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Effects of winter convection on the deep layer of the Southern Adriatic Sea in 2012

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[1] We analyze aspects concerning the thermohaline changes observed in the near-bottom layer of the Southern Adriatic Pit (SAP), in the Eastern Mediterranean, after the arrival of abundant and exceptionally dense water ($\sigma_\theta > 30$ kg m^{-3}) produced in the shallow Northern Adriatic Sea during winter 2012. For this purpose, we use temperature (*T*), salinity (*S*), and current time series collected at the E2M3A deep-ocean observatory of the Southern Adriatic, and Conductivity-Temperature-Depth data obtained both in the Southern and Middle Adriatic from freely drifting profiling floats. The dense water produced in the Northern Adriatic arrived in the central and deepest part of the SAP as a series of individual pulses starting on 10 March 2012; while, a stronger and prolonged signal that significantly modified the local deep water stratification arrived after 10 April 2012. As a consequence, T and S suddenly decreased ($\approx$0.15°C and $\approx$0.015), thus interrupting positive T and S bottom trends observed during the previous 5 years and producing a density increase of $\approx$0.02 kg m^{-3}. Such variability has been rarely observed in the area. We ascribe its occurrence to the concomitance of exceptionally harsh and long-lasting Bora wind, scarce precipitation, and low river discharge over the Northern Adriatic during winter 2011/2012. Eventually, this newly formed AdDW reached the Strait of Otranto during July 2012. Its characteristics profoundly differed from those observed in the previous decade. Hence, a noticeable variability in structure and circulation of the abyssal layers of the Ionian basin is likely to occur in the near future.

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1. Introduction

[2] Dense water is produced both on the continental shelf and in the open ocean. In case of continental shelves, dense water is formed under the effects of cooling, evaporation, and mixing; in the polar regions, it is formed also due to a salinity increase produced by brine injection during surface freezing [see e.g., *Marshall and Schott*, 1999; *Shapiro et al*., 2003]. In the open-sea areas, it is necessary to have a persistent cyclonic circulation, because it preconditions the water column by isopycnic doming [*Marshall and Schott*, 1999]. Moreover, in the process of continental shelf dense water formation, also freshwater injections of riverine origin can play a fundamental role. Once formed, dense water is often exported toward the abyssal ocean by means of bottom-arrested currents [see e.g., *Smith*, 1975; *Jungclaus and Backhaus*, 1994; *Shapiro et al*., 2003; *Ivanov et al*., 2004]. These are forced by their density contrast with the overlying layers and can reach very high velocities, especially when constrained by narrow bathymetric features. Earth rotation exerts a deep influence on their motion, which is often in almost geostrophic equilibrium [*Smith*, 1975; *Jungclaus and Backhaus*, 1994]. As a result, current penetration depth, velocity structure, and rate of mixing are determined by the above mentioned parameters, together with the interactions with motions of the upper ocean, which can be particularly important in shallow areas [*Jungclaus and Backhaus*, 1994; *Rubino et al*., 2003; *Hainbucher et al*., 2006; *Rubino and Hainbucher*, 2007].

[3] In the Adriatic Sea, which represents the main source of dense waters for the Eastern Mediterranean basin, both the continental shelf and the open-ocean convection are known to occur [see e.g., *Pollak*, 1951; *Ovchinnikov et al*., 1985; *El-Gindy and El-Din*, 1986]. The hydrodynamics of the Adriatic Sea are strongly affected by the Bora, a dry and cold northeasterly wind that, particularly under the influence of the local orographic features, plays a fundamental role in winter cooling, as it leads to increased evaporation and lowers the sea surface temperature through conduction. It is usually stronger during winter [gusts can frequently exceed 20 m s^{-1}, *Tutiš*, 2002] and, normally, it lasts no more than a few days [*Lavagnini et al*., 1996].

