carbon, atmospheric nutrient load, particles, biotic material, etc., to the deep ocean layers (e.g., Stabholz *et al.*, 2013; Tamburini *et al.*, 2013). For the latter, the transport is limited mostly to coastal seas, where the downslope and cascading density currents are enforced by submarine

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canyons, but it has similar effects on the physical and biogeochemical processes as the open-ocean convection (e.g., Puig *et al.*, 2013; Salvado *et al.*, 2017).

Both processes occur in the Mediterranean Sea (Robinson *et al.*, 2001; Malanotte-Rizzoli *et al.*, 2014), and particularly in its 800 km long and 200 km wide northernmost embayment, the Adriatic Sea (Fig. 1). The northernmost third of the Adriatic Sea (i.e., the northern Adriatic Sea) is a shelf with depths up to 100 m. It is connected to the Southern Adriatic Pit (SAP; 1200 m deep), a circular bathymetric feature that strongly shapes the Adriatic circulation (Artegiani *et al.*, 1997a, b), through, first, transitional middle Adriatic depressions also known as the Jabuka Pit (JP; 280 m deep) and, second, a 170-m deep sill known as the Palagruža Sill (PS). The water exchanges between the Adriatic Sea and the rest of the Mediterranean Sea are made through the Strait of Otranto (800 m deep). In particular, saline waters are entering the Adriatic in the intermediate layers of the eastern part of the strait and Adriatic waters mostly outflow through the western shelf of the strait and the deep section of the strait (Gačić *et al.*, 1996; Civitarese *et al.*, 1998). In these conditions, the highly oxygenated dense Adriatic waters spread – through an interplay with the Aegean source of dense waters – to the deep Ionian and Eastern Mediterranean layers (Roether and Schlitzer, 1991; Robinson *et al.*, 2001).

Adriatic water masses, either originating from or being advected in or transported out of the Adriatic Sea, have been first systematically classified by Mira Zore-Armanda (Zore-Armanda, 1963) 60 years ago. This famous Croatian oceanographer produced not only this seminal work on the Adriatic water masses but, during her entire carrier between the 1950s and the 1990s, she also built solid foundations for modern Adriatic physical oceanography (see bibliography in Morović, 2012, and Orlić, 2012). In particular, by introducing four types of Adriatic water masses – (1) North Adriatic Dense Water (NAddW, often found in literature as NAdDW, or Type S), (2) Middle Adriatic Deep Water (or Type M), (3) South Adriatic Deep Water (or Type J) and (4) Modified Levantine Water (or Type A) – Mira Zore-Armanda irrevocably shaped the Adriatic oceanography, including physics, biogeochemistry and even fisheries (e.g., Kršinić and Grbec, 2006; Grilli *et al.*, 2013). Nowadays, despite the more accurate knowledge of the Adriatic water masses through hundreds of publications based on both observations and numerical modelling, the classification proposed by Mira Zore-Armanda is still used within the Adriatic (e.g., Artegiani *et al.*, 1997a; Vilibić and Orlić, 2001, 2002) and the Mediterranean (Schroeder *et al.*, 2012; CIESM, 2022) oceanographic communities.

This work focuses on the NAddW which is also known to strongly influence the northern Adriatic organisms (Kraus *et al.*, 2015), including most of the benthic organisms (Blasnig *et al.*, 2013; Djakovac *et al.*, 2015) that might be affected by hypoxia and anoxia. That is even more relevant for the major nursery of benthic organisms in the JP serving as a collector of

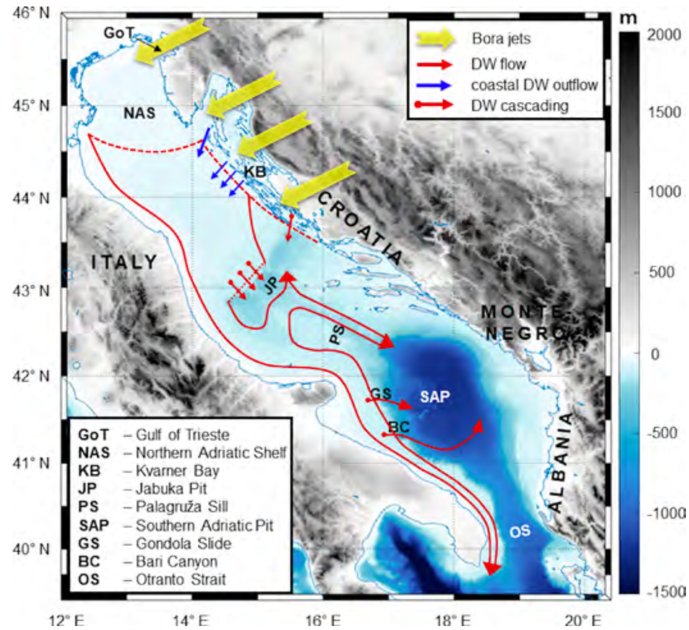

Fig. 1. The Adriatic Sea bathymetry and orography, with indicated North Adriatic Dense Water formation sites (NAS – northern Adriatic shelf, KB – Kvarner Bay, GoT – Gulf of Trieste), NAddW pathways (arrows) and accumulation sites (JP – Jabuka Pit or middle Adriatic depressions, SAP – Southern Adriatic Pit, KB – Kvarner Bay). Dominant bora wind patterns associated with the NAddW formation are also indicated.

dense waters, while exhibiting a decrease of oxygen in the recent decades (Lipizer *et al.*, 2014). Further, the warming climate and warmer NAddW may endanger some organisms favouring cold oceans, such as shrimps (Matić-Skoko *et al.*, 2022). Finally, dissolved oxygen concentrations in the deep SAP (Manca *et al.*, 2006) and transport of carbon to the deep layers (Cossarini *et al.*, 2015; Cantoni *et al.*, 2016; Ingrosso *et al.*, 2017) are also directly influenced and driven by the NAddW. For these reasons, updating the previous review done by Vilibić and Supić (2005) with the current knowledge related to the NAddW is of critical importance for Adriatic marine researchers.

Consequently, this review article addresses this need and is structured as follows. Section 2 details the founding contribution of Mira Zore-Armanda to the knowledge of Adriatic water masses and dynamics (Zore-Armanda, 1963). Section 3 provides details of the NAddW dynamics, from preconditioning through generation, spreading and accumulation at the dense water collectors as well as how it affects the biogeochemistry and biology of the Adriatic. Section 4 presents the connection of the NAddW with the decadal thermohaline variability, trends and the Adriatic-Ionian Bimodal Oscillating System mechanism (BiOS), internally-driven processes that alternate physical and biogeochemical conditions in the Adriatic every 5 to 10 years. Section 5 reviews the NAddW observing efforts and the numerical modelling studies at event, decadal and climate scales. Section 6 highlights research gaps and Section 7 provides concluding remarks.

TRIBUTE TO THE PIONEERING WORK OF MIRA ZORE-ARMANDA

A prelude to Mira Zore-Armanda's research on water masses

Temperature and salinity data have been systematically collected and processed in the Adriatic Sea since the 19th century when the first insight of the Adriatic thermohaline properties was published (Wolf and Luksch, 1881). However, multi-annual collection of data samples at prescribed hydrographic transects started in the early 1900s. Indeed, the data collected between 1911 and 1914 by the Austrian and Italian research vessels Najade and Ciclope, together with the Vila Velebita cruises in the Kvarner Bay and the northern Adriatic, allowed for proper quantification of multi-annual changes and seasonal variations of thermohaline Adriatic properties over the vertical, transversal (from Italy to Austrian-Hungarian Empire), and from the northern Adriatic till the Strait of Otranto and northern Ionian Sea (Fig. 2). These data have been used to document variations of temperature and salinity between years (Buljan, 1953), pointing to the existence of "Adriatic ingressions" – i.e., intrusions of highly saline waters. The ingressions have been, at that time, associated with changes in the Strait of Otranto transport. Among all of these research activities, the work of Mira Zore-Armanda (Fig. 3) emerges, as it first confirms the long-term fluctuations of current velocities and the Adriatic circulation and then connects them with seasonal variations in thermohaline properties of the Adriatic (Zore, 1956). However, the beacon paper in which the Adriatic water masses were classified for the very first time was published in 1963 (Zore-Armanda, 1963), and was, interestingly, written in French which was, at that time, a language largely used by the research community. However, this was in contrast to Mira Zore-Armanda's other articles predominantly written in English and Croatian (Zore-Armanda, 1969, 1991; Buljan and Zore-Armanda, 1976).

Fig. 3. Photo of Mira Zore-Armanda (taken from Orlić, 2012).

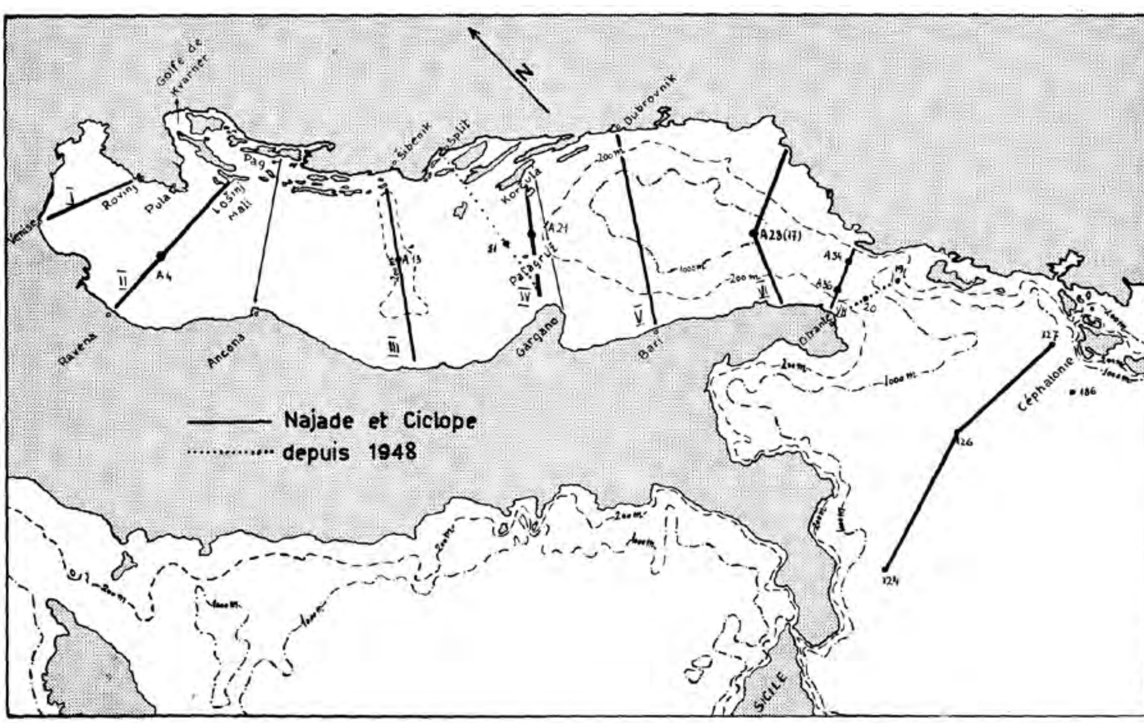

Fig. 2. Map of oceanographic transects and meteorological stations used by Mira Zore-Armanda for classification of Adriatic water masses (reproduced from Zore-Armanda, 1963).

The 1963 article on the classification of Adriatic water masses came out after a decade of research career during which Mira Zore-Armanda took several international visits, including these related to her Ph.D. research carried out in collaboration with the Laboratoire d'Océanographie Physique du Muséum National d'Histoire Naturelle de Paris and was defended at the Sorbonne University. For that reason, the work on the Adriatic water masses, being a part of the Ph.D. thesis, was written in French. It should be emphasized here that this international experience truly shaped Mira Zore-Armanda's work. Indeed, she decided to get her Ph.D. at a renowned university after a conflict with a collaborator of her unfortunately deceased supervisor. She thus left Croatia due to "*jealousy and some unfinished issues from the study*" and went to France keeping in mind "*that they wouldn't blame me later that I got my doctorate cheaply*" (Zore-Armanda, 1997). More about the life and professional career of Mira Zore-Armanda may be found in Morović (2012) and Orlić (2012), and in her memoirs (Zore-Armanda, 1997).