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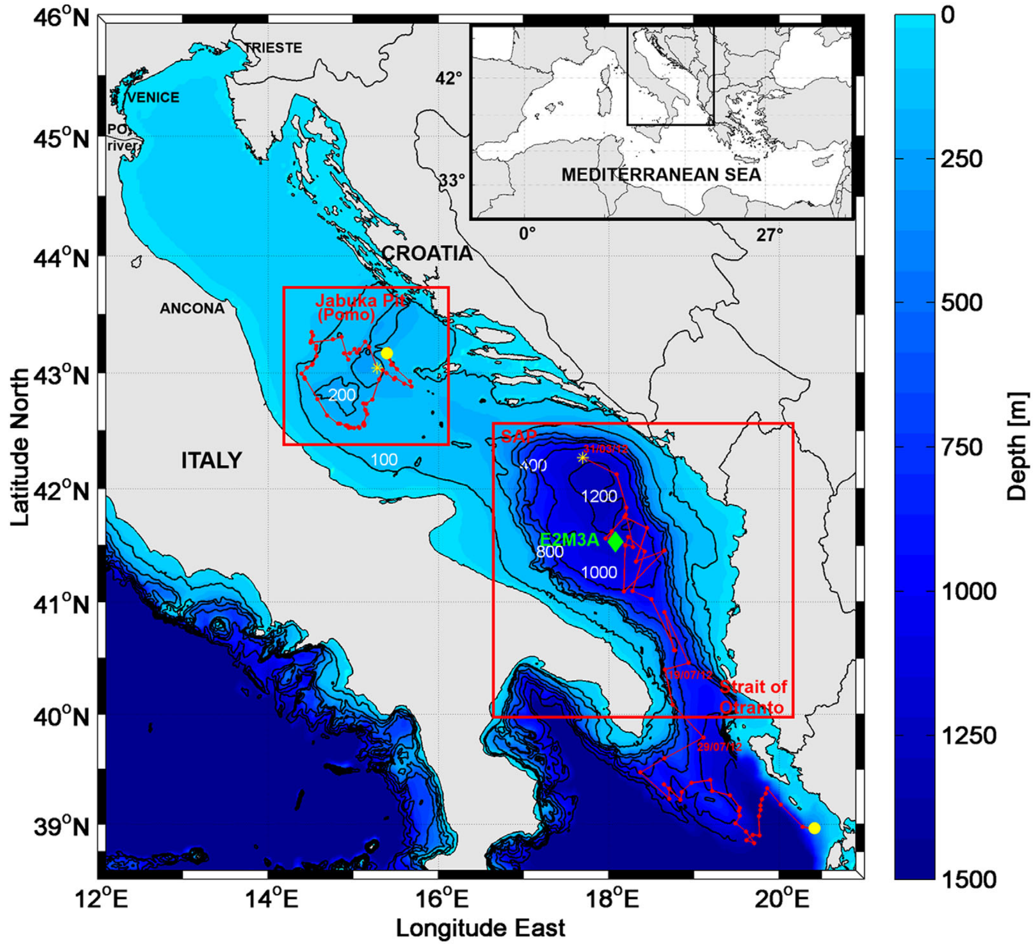

Figure 1. Bathymetry of the Adriatic Sea. Red squares indicate the Middle (Pomo, also Jabuka, pit) and Southern Adriatic (SAP = Southern Adriatic Pit) areas. Red dots and lines indicate the float stations and trajectories during the period starting from 1 December 2011 for the float in the Pomo pit and from 31 March 2012 for the float in the SAP (yellow stars). Endpoints are marked by yellow circles and they refer to 31 December 2012. The position of the E2M3A observatory is indicated in green.

The Adriatic Sea can be divided into three main subareas: the Northern Adriatic, extending south as far as Ancona (see Figure 1) where the maximum depth does not exceed 100 m; the Middle Adriatic, where maximum depths (~275 m) are encountered in a depression called Pomo pit (also Jabuka Pit); and the Southern Adriatic, between the Gargano Peninsula and the Strait of Otranto, where the maximum depth reaches about 1250 m in the Southern Adriatic Pit (hereafter SAP).

[4] In such distinct areas, dense water formation occurs not always simultaneously and, notably, it involves various and variable volumes [see e.g., *Cardin and Gačić*, 2003; *Vilibić*, 2003; *Supić and Vilibić*, 2006; *Mantziafou and Lascaratos*, 2008; *Cardin et al.*, 2011; *Rubino et al.*, 2012].

[5] In particular, different studies [see e.g., *Gačić et al.*, 2002; *Mantziafou and Lascaratos*, 2008] report a significant variability of deep convection in the SAP. Limiting our discussion to the last two decades, for which data are more abundant, we note that winters 1996–1997 and 2006–2007 were characterized by a very shallow or even no convection [*Manca et al.*, 2002; *Gačić et al.*, 2002; *Bensi et al.*, 2013a]. An abundant deep convection was instead observed in winters 1986–1987, 1991–1992 [*Gačić et al.*, 2002] and, more recently, in 2008, 2009, and 2010 [*Cardin et al.*, 2011; *Bensi et al.*, 2013a]. However, the newly formed dense water did not reach the bottom of the SAP during the above mentioned years, and its manifestations were not observed at depths exceeding 1000 m. Consequently, it can be stated that this deep layer usually remains unaffected by vertical mixing induced locally by open-sea convection, while it is ventilated by the cascading of dense waters generated on the Northern Adriatic shelf [see e.g., *Bignami et al.*, 1990; *Rubino et al.*, 2012]. This water, called North Adriatic Dense Water (NAdDW), is the densest water of the Mediterranean Sea [*Franco et al.*, 1982; *Malanotte-Rizzoli et al.*, 1997]. It can reach density values larger than 1030 kg m^{-3} during severe winters, as in the recent case of winter 2012 [*Mihanović et al.*, 2013], and contributes, on average, to 20% of the total Adriatic deep waters, although it may be virtually absent in some years [*Vilibić and Orlić*, 2001, 2002; *Mantiafou and Lascaratos*, 2008; *Cardin et al.*, 2011]. Once formed, the NAdDW flows as a bottom-arrested current, preferably along the

Italian shelf, in near geostrophic equilibrium [*Rubino et al.*, 2012]. Its mean velocity is 5–10 cm s^{-1}, but peaks up to 30–45 cm s^{-1} during strong Bora events have been observed and simulated [see *Book et al.*, 2005; *Querin et al.*, 2013]. Note that along its way toward the Southern Adriatic, dense water produced in the Northern Adriatic basin changes its properties due to entrainment with the ambient waters. Hence, its final density is the result of complex interactions with other water masses. However, in years of large NAdDW production, its temperature and/or salinity anomalies remain largely preserved during its southward propagation and are clearly detectable in the deep layer of the SAP.