Description of the data, methods and water mass types

Several challenges related to the research that ended with the classification of the Adriatic water masses existed in the mid twentieth century. One of the largest issues was the collection of the research data, including their quality control and preparation for analyses. Fortunately, data coming from 1911-1914 Najade and Ciclope cruises were available for the research, each taken at four transect in the Adriatic (Fig. 2). In addition to that, Zore-Armanda (1963) used more temperature and salinity data collected over the PS transect, while also taking inland meteorological data. Altogether, 10 000 temperature data and 10 000 salinity data were used for the research, an impressive amount of data which – in that pre-computer era – was analyzed manually, requiring a lot of patience and meticulousness in the research. It should also be emphasized that these datasets were freely available for any researcher in the Adriatic oceanographic community. In particular, all ocean data from the Institute of Oceanography and Fisheries were regularly published (Buljan and Zore-Armanda, 1966, 1979; Zore-Armanda et al., 1991) till 1983 when, unfortunately, it stopped. Instructively, these publications followed today's FAIR principles (Findability, Accessibility, Interoperability, and Reuse) established a half of century later (Wilkinson *et al.*, 2016).

The methods used by Mira Zore-Armanda to analyze the observational datasets were mostly T-S diagrams and estimation of geostrophic currents during seasons. The first were used to classify the Adriatic water masses, and the second to connect the water mass dynamics with the Adriatic circulation regimes during different seasons (Fig. 4) and to estimate exchange rates between the Adriatic and the Ionian seas. At end, she classified four different Adriatic water masses, of which three are formed within the Adriatic Sea, while the fourth is advected from the Ionian Sea through the Otranto Strait.

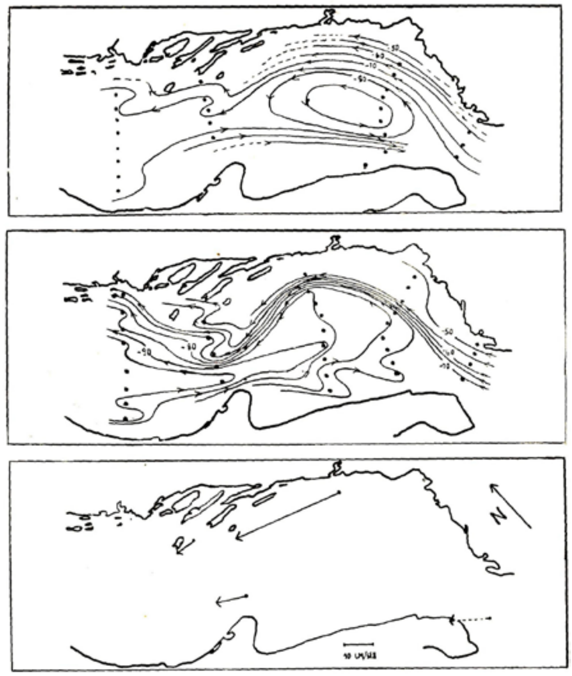

Fig. 4. Geopotential heights and indicated geostrophic currents estimated from temperature and salinity data collected in February-March 1912 (0-100 dbar, upper plot), February-March 1914 (0-150 dbar, middle plot), as well as 24-h currents measured during March (bottom plot) (reproduced from Zore-Armanda, 1963).

The first type of water masses defined by Zore-Armanda (1963) is Type S, later renamed to North Adriatic Dense Water (NAdDW) by Artegiani *et al.* (1997a) and recently changed in acronym to NAddW following recommendations by the Committee on the Mediterranean water masses (CIESM, 2022). Following Zore-Armanda (1963), Type S water mass is characterized by temperature and salinity values of 11 °C and 38.5 respectively, being the densest of all Adriatic water masses – i.e., its potential density anomaly (PDA) value is 29.4 kg/m^3. Type S water mass is formed during extensive cooling events and in higher salinity conditions in the shallow northern Adriatic (Fig. 5). Then, it is transported towards the JP where it accumulates and resides for some time as not renewed every year. Type S water mass has not been found, at least in its pure state, south of the PS, and not quoted to reside at the bottom of the SAP. In years when no Type S water mass is produced (i.e., in low salinity conditions), Type M water mass – sometimes referred as Middle Adriatic Deep Water (MAdDW; Artegiani *et al.*, 1997a) – is formed through open-ocean convection and resides in the middle Adriatic, also accompanied with a low transport from the south Adriatic. Type M water mass is characterized by temperature and salinity of 12 °C and 38.2, respectively. In years with high salinity conditions, Type M water mass is claimed absent.

Type A water mass – known today as Levantine Intermediate Water (LIW; Malanotte-Rizzoli *et al.*, 2003; Fedele *et al.*, 2022) – has its origin in the Levantine Basin. It is the warmest and most saline Adriatic

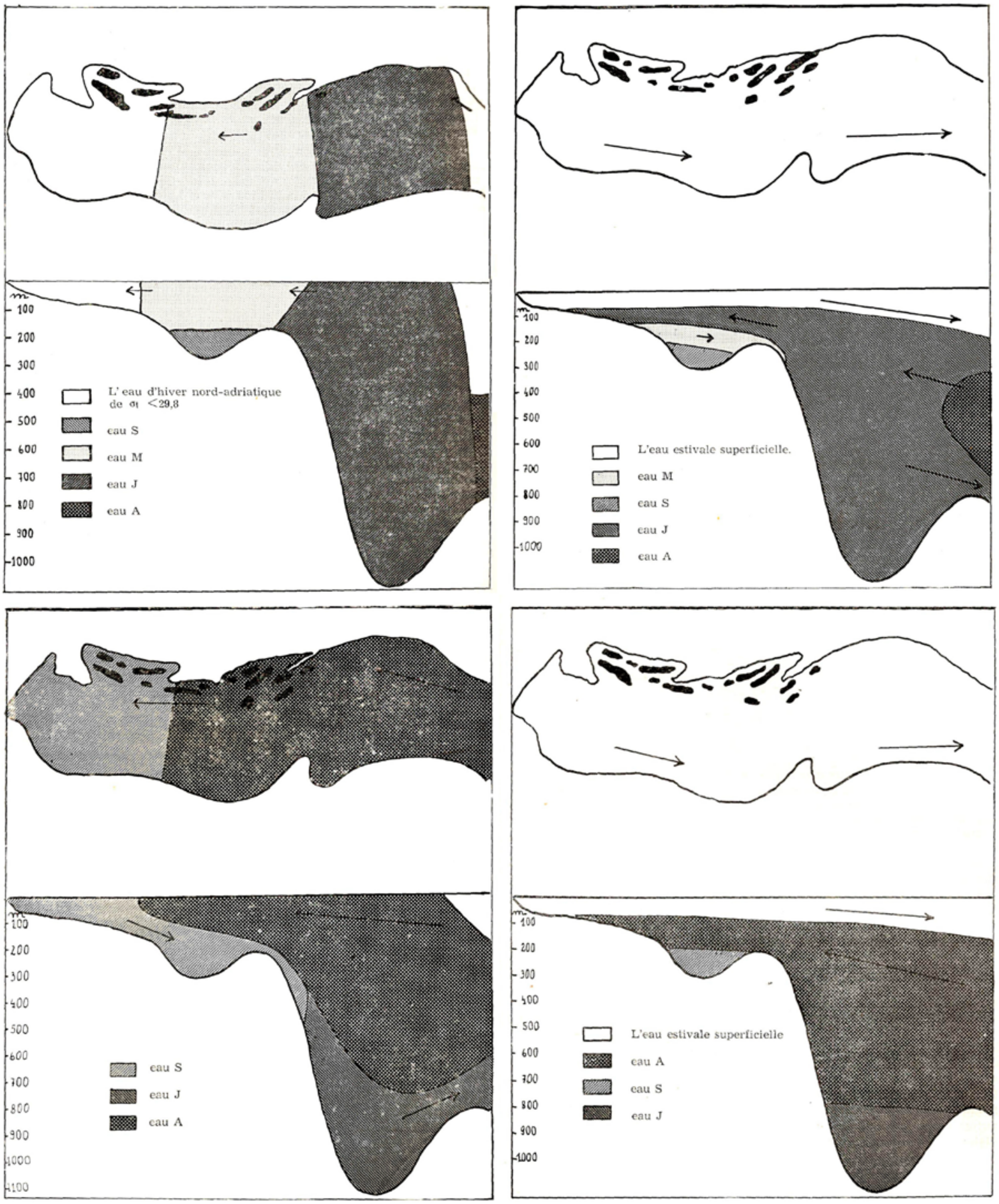

Fig. 5. Schematic representation of water type characteristics in the surface layer and along a latitudinal cross section of the Adriatic during winter (left panels) and summer (right panels) and for low (upper panels) and high (lower panels) salinity periods (reproduced from Zore-Armanda, 1963).

water mass, with temperature and salinity of 14 ˚C and 38.7, respectively. According to Zore-Armanda (1963), Type A water mass is largely blocked in the Strait of Otranto, therefore not advected inside the Adriatic, during low salinity conditions, while flowing in intermediate layers (100-500 m) towards the northern Adriatic during high salinity conditions. The interplay between high salinity and low salinity conditions in the Adriatic Sea was thus explained by the rate of transport in the Strait of Otranto, that is assumed high during high salinity conditions and low during low salinity conditions. Also, the difference between summer and winter conditions was explained mostly by the stratification, where the surface waters are overlaying the Adriatic water masses, which are then spread mostly in horizontal, while suppressing their vertical movement.

Type J water mass – also referred to as Adriatic Deep Water (AdDW; Artegiani *et al.*, 1997a) – is formed in the middle of the SAP during low salinity conditions, through extensive cooling and with convective mixing up to the bottom, according to Zore-Armanda (1963). During high salinity conditions, Type J water mass is suppressed to the bottom of the pit. Zore-Armanda (1963) hypothesized that Type J water mass is a mixture of three other water masses: 63% of Type A, 11% of Type M and 26% of Type S. This implies that most of the SAP waters have a Mediterranean origin. Further, the paper hypothesized that Type J water mass is, once generated, flowing in the deep layers of the Eastern Mediterranean Sea, following earlier works such as Pollak (1951). Type J water mass is characterized by temperature and salinity of 13 ˚C and 38.6, equal to a PDA value of 29.2 kg/m^3, the latter frequently used in present-day studies for quantifying transports of dense waters in the Adriatic and the Strait of Otranto (see Section 4.2). The scheme of the Adriatic water masses as defined by Zore-Armanda (1963) is illustrated in Figure 5.

The legacy

Since the pioneering work of Mira Zora-Armanda, the state-of-the-art knowledge of the Adriatic water masses somewhat changed when new data became available (Artegiani *et al.*, 1997a; Malanotte-Rizzoli *et al.*, 1997; Vilibić and Orlić, 2001, 2002; Lipizer *et al.*, 2014). First, Type M water mass is normally no longer considered a water mass, but a mixture of other water masses. Second, the generation of the NAddW and the AdDW is known to occur during most winters even though their characteristics may substantially change during high- or low-salinity conditions. Third, the deep convection is known not to reach the bottom of the SAP, but just layers up to 900 m (Gačić *et al.*, 2002; Cardin *et al.*, 2011, 2020, Pirro *et al.*, 2022), while the NAddW is known to cascade towards the bottom of the pit (Bensi *et al.*, 2013; Querin *et al.*, 2016). Fourth, the transport rates in the Strait of Otranto are known not to be responsible for the interplay between high- and low-salinity conditions which is known to be driven by the internal vorticity dynamics in the northern Ionian Sea – i.e., the so-called Adriatic-Ionian Bimodal Oscillating System (BiOS; Gačić *et al.*, 2010; Mihanović *et al.*, 2015; Borzelli and Carniel, 2023). Despite these changes and updates, the foundation of all the Adriatic water mass research, mostly based on 4-year long datasets collected a century ago, was provided by Mira Zore-Armanda's work in 1963.

NAddW DYNAMICS

This chapter presents the state-of-the-art knowledge of the NAddW preconditioning, generation, spreading and accumulation, based on numerous research activities carried out since the last NAddW review by Vilibić and Supić (2005). Findings by Vilibić and Supić (2005) are summarized as follows:

A. Long-term wintertime thermohaline measurements along the Po-Rovinj transect in the northern Adriatic indicate that maximum density (mostly reached in February) is highly variable (ca. 1 kg/m^3), which implies that the dense water formation (DWF) intensity may significantly vary between years. Further, east-to-west difference in near bottom density indicates different wintertime circulation regimes in the northern Adriatic.
B. Generation of the NAddW is normally occurring in the cyclonic gyre off the Po River delta, driven mostly by the longshore changes in the bora wind which may blow up to a week and may generate heat losses up to 1000 W/m^2 from the sea along its jets (Supić and Orlić, 1999). Buoyancy effects driven by the Po River discharge are also important in shaping the cyclonic-anticyclonic circulation in the northern Adriatic (Hendershott and Rizzoli, 1976; Zore-Armanda and Gačić, 1987; Beg Paklar *et al.*, 2001).
C. After generation, the NAddW is flowing along the western Adriatic shelf as a bottom density current (Fig. 6; Nof, 1983; Ivanov *et al.*, 2004), partially cascades in the JP (Artegiani and Salusti, 1987; Vilibić *et al.*, 2004) and partially goes over the PS, south of Palagruža Island. The cascading into the JP mostly occurs in the westernmost part of the depressions but easternmost transports were indicated by temperature and salinity profiles after the severe winter of 1956 (Vilibić, 2003). The hypothesis is thus that the dense waters can be advected to the depressions also along the eastern shelf, being bifurcated by a shoal off the Kvarner Bay. Once filling the JP, a weak overflow density current is going over the deepest section of the sill (north from Palagruža Island). When reaching the slope of the SAP, a downslope current transports the NAddW to the deep layers of the SAP, largely through the canyon

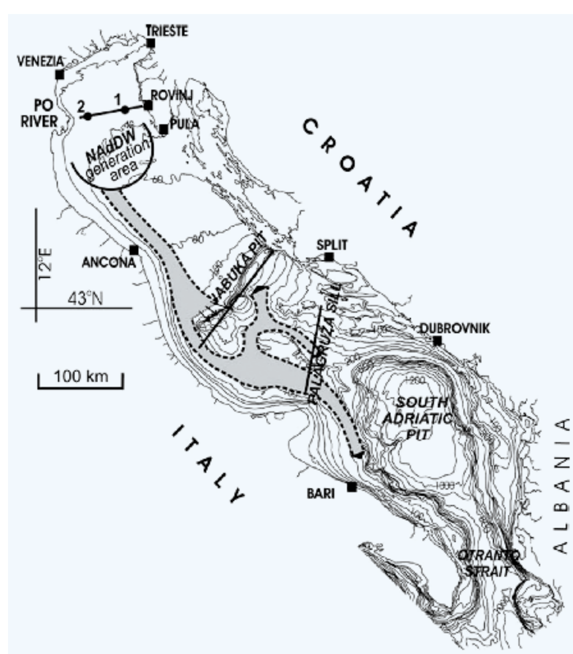

Fig. 6. Pathways of the NAddW, as documented by Vilibić and Supić (2005).

system off Bari, but also partially going along the Italian shelf towards the Strait of Otranto (Bignami *et al.*, 1990).

D. Accumulated NAddW may reside at the bottom of the SAP for years till the next strong generation of dense waters, preventing open-ocean convection in the SAP from reaching the bottom (e.g., Gačić *et al.*, 2002). The dense waters are also residing in the JP but only for a year or two contrarily to the SAP. During this period a substantial decrease in dissolved oxygen may occur (Artegiani *et al.*, 2001; Vilibić, 2003) due to a significant level of biogeochemical activity (Krasakopoulou *et al.*, 2005).

Preconditioning

Both temperature and salinity are shaping the wintertime hydrography in the northern Adriatic. Temperature is largely preconditioned by the heat losses occurring between October and February (Supić and Vilibić, 2006). In contrast, salinity is largely preconditioned by both (1) river discharges, that may lower salinity if having large discharges a few months before the DWF, and (2) advection of water masses from the southeast, i.e., the Ionian Sea, strongly shaped in salinity by the BiOS (Vilibić *et al.*, 2020). On top of it, autumn and winter thermohaline circulation regimes in the northern Adriatic resemble a large interannual variability which strongly influences the DWF (Supić *et al.*, 2012; Dunić *et al.*, 2022).

In particular, preconditioning has been found important for the centennial DWF event in winter 2012 which occurred due to a salinity increase of about 0.3 during summer and autumn 2011 (Mihanović *et al.*, 2013; Janeković *et al.*, 2014). During this period, dry conditions during most of 2011 resulted in lower river discharges and penetration of highly saline water deep into the northern Adriatic coastal regions. One of these regions is the Kvarner Bay (Vilibić *et al.*, 2018), where no DWF was documented before 2012 due to a lack of available measurements and biases in freshwater discharges (i.e., 6-7 times larger than the reality) due to improper climatology used in previous modelling studies (Martin *et al.*, 2009; Oddo and Guarnieri, 2011). Another coastal region is the Gulf of Trieste (Raicich *et al.*, 2013), normally influenced by the freshwater load of the Isonzo River (Comici and Bussani, 2007) and characterized by much lower salinity than the open northern Adriatic (Malačič *et al.*, 2006). In general, it has been found that the northern Adriatic physical and biogeochemical conditions are largely dependent on the Po River discharges (Campanelli *et al.*, 2011; Cozzi and Giani, 2011), that also defines all aspects of the generated NAddW at the shelf and their transport towards the deep Adriatic layers.

Generation

The description of the open northern Adriatic circulation during the DWF events, in particular the double cyclonic-anticyclonic dipole generated by the bora wind and wind curl (Fig. 7; Kuzmić *et al.*, 2007), was updated since the previous review (Vilibić and Supić, 2005). But more importantly, several important aspects of the NAddW generation were discovered after the severe cooling event that occurred in January/February 2012 and lasted for about three weeks (Mihanović *et al.*, 2013; Benetazzo *et al.*, 2014; Davolio *et al.*, 2015; Carniel *et al.*, 2016a). First, the level of severity of this event was at the centennial scale as the last known similar cooling event occurred during winter 1929 (Vatova, 1934). Second, the heat losses were doubled compared to previously documented severe cold outbreaks, driven by both gale winds and extremely low air temperatures (up to -10 ^{o}C). The heat losses peaked at 2000 W/m^2 in the lee of the Velebit Mountain (Fig. 8; Janeković *et al.*, 2014). Third, atmosphere and ocean models with much higher resolutions than the ones used before this event were capable to properly reproduce the orographically-driven variability of the bora wind (Kuzmić *et al.*, 2015; Denamiel *et al.*, 2021a). Fourth, the role of air-sea feedback was found to strongly influence the intensity of the bora wind (Pullen *et al.*, 2006, 2007; Ličer *et al.*, 2016; Denamiel *et al.*, 2021a), which was not considered in previous modelling studies. Indeed, the sea surface might be a substantial source of water vapour during extreme bora events that, at end, can produce a metre or more of snow along the Apennines as a consequence of lake-effect snow (Bisci *et al*., 2012). Lastly but probably most importantly for the dense water dynamics, new formation sites have been documented in coastal regions, along the eastern Adriatic coastline, in which the densest waters have been formed during the 2012 cooling event: the Kvarner Bay and the Gulf of Trieste.

Indeed, record-breaking PDA was measured deeply inside the 20-m shallow Gulf of Trieste, with the value of 30.59 kg/m^3 (Mihanović *et al.*, 2013; Raicich *et al.*, 2013). Further, in the Kvarner Bay which is separated from the open waters by many islands but is also deeper (60-100 m) than the open waters (50-70 m) and normally prone to substantial freshwater load, PDA values reached 30.0 kg/m^3 in the lee channel of the Velebit Mountain (Mihanović *et al.*, 2013), where bora blows the strongest in the whole Adriatic Sea (Grisogono and Belušić, 2009). As the preconditioning period was characterized by a dry weather, this allowed for the replacement of coastal waters by more saline open waters within a week to several weeks, which is the estimated flushing time for these coastal regions (Malačič and Petelin, 2009; Vilibić *et al.*, 2018). The contribution of the DWF site in the Kvarner Bay to the overall DWF has been estimated to reach 40 % during the winter of 2012 (Janeković *et al.*, 2014). After this event, the DWF in other winters have been quantified, being substantial in the Kvarner Bay if preconditioned with dry and high salinity conditions (Mihanović *et al.*, 2018). However, these contributions have been estimated by numerical models, which – particularly inside the Kvarner Bay – are sensitive to both forcing from the atmosphere and to freshwater load (e.g., Vilibić *et al.*, 2016, Vodopivec *et al.*, 2022, see also the discussion in Section 5). Already

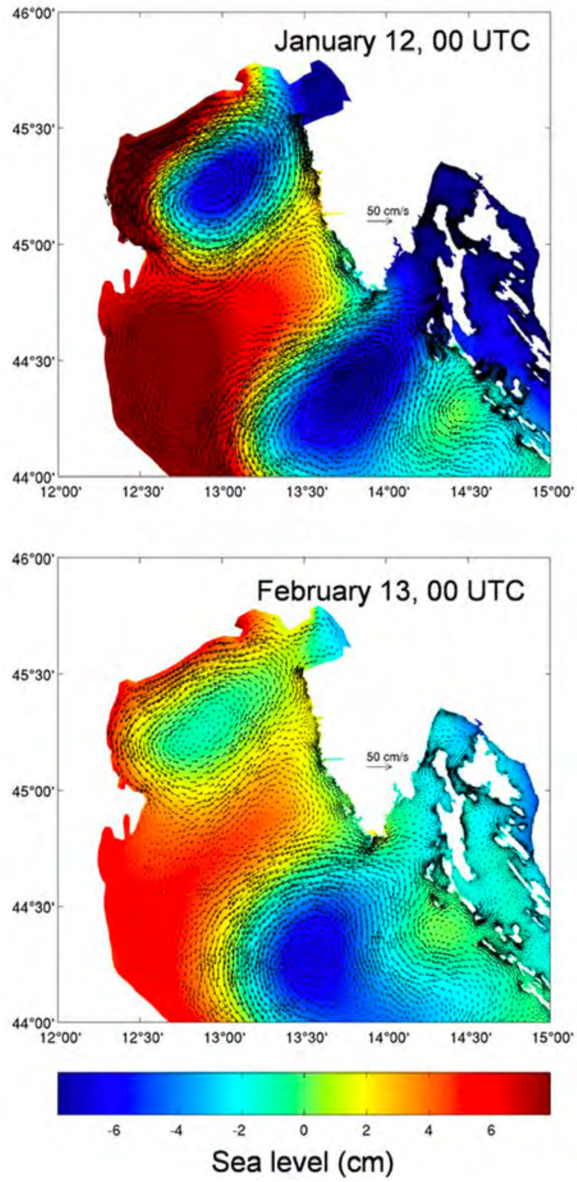

Fig. 7. Snapshots of surface currents and sea levels modelled during two bora wind episodes in 2003 (after Kuzmić *et al.*, 2007).

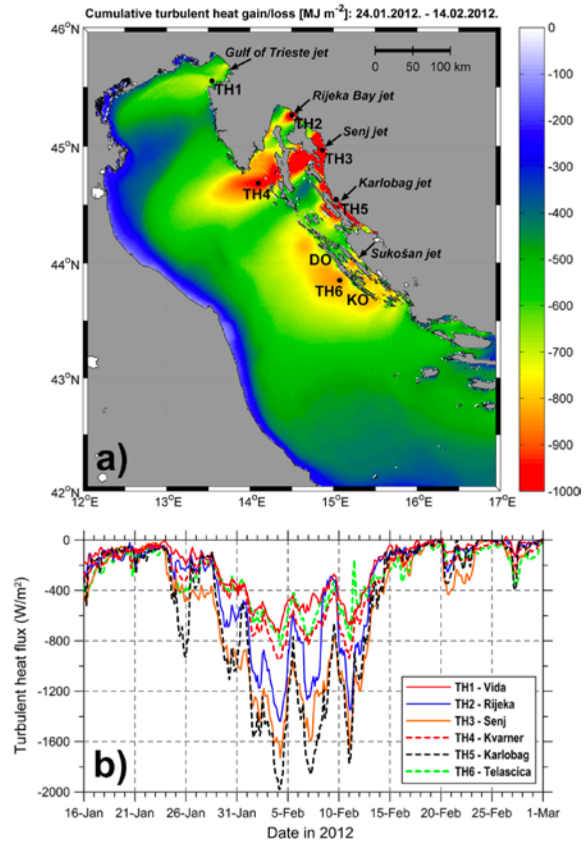

Fig. 8. Cumulative (upper plot) and 3-h (lower plot) turbulent heat fluxes estimated from the ALADIN/HR (Aire Limitée Adaptation dynamique Développement InterNational) atmospheric model during the severe bora episode in the winter of 2012 (after Janeković *et al.*, 2014).

during the generation, the dense waters are pushed out by the bora wind from the Kvarner Bay through numerous channels, generating strong thermohaline fronts between dense waters and warmer and saltier waters being advected from the southeast with the Eastern Adriatic Current (Lee *et al.*, 2005; Carniel *et al.*, 2016a; Kokkini *et al.*, 2017).