[6] Among the different local phenomena affecting the formation of dense waters, river discharge seems particularly important in the Northern Adriatic, as a large part of its stratification and hydrodynamics is dominated by the Po River outflow [average discharge of 1500 m^3 s^{-1}, *Raicich*, 1996]. A weak river discharge during autumn and early winter can favor the formation of particularly salty and hence dense NAdDW. This was the case occurred during winter 2012. A large river discharge, however, contrasts the formation of very dense water, as it reduces the salt content in water [*Vilibić and Supić*, 2004; *Campanelli et al.*, 2011]. The picture is made even more complicated by the fact that, as quoted above, in the Northern subbasin, NAdDW can be formed in different yearly variable generation areas [*Supić and Vilibić*, 2006; *Querin et al.*, 2013]. Indeed, in addition to the well-known areas in the northernmost part of the Adriatic Sea, dense waters are likely to form also along the Croatian coast under favorable meteorological conditions [*Mihanović et al.*, 2013]. Depending on many factors—such as its density excess, volume and mixing/entrainment with the surrounding water [see e.g., *Rubino et al.*, 2003; *Rubino and Hainbucher*, 2007, for a discussion on entrainment on bottom-arrested currents]—the equilibrium depth at which the NAdDW sinks into the SAP can vary from year to year [*Hainbucher et al.*, 2006].

[7] Since 2006, the Southern Adriatic has been almost continuously monitored by a deep-ocean observatory located at 41°32′N, 18°05′E, and named E2M3A. It enables a detailed observation of local phenomena, including open-ocean convection, mesoscale circulation, as well as seasonal and long-term thermohaline variability. Indeed, in the last 6 years (2007–2012), positive trends close to the bottom were observed as regards temperature (≈0.05°C y^{-1}) and salinity (≈0.004 y^{-1}), whose causes are still to be completely understood [*Bensi et al.*, 2013a]. Obviously, the variability of the NAdDW formed on the Northern shelf during strong winter air-sea interaction events has played a fundamental role for the said deep water variability [*Vilibić*, 2003; *Bensi et al.*, 2013a].

[8] However, in order to assess the spatial distribution of these phenomena, an integrated oceanographic approach is required: data obtained from fixed-point observations have to be merged with data obtained from hydrographic surveys or autonomous platforms such as profiling floats.

[9] For the purpose of this paper, we merged temperature, salinity, and current time series collected at the E2M3A deep-ocean observatory of the Southern Adriatic with CTD (Conductivity-Temperature-Depth) profiles obtained from freely drifting Argo profiling floats so as to analyze the large (compared with the local long-term variability) thermohaline changes which occurred in the deep layer of the SAP after the arrival of dense waters formed on the northern shelf and in the Pomo pit during winter 2012. Thus, we here analyze aspects concerning the thermohaline variability associated with the Adriatic dense waters during and after an extreme meteorological event occurred in the Adriatic Sea in winter 2012.

[10] The paper is organized as follows: section 2 presents the data set and methods used in this study; section 3 analyses and discusses the heat fluxes and oceanographic data collected from ECMWF operational data sets, profiling floats, and E2M3A. Finally, in section 4 we present the main conclusions of our investigation.

2. Data and Methods

[11] In this paper, we use temperature (*T*), salinity (*S*), and current time series collected at the E2M3A (see Figure 1) as well as CTD (Conductivity-Temperature-Depth) data obtained from freely drifting Argo profiling floats. From each of these data sets, potential temperature (θ) and potential density anomaly (σ_θ) were calculated.

[12] The E2M3A station is located in the central part of the SAP, at 41°32′N, 18°05′E (Figure 1). In order to study more in detail the dense water formation which occurred in winter 2011/2012, we considered particularly the data from 27 May 2011 to 19 May 2012. The payload of the observation site consisted of Conductivity-Temperature (CT; SBE37 MicroCAT) and CTD sensors (SBE16plusV2 SEACAT) at different nominal depths (350, 550, 750, 1000, and 1200 m). An upward-looking acoustic Doppler Current Profiler (ADCP) RDI 150 kHz located at ~300 m and an Aanderaa Recording Current Meter (RCM11) located near the bottom, at ~1200 m, provided current measurements at E2M3A. Unfortunately, due to technical problems, the RCM11 did not work properly during the deployment in 2011/2012. All sensors were configured with a sampling period of 60 min, checked, and calibrated before and after each deployment at the CTO (Oceanographic Calibration Center) of the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, OGS, Trieste. All time series were processed applying a postprocessing methodology, based on a routine package created with MATLAB, to obtain cleaned and despiked data. The method of despiking consists of a first visual check, and a later check of the consistency of the data. In particular, we verified that the data belong to given instrumental and physical ranges and checked stationarity. Assuming for the time series a normal distribution, we accepted all values within the interval $\mu \pm 3\sigma$, where μ is the mean value and σ is the standard deviation [see e.g., *Emery and Thompson*, 2001]. Furthermore, we applied a low-pass filter with a cutoff period at 33 h to the hourly data [*Flagg et al.*, 1976] in order to obtain subinertial nontidal flow. The overall accuracies were within ±0.002°C for T and ±0.005 for *S*, ±1% ± 0.5 cm s^{-1} for current speed from ADCP (±2° for current direction) and ±0.3 cm s^{-1} for speed from RCM11 (±0.35° for direction).