Spreading

Once generated, the NAddW is outflowing towards the southeast along the western Adriatic shelf and many observational and modelling studies have provided much more insight to this process since the review of Vilibić and Supić (2005).

Initially, the bottom density current flowing along the western Adriatic shelf is few metres thick and potentially quite intense before cascading into the JP (Fig. 9; Vilibić and Mihanović, 2013). During winter 2012, the first pulse of bottom density currents (hereafter referred as vein of density currents), reaching ca. 20 cm/s or more, was observed just two weeks after the beginning of the extensive cooling along the northern Adriatic shelf. On average, the travelling between the DWF shelf area and the JP takes about a month (Mihanović *et al.*, 2018). In 2012, from April to June, the vein of the NAddW bottom currents decreased in speed to ca. 2-6 cm/s, while the thickness of the density plume presented a substantial temporal variability: it reached a maximum of 50 m in height but also vanished during intrusions of adjacent waters (Vilibić and Mihanović, 2013). Pulsations of the NAddW density current have been confirmed by modelling studies showing that the NAddW outflow lasted for months after its generation (Benetazzo *et al.*, 2014; Janeković *et al.*, 2014). Two major pulses of NAddW density currents occur toward the JP. The first is rapidly formed after the cooling event, having quite large front speed due to large density difference between the NAddW and ambient waters, and might be further pushed towards the southeast by winds (Book *et al.*, 2005). The second pulse occurs a few weeks to a few months later, emptying relatively slowly the north-

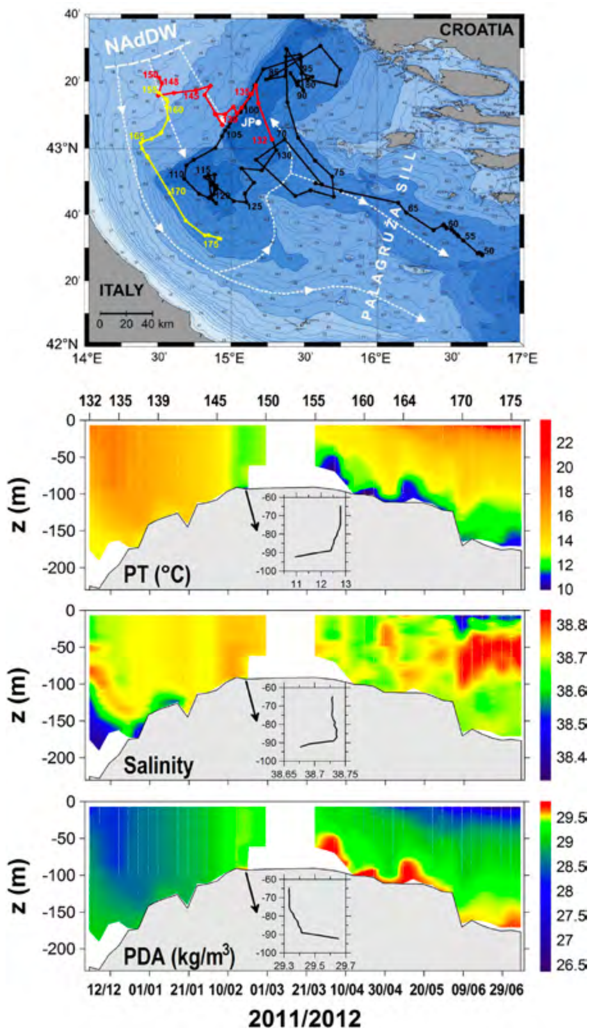

Fig. 9. Argo profiler trajectory (upper plot; red line stands for the trajectory before and during the DWF and yellow line for the trajectory when the NAddW spreading was measured by the profiler) and measurements (middle and lower plots) of potential temperature (PT), salinity and density (PDA) in winter and spring 2012, northwest and west from the westernmost middle Adriatic depression (after Vilibić and Mihanović, 2013).

ern Adriatic shelf as the PDA difference between the vein and the adjacent waters is much lower than during the first pulse (Janeković *et al.*, 2014; Benetazzo *et al.*, 2014). Then, in late spring, bottom dense waters on the shelf are largely replaced by the advected warmer and saline water though the thermohaline circulation (Orlić *et al.*, 2007), while keeping in isolation some pockets of dense water at depressions or flat regions of the northern Adriatic shelf (Vilibić *et al.*, 2008).

In the Kvarner Bay, the NAddW is transported towards the western slope. This process can generate fast bottom currents (up to 10-20 cm/s) which are accelerated by the along-current bora wind peaking in intensity along the connecting channels (Vilibić *et al.*, 2018). Consequently, veins of dense waters are created off the Kvarner Bay reaching rapidly the major NAddW bottom current coming from the northern Adriatic shelf (Mihanović *et al.*, 2013; Pranić *et al.*, 2023). This flow also creates strong thermohaline fronts off the Kvarner Bay (Lee *et al.*, 2005), where enhanced mesoscale activity occurs after the wind relaxation (Kokkini *et al.*, 2017). Finally, this flow rapidly decreases after the end of the bora episode, as the DWF area in the Kvarner Bay is deeper than the outer open Adriatic shelf, so the dense waters are kept in the bottom layer inside the bay (Janeković *et al.*, 2014; Pranić *et al.*, 2023).

After being transported from the northern Adriatic shelf and the Kvarner Bay, the NAddW reaches the JP where they turbulently sink along a steep slope in the westernmost depression. First, this flow gradually fills the depressions and, second, downslope currents are generated inside the canyon systems. Interestingly, during severe events, like winter 2012, the cascading of dense waters into the JP may also occur along the eastern side of the depressions, in the form of 5-10 m thick density current that directly sinks into the easternmost depression (Mihanović *et al.*, 2013). Contrary to previous hypotheses (Vilibić and Supić, 2005), all recent observational and modelling studies indicate that the cascading into the easternmost depression is just a local effect, coming from extensive cooling of coastal waters adjacent to the easternmost part of the JP (Mihanović *et al.*, 2013).

The transport of the NAddW across the PS is occurring first on its southern side, entering the shelf west of the SAP, partially going along the shelf, while largely sinking on the slope (Chiggiato *et al.*, 2016) and inside the Bari Canyon system (Turchetto *et al.*, 2007; Trincardi *et al.*, 2007; Rubino *et al.*, 2012; Langone *et al.*, 2016). The downslope currents may occur over different segments of the shelf break, depending on the density of the incoming NAddW. A month later, the flow is also coming over the sill north of the Palagruža Island. Indeed, the NAddW flow across the sill and its sinking along the western SAP perimeter is detectable at the seabed bedforms and sediments (Bonaldo *et al.*, 2016; Foglini *et al.*, 2016; Langone *et al.*, 2016; Rovere *et al.*, 2019). The flow normally reaches the bottom of the SAP every few years (Querin *et al.*, 2016; Cardin *et al.*, 2020), but can sink to intermediate layers in the case of weaker DWF that reduces the buoyancy of the cascading NAddW. The density currents are rich in sediment, enough to be tracked in great detail by the seismic profiling (Carniel *et al.*, 2012). Pulsations of the NAddW downslope currents may also be strongly modulated by continental shelf waves, which are found to travel counter-clockwise along the SAP perimeter with the wavelength of ca. 50 km and period of 2-4 days (Bonaldo *et al.*, 2018)

The least dense part of the NAddW flow that crosses the PS at its southern section is transported along the western shelf towards the Strait of Otranto (Fig. 10, Rovere *et al.*, 2019). This NAddW branch is flowing at depths between 80 and 120 m. When crossing the Strait of Otranto, this southernmost branch of the NAddW is mixing with northern Ionian waters along the shelf break.

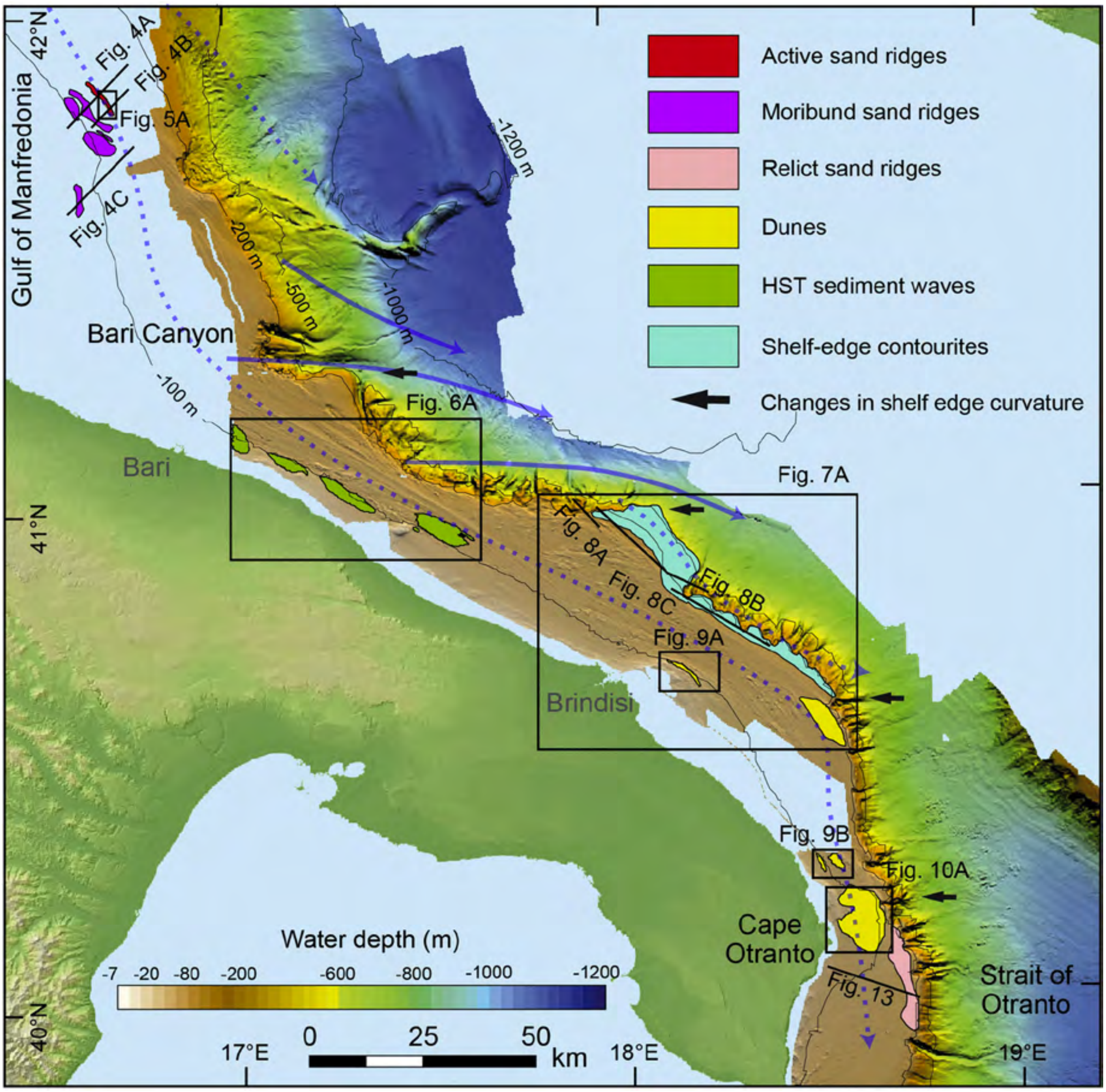

Fig. 10. NAddW pathways (dotted blue arrows) and bedforms along the southwestern SAP margins (after Rovere *et al*., 2019).

Accumulation

On it's way along the slope, the NAddW may reach depressions in which it accumulates. In the Adriatic, the first place for accumulation of the NAddW, emerging from the Adriatic bathymetry, is the JP, consisting of three depressions in which the dense waters are known to cascade after their transport along the western side of the northern Adriatic shelf (Mihanović *et al.*, 2013). There, dense waters are residing at depths below 200 m and slowly mixing with the overlaying warmer and more saline waters till the moment when new NAddW is generated and advected with higher PDA than the residing waters. The renewal of bottom waters in the JP after severe events, like winter 2012, may occur after 3 years or more (Marini *et al.*, 2006). This results in time evolution of the bottom density having a shape of a saw-tooth (Mihanović *et al.*, 2018). In such cases, the bottom waters are losing the dissolved oxygen due to mineralisation and other processes, while increasing strongly in nutrient content in the pit (Marini *et al.*, 2006).

Another accumulation site is the SAP, where the NAddW is accumulated at depths below 1000 m (Bensi *et al.*, 2013). Saw-tooth shape of the temperature, salinity and PDA time series are observed as in the JP (Fig. 11). However, the renewal of bottom waters by the NAddW cascading is occurring less frequently (i.e., every 5 to 10 years instead of every 2 to 3 years) due to smaller buoyancy difference between the cascading and the residing waters (Querin *et al.*, 2016). Here, the NAddW residing waters are also slowly mixing with overlaying waters through local mixing that is fostered by flow instabilities and mesoscale turbulence, where the temperature effect – warming of deep waters – is dominating over salinity effect and transport of salt towards the bottom.

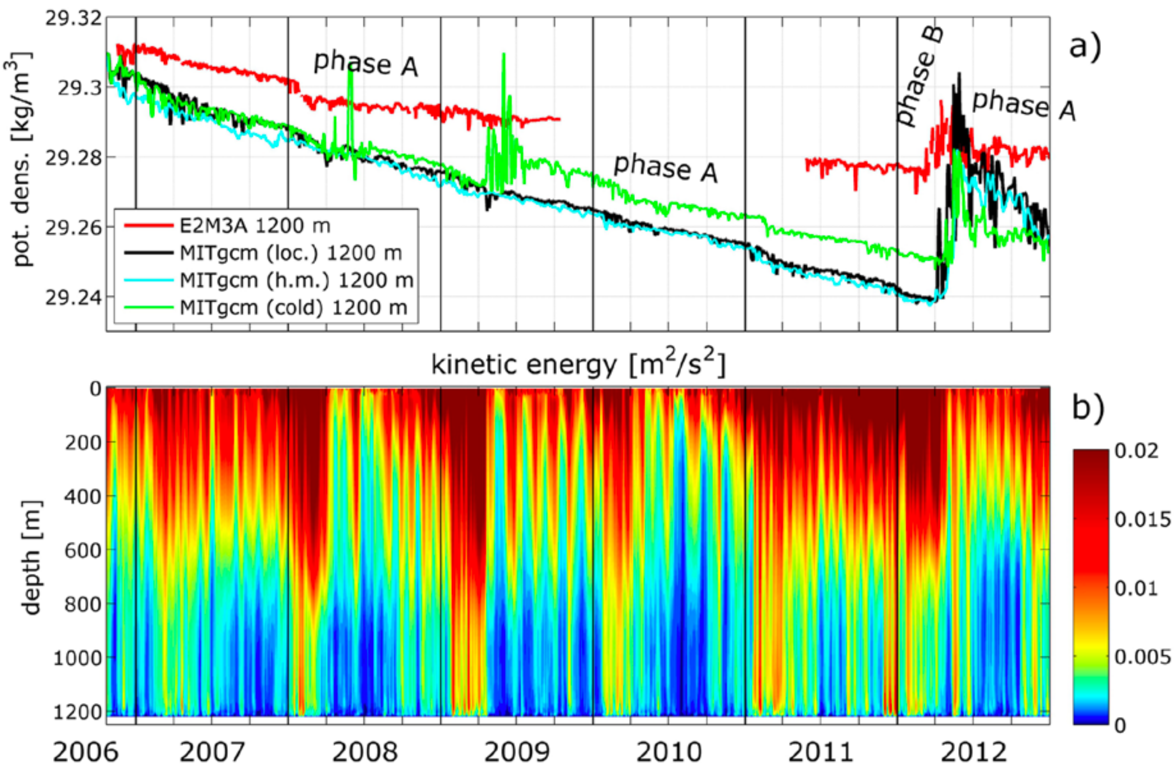

Fig. 11. Measured (E2M3A buoy) and modelled changes at the bottom of the SAP (after Querin *et al.*, 2016).

The last NAddW collector, not taken into account up to now, is the Kvarner Bay itself, which also serves as the NAddW generation site. However, the bay is deeper than the open Adriatic, so its bottom layers and depressions below 80-90 m are collecting the densest waters generated during a winter that are slowly spreading along sea bottom and gentle slopes of the bay for a few months (P. Pranić, pers. comm.). The dense waters normally reside in its deepest parts till the destruction of the pycnocline and vertical homogenization of the water column that normally occurs in November/December, a month later that it occurs on the northern Adriatic shelf (Vilibić *et al.*, 2018).

Effects on the biogeochemistry and biology of the Adriatic Sea

As for any other bottom density current, cascading of dense waters from its source in the northern Adriatic to deep layers of the middle Adriatic depressions and the SAP is bringing lots of particulate matters and sediments (Turchetto *et al.*, 2007; Tesi *et al.*, 2008; Langone *et al.*, 2016; Carniel *et al.*, 2016b). Shaped also by the background currents, geological bedforms are indicating the NAddW flow (Rovere *et al.*, 2019). With sediments, the NAddW bottom density current can also transport pollutants or metals to the deep Adriatic layers (Ilijanić *et al.*, 2014). However, the most important role of the NAddW is to transport oxygen to deep layers, in particular to the middle Adriatic depressions, which are a nursery for many benthic species (Chiarini *et al.*, 2022). In addition, the NAddW is also transporting carbon from the surface of the northern Adriatic to deep Adriatic layers (Cossarini *et al.*, 2015; Cantoni *et al.*, 2016; Ingrosso *et al.*, 2017), contributing to the overall carbon budget of the Mediterranean Sea (Hassoun *et al.*, 2022).

CHANGING NAddW PROPERTIES

Connecting NAddW to decadal thermohaline oscillations and the BiOS

As Zore-Armanda (1963) hypothesized, the formation of the NAddW occurring on the shallow northern Adriatic shelf and in the northeastern Adriatic coastal area may be preconditioned by either more or less saline conditions that interplay on a decadal scale. Consequently, the NAddW may be characterized by either lower or higher salinity and PDA, which is indeed observed on the long-term series in both formation areas (Supić and Vilibić, 2006) and dense water collectors (Mihanović *et al.*, 2018). Regarding the long-term changes in thermohaline parameters in the northern Adriatic, Supić and Vilibić (2006) analyzed the data collected in February during the 1967-2000 period at two stations in the northeastern and northwestern Adriatic. Bottom temperatures were in the range 8.5-11.2 °C and 7.0-10.5 °C, while bottom salinities were 37.8-38.8 and 37.4-38.4, respectively. The analysis revealed that the temperature was higher in the early 1970s than during the 1980s and 1990s, whereas salinity and density were lower in the early 1970s and 1990s than in other years of the studied period. These temperature and salinity ranges indicate that there might be years with no NAddW formed on the shelf, while the NAddW might be characterized by either very low temperatures or high salinities, or both – in that case PDA at the DWF sites may reach 30.0 kg/m^3 or more.

The changes in temperature and salinity of the deepest layer of the SAP (1000 m – bottom) were investigated for the 1990-2009 period (Cardin *et al.*, 2011). Between 1995 and 2004 the bottom layer was filled by relatively low-density waters (~ 29.23 kg/m^3), under the influence of the Eastern Mediterranean Transient (EMT; Klein *et al.*, 1999). After 2004, a net increase in salinity in the bottom layer led to a subsequent increase in PDA. Temperatures and salinities rose up in the second half of the studied period, from 12.78 to 13.00 °C and from 38.61 to 38.73, respectively.

Together with the AdDW, the NAddW outflows drive the Adriatic-Ionian thermohaline circulation, bringing water masses from the northern Ionian Sea to the Adriatic (Orlić *et al.*, 2007). When reaching the northern Ionian Sea, both NAddW and AdDW are changing vorticity there, which – together with wind forcing - switch circulation regimes between cyclonic and anticyclonic (Gačić *et al.*, 2010; Borzelli and Carniel, 2023). This phenomenon is called Adriatic–Ionian Bimodal Oscillating System (BiOS; Gačić *et al.*, 2010). Gačić *et al.* (2021) have demonstrated, with a laboratory experiment, that the internal forcing could be sufficient to create inversions of the cyclonic circulation to anticyclonic circulation in the Ionian Sea, as hypothesized by the BiOS theory. A numerical study of Liu *et al.* (2022) also confirmed that the reversal of the circulation in the North Ionian Gyre occurs 1-2 years after a major cooling event driving the Adriatic dense water formation. However, Borzelli and Carniel (2023) suggested that the BiOS attenuates in absence of wind that is occasionally pumping the energy to the northern Ionian basin.

In general, the BiOS has been connected to many processes observed in the Adriatic Sea (Civitarese *et al.*, 2010; Batistić *et al.*, 2014; Lavigne *et al.*, 2018; Vilibić *et al.*, 2020; Ciglenečki *et al.*, 2020). Particularly, the influence of the BiOS on the dense water formation process in the Adriatic is explained as follows. During the cyclonic phase, the saline LIW is advected into the Adriatic Sea, therefore increasing the density of the water which gradually leads to a reversal to an anticyclonic circulation pattern. In the anticyclonic phase, fresher Atlantic Water is advected into the Adriatic Sea, inhibiting the vertical convection and resulting in lower density of the water formed. Consequently, this leads to a reversal of the circulation from anticyclonic to cyclonic phase (Gačić *et al.*, 2010, 2014).

Regarding the influence of the BiOS on the dense water formation in the shallow northern Adriatic, and consequently on the thermohaline circulation, the salinity signal due to BiOS propagates from the south Adriatic towards north and then via vertical mixing affects the NAddW. In the observational study by Vilibić *et al.* (2020), thermohaline variables measured in the northern Adriatic between 1979 and 2017 were correlated, among other drivers, with the BiOS. A large correlation was found between the yearly averaged BiOS index (definition can be found in the referred article) and the yearly averaged salinity at phase lags of -2 to -4 years. However, the freshwater discharges have the dominant role on the short-term, i.e., up to a period of 4 months before the DWF. Thus, the NAddW density (salinity) may be also preconditioned by the autumn freshwater discharges, to which the intensity of wintertime cooling is determining the NAddW temperature.

Indeed, a dominant impact of the BiOS on salinity is quantified for the most of the deep Adriatic (Denamiel *et al.*, 2022) with the lag of 2 years, as the BiOS-advected waters need some time to advance along the Adriatic and to replace/mix with residing waters. The Empirical Orthogonal Function (EOF) mode 1 for bottom salinity accounts for 37% of the total salinity variance and have the highest amplitude in the northern Adriatic. It is highly correlated (with a 2-year lag) with the BiOS-derived sea-surface height EOF pattern (Fig. 12). At the same time, the effect of the BiOS on bottom temperature is much smaller as being dominated by the atmosphere-ocean heat fluxes, yet still resembling patterns of dense

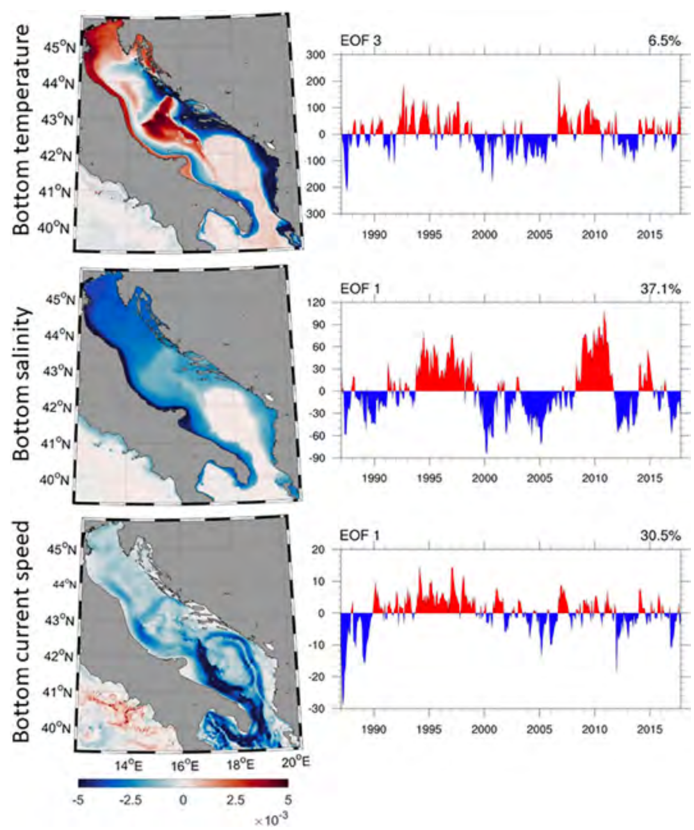

Fig. 12. Adriatic Sea and Coast (AdriSC) ROMS 1-km sea-surface temperature (top panels), salinity (middle panels) and current speed (bottom panels) normalized spatial EOF components (left panels) and associated time series of amplitude (right panels) with the highest (anti)correlation to the BiOS signal (including a 1-year or 2-year lag) during the 1987–2017 period (after Denamiel *et al.*, 2022).

water generation and outflow where the maximum positive amplitudes are found (Fig. 12).