[13] For this work, we also used data collected from two profiling floats. They were deployed in the Southern Adriatic between 2010 and 2012 in the framework of the

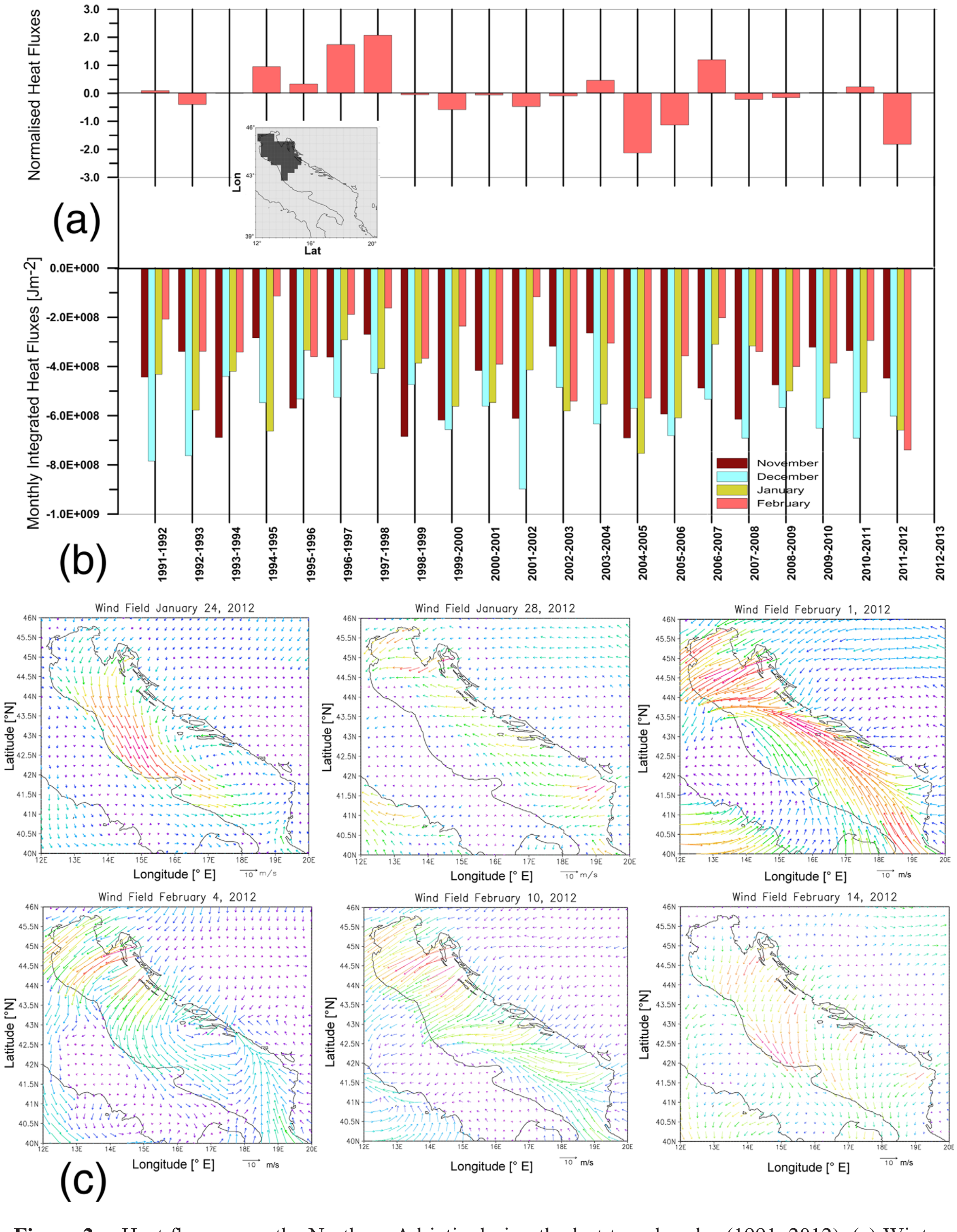

Figure 2. Heat fluxes over the Northern Adriatic during the last two decades (1991–2012). (a) Winter heat flux anomalies and (b) integrated monthly (November-February) values are shown. Winter anomalies are obtained by subtracting the long-term (1991–2012) winter (November-December-January-February) average Q_{net} from each yearly winter average calculated from daily values and dividing the result by the long-term (1991–2012) winter (November-December-January-February) Q_{net} standard deviation. The grid (83 points) used for the flux calculations is shown in the small plot. Plot (c) shows the temporal evolution of wind vectors at the sea surface during the harsh Bora event occurred in winter 2011/2012. Data are retrieved from the ECMWF Operational Analysis Data Set (each plot corresponds to a selected daily average snapshot).

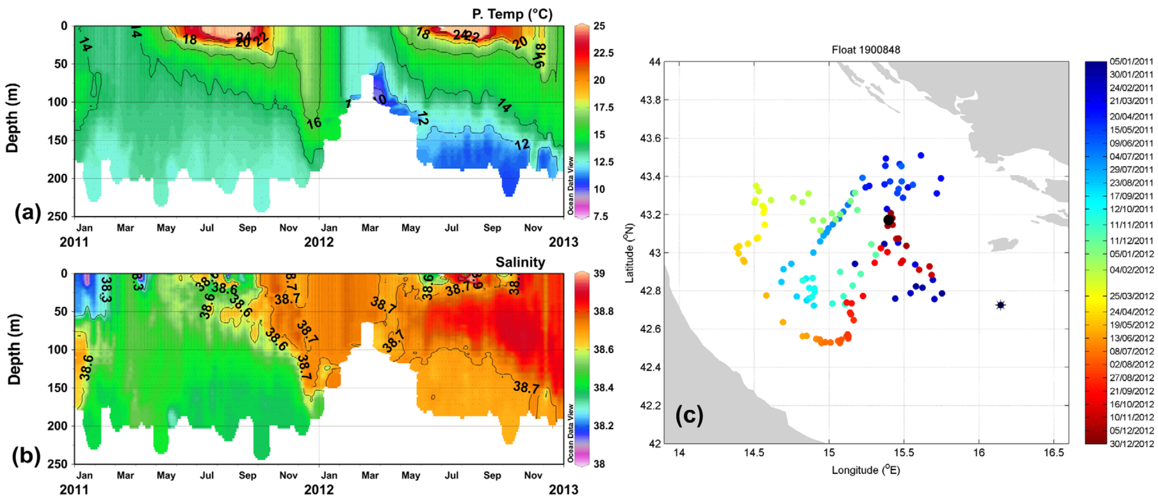

Figure 3. Time-depth diagram of (a) θ and (b) S obtained by the float in the Pomo pit from 1 January 2011 to 31 December 2012. Plot (c) shows the trajectory of the same float (s/n 1900848).

Argo program in the Mediterranean Sea (MedArgo). One of them (WMO 1900848) moved from the SAP to the Pomo pit after October 2010, while the other (WMO 6901040) remained in the SAP for several months (from April until July 2012), then it entered the Ionian, and eventually returned in the SAP in January 2013. The floats are Arvor instruments manufactured by the NKE instrumentation. They are equipped with Sea-Bird CTD sensors (model SBE41CP) with accuracies of $\pm 0.002°C$, ± 0.005, and ± 2.4 dbar for *T*, *S*, and pressure, respectively. They were programmed following the specifications of the MedArgo program [*Poulain et al.*, 2007] with a cycle length of 5 days, a drifting depth of 350 m and a maximal profiling depth of 2000 m. The float data are transferred to one of the Argo Data Assembly Centre (DAC), where they are processed and quality-controlled using a basic set of tests, and then sent to one of the Global Data Assembly Center (GDAC). We downloaded the data from the Coriolis Data center (a GDAC center) located at IFREMER (*Institut français de recherche pour l'exploitation de la mer*) in Brest (France) in NetCDF (Network Common Data Form) format. A delayed-mode quality control of pressure, T and S data was applied in accordance to the *Argo Quality Control Manual* [2013], and in particular the Owens-Wong method was adopted [*Owens and Wong*, 2009] to check the salinity data. The float salinity profiles were also qualitatively compared to a reference data set and the analyses performed here have shown that no drift or offset of S is larger than the natural variability of the water column (see details on delayed mode quality control in *Notarstefano and Poulain* [2008]).

[14] Air-sea heat fluxes (Q_{net}) were calculated at the air-sea interface every 6 h (00, 06, 12, 18 UTC) from the European Center for Medium Range Weather Forecast, Reading, UK (ECMWF) Operational Analysis Data Set using a 0.25° interpolated lat./long. Gaussian grid [*Cardin and Gačić*, 2003]. From the six hourly values, daily net heat fluxes at the air-sea interface were computed taking into account four heat flux components. The solar radiation (Q_s) was calculated using the modified Reed formula [*Schiano*, 1996], the net long wave radiation (Q_B) was obtained by applying the *May* [1986] formula, while the sensible (Q_H) and latent heat (Q_L) fluxes were obtained from the bulk aerodynamic formulas. More information on the formulas applied and coefficients can be found in *Cardin and Gačić* [2003]. Total winter heat losses were then calculated as a time-integral for the period spanning from 1 November to 28/29 February using a grid of 83 nodes for the Northern Adriatic basin (Figures 2a and 2b).

3. Results and Discussion

3.1. Heat Fluxes in the Adriatic Sea

[15] Our main goal is to elucidate aspects concerning the thermohaline changes observed in the Southern Adriatic basin due to the arrival of very dense water formed in the Northern basin during winter 2011/2012 and to put this episode in the context of the basin-wide long-term variability. For this purpose, we first quantified aspects of the forcing leading both to single episodes and affecting long-term modes of variability of water mass formation and propagation in the region. We thus considered heat fluxes observed over the Adriatic from 1991 to 2012 (see Figures 2a and 2b). In particular, for each year considered, integrated heat fluxes were calculated for the period from November to February (see also section 2, for a detailed description of the methods used) so as to understand both the effects of the heat fluxes on the initial water stratification during the preconditioning phase and the induced thermohaline variability during the following winter months.