NAddW in a changing climate

Lipizer *et al.* (2014) provided a centennial climatology of the Adriatic Sea, for the 1911-2009 period, and investigated the long-term variability of thermohaline properties in the deep middle and southern Adriatic. The deepest part of the SAP was demonstrated to be significantly saltier (+0.18 since the period 1910–1914, with an increase of +0.018 decade^{-1} since 1945) and warmer (+0.54 °C since 1910–1914). However, no clear trends were found for temperature and salinity in the JP. In particular, the deep waters of the SAP have lowest median temperature at the beginning of the time series (12.65 °C) and the highest in the late 1970s (13.23 °C). The early 1980s were characterized by a significant temperature decrease (−0.16 °C), as also documented by Vilibić and Orlić (2001). The end of this time series was also characterized by a significant temperature rise in comparison with the late 1990s (+0.27 °C). Salinity is characterized by an overall increase throughout the time series, with the lowest median in the 1940s (38.51) and the highest in the 2005–2009 period (38.73), with large variability.

At the PS, trends in temperature, salinity and dissolved oxygen between 1952 and 2010 indicated a weakening of the thermohaline circulation (Vilibić *et al.*, 2013) due to both smaller river discharges and weakening of the DWF in the northern Adriatic. The latter has been derived from negative dissolved oxygen trends at the deepest parts of the sill, where the NAddW is known to outflow. Further, spatial patterns of temperature and salinity trends indicate both weakening of the freshwater-driven discharges and the associated coastal currents, and the deep water outflow over the sill.

These trends were also reproduced by a kilometer-scale climate model (Tojčić et al., 2023), which – during the 1987-2017 period and in respect to the NAddW – provided: (1) warming and salting of near-bottom waters, in particular in the middle and northern Adriatic dense water collectors, with rates up to 0.2 °C and 0.1 over a decade, respectively, and (2) a decrease of the Adriatic deep water outflow and therefore the Adriatic-Ionian thermohaline circulation.

To map long-term trends of the NAddW collected in the near-bottom SAP, temperature and salinity profiles measured during selected cruises, in May 1911, September 1966, June 1990 and June 2007, as well as the data from Argo float 6903799 for the period from July 2022 to January 2023 (https://fleetmonitoring.euro-argo.eu/float/6903799), are plotted in Fig. 13. It should be noted that only the data measured below 50 m is used, in order to minimize the influence of the surface forcing. Further, one should be aware that the historical data have lower accuracy, estimated for the mid twentieth century to ±0.02 °C and ±0.01 for temperature and salinity, respectively (Vilibić *et al.*, 2013), while their reliability is much lower than of the data collected by the CTD probes and Argo profiling floats. Still, both temperature and salinity clearly increased over the centennial period and over the whole water column, yet with unprecedented rates in the last two decades (about 1 °C and 0.2, respectively, between 2007 and 2022). Concerning the density of the deepest layer where the NAddW is known to accumulate, PDA was slightly below 29.20 kg/m^3 in 1911, 1966 and 1990. Somewhat higher PDA was obtained in 2007 (29.27 kg/m^3), whereas the newest data (2022-23) show that the layer of the NAddW in the SAP exhibits PDA between 29.20 and 29.22 kg/m^3. These changes apparently follow the projected warming and salting of the Mediterranean (Soto-Navarro *et al.*, 2020), accelerated in recent decades, while the NAddW density is not foreseen to substantially change.

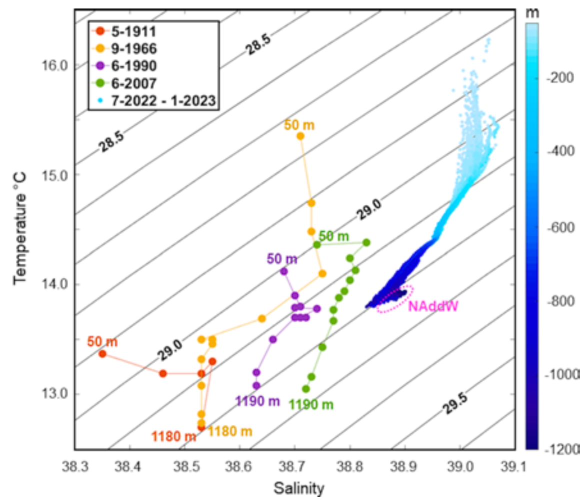

Fig. 13. Diagram of temperature and salinity measured in the SAP (below 50 m) during 1 May 1911, 2 September 1966, 3 June 1990 and 4 June 2007, as well as from Argo float 6903799 for the period from July 2022 to January 2023.

NAddW OBSERVATIONS AND MODELLING

Observation and modelling efforts of the northern Adriatic wintertime dynamics and DWF started in the 1910s and the 1970s, respectively (Zore-Armanda, 1963; Hendershott and Rizzoli, 1976) and, up to the Vilibić and Supić (2005) review, can be summarized as follows:

A. Multi-year ocean cruises established in the 1910s by Austrian and Italian researchers, primarily through the Najade and Ciclope cruises between 1911 and 1914, shaped the Adriatic oceanography (Zore-Armanda, 1963). However, this activity stopped with the First World War, not revived till the early 1950s. In 1950s, several cross-Adriatic transects were established, along the JP, PS and SAP, with the aim of collecting long-term observations and to quantify seasonal, interannual and decadal changes along these key regions for the Adriatic (and the NAddW) dynamics (Buljan and Zore-Armanda, 1966). Later, a similar long-term transect was established between Po River delta and Rovinj, which allowed for assessment of thermohaline and biogeochemical changes at the NAddW generation site.

B. Sustained observations on the NAddW formation site (northern Adriatic shelf), spreading regions (western Adriatic shelf) and dense water collectors (the JP and the SAP) were found to have to be done on regular basis (interannually and seasonally), to capture seasonal cycle of all NAddW phases, and interannual variability. Thus, the continuity of measurements at decadal time scales was found to be a must along the northern Adriatic transects, in the JP and the SAP as well as along the PS transect (Buljan and Zore-Armanda, 1976). Not much advances have been achieved in that direction for the last 20 years, aside from the introduction of new ocean platforms capable of detecting and documenting fine-scale structures related to the NAddW dynamics.
C. The first attempts to model the Adriatic circulation on the interannual scale were conducted in early 2000s, using climatological (perpetual) forcing (Mantziafou and Lascaratos, 2004). These estimates quantified the contribution of the NAddW to the overall outflow of the Adriatic dense waters through the Strait of Otranto to be about 20 %, a bit larger than derived by observation-based box model over limited time interval (Vilibić and Orlić, 2002). These simulations used Princeton Ocean Model and had resolutions of ca. 5 km, yet, the larger problem was an inadequate atmospheric forcing.
D. Strong cooling by the atmospheric models was found to be needed to qualitatively reproduce the DWF in the northern Adriatic and the associated thermohaline circulation (e.g., Vested *et al.*, 1998). For proper quantification of dense water generation in the open northern Adriatic, high-resolution atmospheric forcing (i.e., 10 km or less) was thus found to be needed, to balance wind stress, curl and river buoyancy effects during severe bora events and to properly reproduce cyclonic gyre off the Po River in which DWF was proposed to occur (Beg Paklar *et al.*, 2001).
E. Circulation in the open northern Adriatic was found to be, on average, much weaker and more stratified than during the severe bora events and the DWF (Wang, 2005).
F. No dense waters were reproduced in the coastal eastern Adriatic (i.e., in the Kvarner Bay). However, dense water outflow was reproduced by models along the western Adriatic shelf in the form of density currents flowing towards the SAP (e.g., Zavatarelli and Pinardi, 2003), partially detouring the JP due to strong density front northeast of them (Bergamasco *et al.*, 1999).

NAddW observing efforts

Since 2005, a great number of observational campaigns taking some focus on the NAddW dynamics and its consequences were carried out in the Adriatic. This includes many interdisciplinary campaigns also dedicated to research of other oceanographic problems like the DART (Dynamics of the Adriatic in Real-Time) campaigns in 2005/2006 led by USA researchers (Haza *et al.*, 2007; Martin *et al.*, 2009), VECTOR (Turchetto *et al.*, 2007), ODW (Chiggiato *et al.*, 2016), SIRIAD (Carniel *et al.*, 2016b) and other campaigns led by Italian researchers targeting the outflow of NAddW in the middle and southern Adriatic. The DART experiment was characterized by several cruise campaigns in which different types of CTD (Conductivity-Temperature-Depth) probes (e.g., bottom mounted, shipborne, with daily vertical profiling from the bottom) collocated with dozen of bottom-mounted ADCPs (Acoustic Doppler Current Profilers) were deployed along the PS. These multiplatform data were used in conjunction with an operational ocean model, to properly design or modify ocean campaigns operationally, i.e., during the subsequent days. The SIRIAD campaigns used also shipborne CTDs and bottom-mounted ADCPs and, additionally, performed side-scan sonar survey to map sea bottom, looking for topographical features (including those potentially generated by the NAddW bottom density current) in order to properly map the bathymetry in some regions (e.g., mapped sea bottom mountain in the SAP that was found non-existent). Much more oceanographic campaigns useful for the NAddW research were carried out, but only three specific cases are described below.

During winter 2012, an Argo profiling float was advected to the shallow northern Adriatic shelf, capturing the NAddW outflow at its very bottom not seen with other approaches like CTDs (Vilibić and Mihanović, 2013). Following this finding, a suggestion emerged for using Argo profilers to be pushed towards the bottom. Nowadays, more instruments are capable to do so (e.g., Arvor-Cm profiler, Andre et al., 2016) in addition to the classical approaches like the moored platforms that were occasionally used in the northern Adriatic (e.g., Book *et al.*, 2005). In the SAP, however, the atmosphere-ocean buoy E2M3A, maintained by the National Institute of Oceanography and Experimental Geophysics (OGS), was moored in 1990s, providing long term-series at the very bottom and being able to capture the NAddW arrival and accumulation in the SAP (e.g., Bensi *et al.*, 2013, 2014; Querin *et al.*, 2016).

In 2015, upon detection of the NAddW formation site in the Kvarner Bay, a multiplatform observation experiment called North Adriatic Experiment (NAdEx 2015) was conducted between late autumn 2014 and early autumn 2015. Its aim was to quantify the formation rates and the NAddW characteristics in this region (Vilibić *et al.*, 2018). This collaborative effort involved many oceanographic institutions which led to the experiment introducing some new techniques in measuring the NAddW. For example, Arvor-C profiling floats quantified the thin density layers existing at the very bottom of the bay. Shallow-water gliders and aqua-shuttles were also used to quantify density fronts in the region (Kokkini *et al.*, 2017). For these observations, NAdEx built upon similar efforts used in previous northern Adriatic campaigns in 2003 (Lee *et al.*, 2005).