[16] More in detail, we also considered normalized anomalies of the winter heat fluxes. These values were obtained by subtracting the long-term (1991–2012) winter (November-December-January-February) average Q_{net} from each yearly winter average calculated from daily values and dividing the result by the long-term (1991–2012) winter (November-December-January-February) Q_{net} standard deviation. In Figures 2a and 2b we present interannual winter heat flux anomalies and monthly (November-

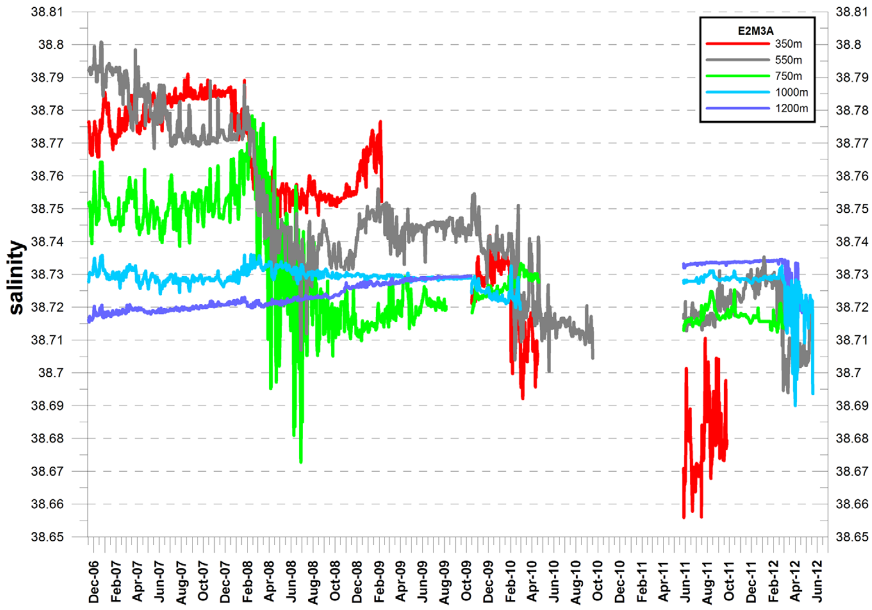

Figure 4. Time series of S at the E2M3A from November 2006 to May 2012. Data are smoothed using a 33 h Hamming filter.

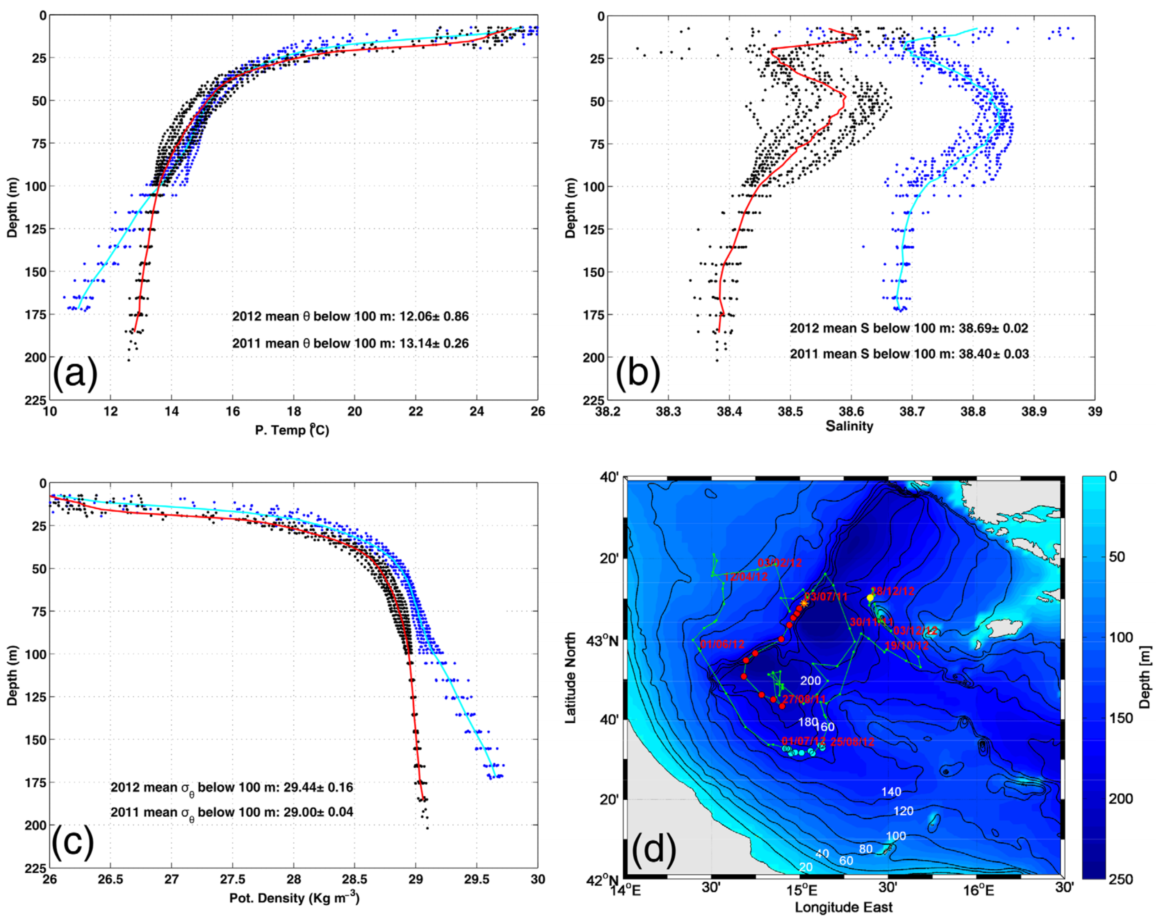

Figure 5. Average (a) θ, (b) S, and (c) σ_θ obtained from CTD float profiles collected in the Pomo pit (Middle Adriatic) in July-August 2011 (red) and July-August 2012 (cyan). Plot (d) shows the trajectory of the float 1900848 between July 2011 and December 2012 (red and cyan circles correspond to profiles collected in July-August 2011 and July-August 2012, respectively).

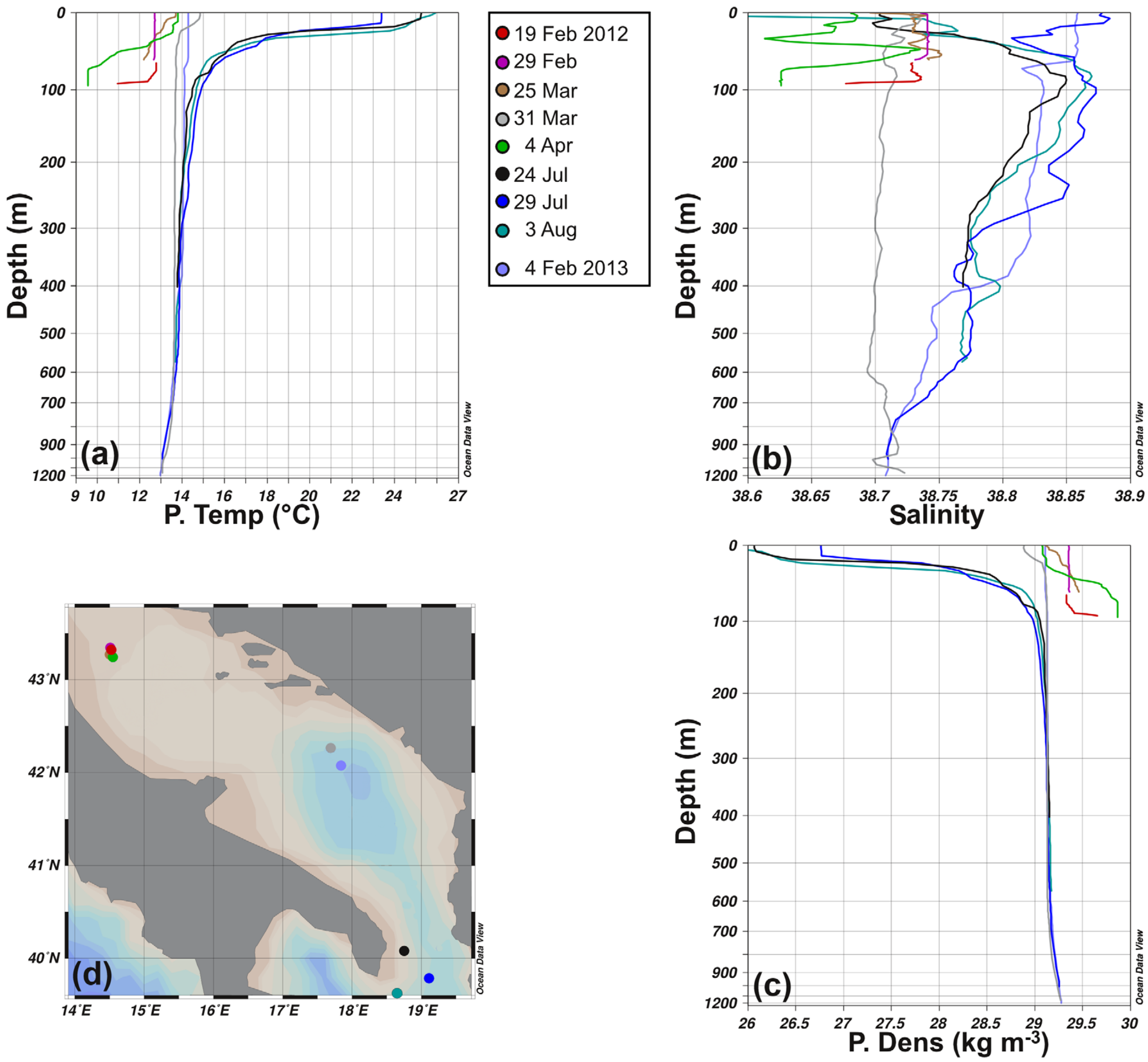

Figure 6. (a) θ, (b) S, and (c) σ_θ obtained from CTD float profiles in the Pomo pit, in the SAP, and in the Strait of Otranto. Plot (d) shows the position of the selected profiles.