Last but not least, a tremendous effort has been placed in collecting of the temperature, salinity and current data since 2012 at the two locations where the NAddW cascading is taking place, the Gondola Slide and the Bari Canyon (Paladini de Mendoza *et al.*, 2022). The moorings collect the data in the last 100 m of the water column, detecting bottom density currents quasi-regularly between February and May, sometimes exceeding 0.5 m/s, on top of the weak currents that are prevailing in the rest of a year. This dataset is publicly available and is compliant with the FAIR principles.

Prerequisites for NAddW dynamics modelling

Reproduction of the NAddW generation and dynamics with state-of-the-art numerical models is extremely challenging.

First, the northern Adriatic is a shallow region where the river dynamics is strongly influencing the DWF rates. There are two aspects here: (1) capacity of an ocean model to properly quantify the river plume dynamics, which is a challenge even for state-of the-art coastal models at high resolutions (Warrick and Farnsworth, 2017), and (2) proper river climatology, which in general should not be problem if adequate measuring and data exchange system is in place (like European Flood Awareness System these days, Dottori *et al.*, 2017). However, introducing proper river climatologies was challenging, as no measured data was available for almost the whole eastern Adriatic coast, with stations not located at the river mouth and not measuring real discharges (Zanchettin *et al.*, 2008). Further, the eastern Adriatic coastal region has numerous submarine karstic springs (Surić *et al.*, 2015), which were never properly quantified in terms of their discharges to the coastal ocean. This is particularly relevant for the Kvarner Bay region, resulting in several times more freshwater discharges in old climatologies than in recent climatologies (Janeković *et al.*, 2014). For that reason, the DWF was prohibited in this region, regardless of the atmospheric forcing and the model resolution (Mihanović *et al.*, 2013; Vilibić *et al.*, 2016). However, this was not the case for the open sea Adriatic DWF sites (Verri *et al.*, 2018). Additionally, new Kvarner Bay DWF studies indicate that contribution of these waters to the NAddW might increase up to 40 % (Janeković *et al.*, 2014). Further, the sensitivity of the DWF even in the centre of the SAP through open convection is largely controlled by the freshwater balance and the introduction of the nearby Albanian waters into the model (Vodopivec *et al.*, 2022). An improper river forcing may impact basin wide salinities, which can result in an underestimation of Adriatic-wide salinities when these conditions are used to force the lateral boundary conditions of another model (e.g., Janeković *et al.*, 2014). In the case of Janeković *et al.* (2014) which produces forecasts and uses operational products, the problem can be bridged by moving the lateral boundary conditions in the middle of the Ionian Sea and using operational products assimilating observations within the whole Mediterranean Sea (e.g., MEDSEA; Clementi *et al.*, 2021) as explained in Denamiel *et al.* (2019). Indeed, even for reanalysis products, the sensitivity of the results to the assimilated data (in particular to salinity data mostly assimilated from the Argo profilers) is extremely high and can result in an improper time-space resolution in the northern Ionian and Adriatic seas (MEDSEA; Fig. 14; Escudier *et al.*, 2021).

Once preconditioned by the freshwater net fluxes, proper introduction of heat losses during bora events is a next challenge. In the Adriatic modelling studies, several modelling aspects are related to this challenge: (1) resolution of atmospheric models used to force ocean models, (2) resolution of ocean models, in particular over complex regions along the eastern Adriatic, particularly in the Kvarner Bay, where they need to resolve processes at the channel dimensions (i.e., at the kilometre or higher resolution), and (3) estimation of the heat losses (e.g., bulk formulas) in extreme conditions (Grisogono and Belušić, 2009).

First, forecast products coming from the Croatian numerical weather prediction models (e.g., hydrostatic ALADIN/HR, Aire Limitée Adaptation dynamique Développement InterNational) reproduce wind conditions on the lee of the Velebit Mountain – where the bora winds are the strongest – with much better accuracy than models developed for the open Adriatic or less orographically complex coastal regions (e.g., Tudor and Ivatek-Šahdan, 2010; Davolio *et al.*, 2015). However, hydrostatic models like ALADIN/HR are not capable to reproduce the strong potential vorticity banners of the bora wind (Grubišić, 2004; Janeković *et al.*, 2014) contrarily to kilometre-scale nonhydrostatic models like the Weather Research & Forecasting (WRF) model used in Denamiel *et al.* (2021a). Additionally, the bora winds are characterized by a strong sub-kilometre variability (Kuzmić *et al.*, 2015) and pulsations at the minute scale (Belušić *et al.*, 2004) which cannot be represented with any coupled atmosphere-ocean models due to their extensive numerical cost.

Second, ocean model resolution is also key to the NAddW dynamics. For example, many modelling studies did not even include the Kvarner Bay channels and thus could not reproduce the coastal eastern Adriatic dense waters. Bathymetry with a proper representation of the channels and connecting passages between coastal and open Adriatic waters is also a prerequisite. These channels, with width ranging from a few kilometres to a few tens of kilometres, are, indeed, the exact locations where the NAddW is being transported out of the DWF sites (Vilibić *et al.*, 2018). Vertical resolution also plays a critical role, in particular in deep and near-bottom layers where dense waters are being transported in just a few metres thick plumes (Vilibić and Mihanović, 2013). Increasing the vertical resolution near the bottom is leading to a more accurate quantification of this process (Reckinger *et al.*, 2015). With increased vertical resolution, the sharp slopes and canyons where the NAddW is cascading into the middle and southern Adriatic will be more accurately represented despite the use of mathematical smoothing to preserve the stability of the model (Dutour Sikirić *et al.*, 2009). Vertical resolution thus controls the representation of the downslope currents and the capacity of collectors to actually accumulate dense waters (qualitatively and quantitatively).

Third, the feedback of the ocean results to the atmosphere (i.e., two-way coupling) is also affecting the marine dynamics and the DWF. Such an approach indeed increased the reliability of ocean results during severe bora events, resulting in a decrease in surface currents and spatial changes in heat losses for about 10 to 20 % (Pullen *et al.*, 2006, 2007). Still, the coupling cannot substantially improve the latent heat flux as it improves sensible heat fluxes (Ličer *et al.*, 2016), pointing to other approaches more feasible for minimizing such biases during severe bora events. Out of the bora events, the differences between one-way and two-way coupling at high resolutions (2-4 km) provides no substantial differences (Ličer *et al.*, 2016). To minimize the problems caused by air-sea interactions, the ocean modelling community adopted several techniques other than two-way coupling. The first was to consider a bias correction when comparing model with measurements, pointing to reliability of a model if having capacity to reproduce the known phases of the NAddW dynamics (e.g., Benetazzo *et al.*, 2014; Carniel *et al.*, 2016a). Another approach, coming from an underestimation of the atmospheric forcing due to improper resolution (e.g., usage of reanalysis data for forcing), was to proportionally increase by a scaling factor the wind stress forcing at the surface (e.g., Callies *et al.*, 2017). A third approach was to move the ocean solution (Regional Ocean Modelling System – ROMS-hind; Fig. 14) towards the observations by using data assimilation techniques (ROMS-full; Janeković *et al.*, 2020). However, the latter was only able to partially improve the solution, as the data was assimilated in 4-day cycles, which created an inconsistency in time (Pranić *et al.*, 2023). The last approach was to try to fulfill most of the prerequisites listed above. It is based on the AdriSC model using nested kilometre-scale nonhydrostatic atmospheric models (WRF at 15 km and 3 km horizontal resolution with 58 vertical levels) one-way coupled with nested kilometre-scale ocean models (ROMS at 3 km and 1 km horizontal resolution with 35 vertical levels) with a correction of the air-sea fluxes based on sea-surface temperature products assimilating remote sensing data (Denamiel *et al.*, 2019). This approach has proven to considerably reduce the atmosphere-ocean biases (Denamiel *et al.*, 2021a, 2021b, Pranić *et al.*, 2021) and to better reproduce the NAddW dynamics (Fig. 14, Pranić *et al.*, 2023) in comparison to the other approaches used in the Adriatic Sea.

Multi-year and climate numerical simulations

In the early 2010s, long-term simulations were already able to differentiate years in which the NAddW was generated or missing. Further, these simulations were able to pick up the temporal difference in the NAddW occurring due to general changes in the Adriatic hydrography, like advection of more saline waters and reduction of freshwater discharges in the northern Adriatic (Oddo and Guarnieri, 2011). However, they also revealed that higher resolution atmospheric forcing than the one provided, at the time, by the European Centre for Medium-Range Weather Forecasts (ECMWF; Oddo *et al.*, 2005) was important for the proper reproduction of the dense water dynamics (Mantziafou and Lascaratos, 2008; Oddo and Guarnieri, 2011).

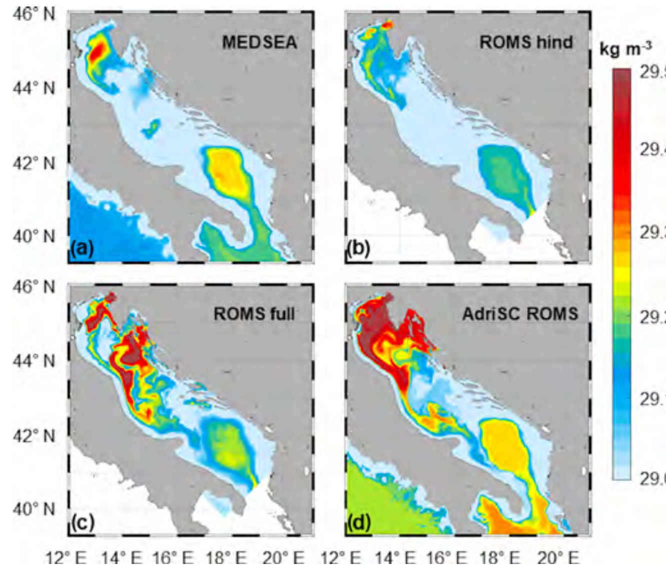

Fig. 14. Spatial distribution of modelled bottom PDAs on 1 March 2015 for (a) MEDSEA reanalysis, (b) ROMS-hind free ocean simulation, (c) ROMS-full ocean simulation with 4D-Var data assimilation and (d) AdriSC-ROMS free climate simulation (after Pranić *et al.*, 2023).

Later, on the one hand, regional climate modelling of the Mediterranean basin was initiated through the Med-CORDEX programme (Mediterranean Coordinated Regional Downscaling Experiment; Ruti *et al.*, 2016). The effort concentrated in the examination of the dominant oceanographic processes like open-sea dense water generation in the Gulf of Lions, Eastern Mediterranean Transient, SAP deep-convection or similar. The first analysis of the NAddW dynamics in a Med-CORDEX model was carried out for a forced configuration of 1/8-degree resolution (i.e., no atmosphere-ocean coupling) and discovered a substantial underestimation of the NAddW production and accumulation (Dunić *et al.*, 2018). With higher resolution coupled Med-CORDEX models, the northern Adriatic biases in temperature and salinity were greatly lowered but remained too high in the JP and the SAP (Fig. 15; Dunić *et al.*, 2019). These biases can be explained by: (1) improper atmospheric forcing, (2) improper bathymetry, in particular within the Kvarner Bay, where most models had no wet points at all, (3) improper introduction of rivers, both in climatology and in their representation as sources. Further, all examined Med-CORDEX models were z-models, having not enough vertical layers (just 4 to 11) in the shallow northern Adriatic, thus having no capacity to reproduce basic circulation features (e.g., double cyclonic-anticyclonic circulation). Still, they were found useful for the classification of the basic circulation types through a proxy, allowing even for the projection of these classified circulations in future climates (Dunić *et al.*, 2022).

On the other hand, high-resolution atmosphere-ocean models were specifically implemented for the Adriatic region. The interannual to decadal Adriatic dynamics was thus derived from results coming from either 8-years of results of the operational model ALADIN/HR-ROMS (Janeković *et al.*, 2014) or a 31-year long hindcast simulation based on the operational configuration of the AdriSC climate model (Denamiel *et al.*, 2019). This follows the concept of merging configurations normally used in the numerical weather prediction systems with climate models (Belušić *et al.*, 2020). The operational forecast results were produced with the ROMS model at 2 km horizontal resolution using 20 vertical levels and forced by the ALADIN/HR model at 8 km resolution (with 2-km dynamical downscaling of the wind). The hindcast results were also produced with ROMS but with nested grids at 3 km and 1 km horizontal resolution, with 35 vertical levels and one-way coupled with nested WRF grids at 15 km and 3 km horizontal resolution. Another important difference between the two models is that the open boundary of the ROMS grid is located within the Adriatic Sea above the Otranto Strait in ALADIN/HR-ROMS and in the middle of the Ionian Sea in the AdriSC model. Mihanović *et al.* (2018) described the variability of the NAddW dynamics over the 8-year period of the ALADIN/HR-ROMS forecast results with the aim to examine the interplay between the DWF in the open northern Adriatic and in the Kvarner Bay. Further, using the AdriSC model to produce a 31-year free run largely improved the performance of decadal simulations in the Adriatic basin (Denamiel *et al.*, 2021b; Pranić *et al.*, 2021) as the AdriSC model was even capable to reproduce the BiOS cycles for the very first time (Denamiel *et al.*, 2022). However, the AdriSC simulations are numerically demanding (i.e., 18 months of run on the ECMWF supercomputers; Denamiel *et al.*, 2021b). The examinations of the NAddW dynamics reproduction of this configuration is thus currently under way. Finally, Vodopivec *et al.* (2022) performed a sensitivity study using several interannual simulations that confirmed that freshwater load climatologies and atmospheric forcing are the main factors influencing the NAddW dynamics through evaporation, precipitation and heat losses over the DWF sites.

Finally, the most recent AdriSC climate simulations allow for the assessment of the NAddW dynamics in the future climate. The full future climate simulation (RCP 8.5 scenario, 2070-2100) is still not examined, but short-term simulations indicate that the cooling in the northern Adriatic will remain similar (Denamiel *et al.*, 2020), at least in the RCP 8.5 climate scenario, despite the decrease of the bora wind. This would happen due to the change in relative humidity during severe winter bora outbreaks, which is compensating the weakening wind effect in estimation of respective heat losses (Denamiel *et al.*, 2020).

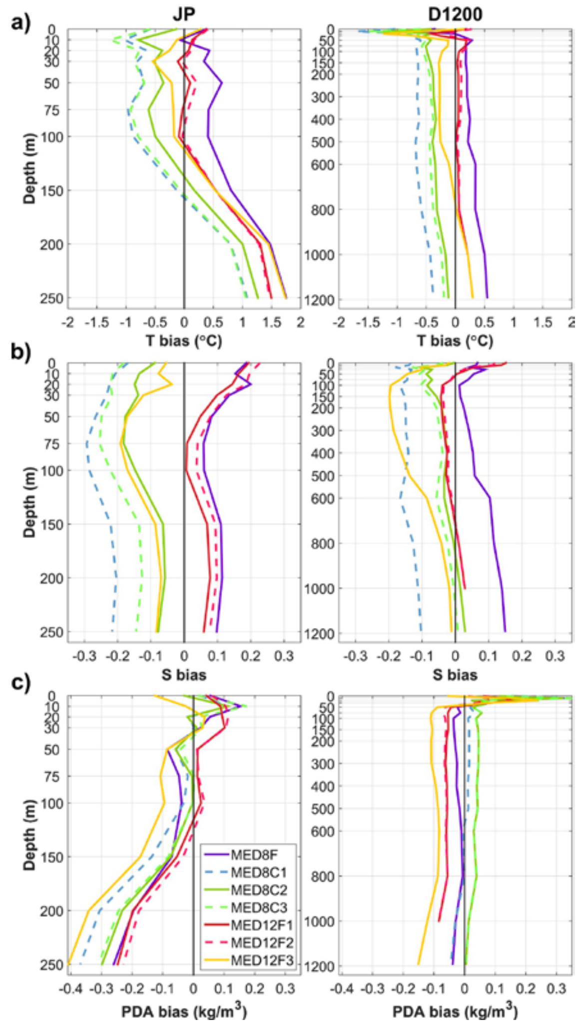

Fig. 15. Vertical profiles of model-to-measurements temperature, salinity and PDA bias of different Med-CORDEX climate models at the NAddW collectors: middle Adriatic depressions (station JP) and the SAP (station D1200) (after Dunić *et al.*, 2019).

ASSESSMENT OF STATE-OF-THE-ART, RESEARCH GAPS AND PERSPECTIVES

Four major shortcomings have been previously highlighted in the review by Vilibić and Supić (2005): (1) knowledge of the NAddW preconditioning, (2) time-space properties of the NAddW generation, (3) measuring the NAddW spreading with regular monitoring programmes, and (4) improper atmospheric forcing due to low-resolution products (like ERA Interim). Following that, one may conclude that in the present-day:

A. Preconditioning of the DWF in the northern Adriatic might be quantified by reanalysis products, e.g., by the MEDSEA reanalysis, which assimilate all available in situ and satellite measurements currently at 9 km resolution (Simoncelli *et al.*, 2019). Still, poor availability of thermohaline data in the northern Adriatic and wrong introduction of rivers into the reanalysis may result in lower reliability of ocean variables, in particular of salinity which are sparsely measured by any of measuring platforms there. Also, no reanalysis is available in the Kvarner Bay area, where the DWF may also occur. However, compared to what was available 20 years before, this is a huge step forward in assessing capacities to quantify the preconditioning phase of the DWF in the northern Adriatic.

B. State-of-the-art measurements and ocean simulations are capable to provide proper time-space properties of the NAddW generation, providing that the initial fields coming from reanalyses and boundary fields (e.g., river discharges) do not fail much. Indeed, state-of-the-art ocean models are capable of reproducing the NAddW generation in both open northern Adriatic and in coastal regions, although discrepancies with observations may still be large.
C. Observations of the spreading phase and accumulation of the NAddW is still non-existent or quite sparse in the northern and middle Adriatic, as no bottom-mounted sensors are moored anywhere over the long-term, like these carried out through the Hydrochanges programme (Schroeder *et al.*, 2013). However, long-term mooring along the western SAP slope and E2M3A buoy in the SAP has deep sensors capable of capturing dense water cascading and accumulation there (e.g., Paladini de Mendoza *et al.*, 2022; Querin *et al.*, 2016).
D. Atmospheric forcing has been considerably improved in the last two decades, presently reaching kilometre-scale resolutions (Janeković *et al.*, 2014; Denamiel *et al.*, 2019, 2021a) and using nonhydrostatic models (Denamiel *et al.*, 2021a, 2021b). Applying nonhydrostatic atmospheric models is a prerequisite for a proper reproduction of highly nonlinear bora dynamics and time-space characteristics at the sea surface.

The following research challenges and recommendations in reproducing the NAddW dynamics by atmosphere-ocean numerical models are foreseen by authors (which, of course, might be restricted by availability of high-performance computing facilities):

E. Introducing proper freshwater discharges to ocean models, in particular in the Kvarner Bay where a lot of submarine karstic springs are loading substantial freshwater to coastal regions. This also includes direct discharges data at the major river mouth, coming from either measurements or hydrological discharge models.
F. Standardising ocean simulations with resolutions of 1 km or finer, at least in the coastal complex area of the eastern Adriatic, while standardising atmospheric models with resolutions of 3 km or finer, the latter in the complex mountain and island regions along the eastern Adriatic coastline.
G. Introducing two-way coupling in atmosphere-ocean simulations that are reproducing severe bora outbreaks and the DWF.
H. Densifying the number of layers in ocean models near the bottom, capable to capture bottom density currents.
I. Running an ensemble of simulations, able to quantify uncertainties related to the dense water formation, spreading and accumulation.
J. Carrying out a reanalysis simulation, that would use a data assimilation technique of all available data to a kilometre-scale ocean model and end with state-of-the-art product of sufficient quality. Indeed, improving initial (free) model run and then applying data assimilating techniques to observations may be the way how to get the most reliable estimates of the DWF and subsequent dynamics of the NAddW, with an ultimate aim to publish the reanalysis of the Adriatic Sea properties in the Marine Copernicus service (https://marine.copernicus.eu).
K. Running of climate simulations at the kilometre scales, including their ensembles capable of quantifying the DWF-related uncertainties, interannual and decadal variability, and trends at the climate scales.
L. Introducing surrogate techniques capable of describing the DWF variables in a simpler manner that require less computational resources than full atmosphere-ocean simulations.

Regarding NAddW-related in situ measurements, the following recommendations may be raised:

M. Carrying on regular research cruises along the climatological transects and stations, in particular during wintertime and spring, such as the Po River-Rovinj transect, the PS transect, the JP station(s) and station D1200 in the SAP.
N. Maintaining deep sensors at the E2M3A buoy in the SAP and moorings along its perimeter, installing bottom-mounted stations in the JP and in the central northern Adriatic, next to the existing oil platforms and in the Kvarner Bay.
O. Deploying shallow-water Argo profiling floats in the northern Adriatic, capable of measurements at the very bottom and vertical profiling, like the Arvor-C float.
P. Carrying out of glider missions in the northern Adriatic during wintertime, when the NAddW is expected to be generated.

Regarding process-oriented studies related to the NAddW dynamics, the following studies may be carried out (not an exhaustive list):

Q. Assessment of interannual variability of the NAddW preconditioning, formation, spreading and accumulation.
R. Quantification of uncertainty during severe and moderate NAddW formation years.
S. Estimation of variability, trends and changes in the NAddW-driven thermohaline circulation, in the present and future climates.
T. Quantifying the role of air-sea feedback in generation of the NAddW.
U. Effects of the NAddW formation to the BiOS cycles and vice versa.
V. Ventilation of deep Adriatic layers and dissolved oxygen trends.
W. Sediment, particle and pollutant transport associated with the NAddW formation and dynamics.

X. Biogeochemical changes occurring during the NAddW generation, spreading and accumulation.
Y. Carbon uptake during the NAddW formation and its transport to the deep Adriatic layers.
Z. Changes in the deep and benthic organisms in relations to the NAddW formation and dynamics.

SUMMARY AND CONCLUSIONS

This review summarizes all known aspects of the North Adriatic Dense Water (NAddW) dynamics, from preconditioning, through generation, spreading and accumulation, including its changeability on interannual, decadal and climate scales. The pioneering work on the Adriatic water masses of Mira Zore-Armanda in 1963 is acknowledged, including its legacy in the present Adriatic and Mediterranean water mass studies. As the NAddW is tightly connected with other Adriatic water masses and Ionian-Adriatic processes (e.g., the Adriatic-Ionian Bimodal Oscillating System or BiOS), this review also aims to address eventual knowledge gaps of all Adriatic water masses, their dynamics, their connection with the Eastern Mediterranean dynamics and water masses, which is found to rapidly change in the recent years and decades (Mihanović *et al.*, 2021; Fedele *et al.*, 2022).

Although some aspects are being indicated in the review, biogeochemical, biological and other aspects of the NAddW are not well researched, while it is known that they might be extremely important as in other similar basins influenced by density currents (e.g., Conan *et al.*, 2018). Therefore, research should be diverted towards these topics, in particular as observational and modelling capacities are growing with time. Biogeochemical models at 10 km resolution are already covering climate periods (e.g., Reale *et al.*, 2022), so they might be used to nest higher-resolution models to properly quantify the processes that are potentially variable at these exact temporal and spatial scales. Together with observations, this will pose a challenge for future research, some of it suggested in the previous chapter. The oceanographic community has now to decide which research directions will become the reality.

LIST OF ACRONYMS

ADCP – Acoustic Current Doppler Profiler
AdDW - Adriatic Deep Water
AdriSC – Adriatic Sea and Coast
ALADIN - Aire Limitée Adaptation dynamique Développement InterNational
BiOS - Adriatic-Ionian Bimodal Oscillating System
CIESM – Mediterranean Science Commission
CTD – Conductivity-Temperature-Depth
DWF - Dense water formation
ECMWF - European Centre for Medium-range Weather Forecast
EMT – Eastern Mediterranean Transient
FAIR – Findability, Accessibility, Interoperability, and Reuse
JP – Jabuka Pit
LIW - Levantine Intermediate Water
MAdDW – Middle Adriatic Deep Water
Med-CORDEX – Mediterranean Coordinated Regional Downscaling Experiment
NAddW - North Adriatic Dense Water
NAdEx – Northern Adriatic Experiment
OGS – National Institute of Oceanography and Experimental Geophysics
PDA – Potential Density Anomaly
PS – Palagruža Sill
ROMS – Regional Ocean Modelling System
SAP – Southern Adriatic Pit
WRF – Weather Research & Forecasting

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