December-January-February) integrated heat fluxes. As far as the general features of our climatological analysis are concerned, we note the presence of an interannual signal and of a significant monthly variability during the whole period considered. Generally, strong heat losses take place in the Northern Adriatic during November and December, contributing first to the weakening of the stability (preconditioning period) and then to the cooling of the water column as a whole. However, it is the heat flux distribution during the following winter months which plays a crucial role in the dense water formation [*Cardin and Gačić*, 2003]. Indeed, when large negative monthly heat flux values are observed at the beginning of winter (e.g., December 2001, Figure 2b) but the event has a limited duration in time (like in the case of winter 2001/2002), the winter integrated heat flux anomaly is low (see Figure 2a). As a result, dense water formation is limited in time and, consequently, in volume. On the contrary, when the months from November to February are all characterized by large heat losses, like in the case of winters 2004/2005 and 2011/2012, the winter integrated heat flux negative anomaly results larger. However, even though winter 2004/2005 heat flux anomaly was larger than that of winter 2011/2012, only winter 2011/2012 showed a progressive heat loss increase from November to February associated with very strong and exceptionally long-lasting (~21 days) wind bursts measured between the end of January and mid-February 2012. During that event, a mean daily heat loss of 428 W m^{-2} and an integrated heat loss of 8.78×10^8 J m^{-2} were estimated, which reveals the exceptionality of the event. Although the details of the oceanographic phenomena induced by these episodes cannot be realistically described without using very high resolution atmospheric and oceanic models [see e.g., *Paklar et al.*, 2001; *Loglisci et al.*, 2004; *Pullen et al.*, 2006; *Dorman et al.*, 2006; *Mihanović et al.*, 2013], coarser heat flux data sets are also able to capture gross aspects of their influences on the Adriatic basin [see e.g., *Zavatarelli et al.*, 2002; *Cardin and Gačić*, 2003]. Figure 2c depicts the evolution of the wind field from 24 January until 14 February 2012 over the whole Adriatic Sea as described by the

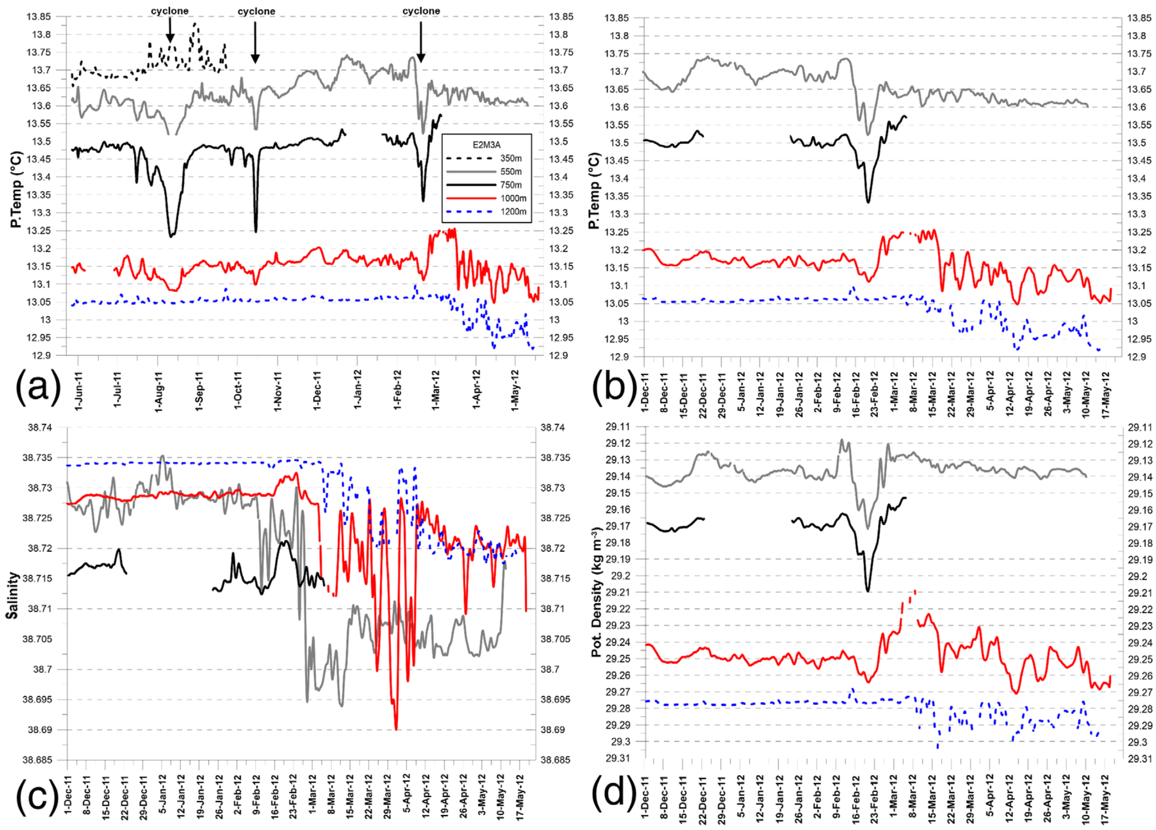

Figure 7. Time series of (a and b) θ, (c) S, and (d) σ_θ at the E2M3A (a) from May 2011 until May 2012, and (b–d) from 1 December 2011 to 23 May 2012. Data are smoothed using a 33 h Hamming filter. Note the evidence of cyclonic eddies in August 2011, October 2011, and February 2012 (indicated by black arrows in (a) and Figure 8), which caused a large displacement of θ and S, and σ_θ throughout the water column. The density scale on the *y* axis in (d) is reversed.

ECMWF operational data set. Initially, the wind was stronger over the central and southern basins and it extended to the Northern Adriatic only after 28 January. Wind gusts measured at a fixed, coastal station in the northernmost part of the basin reached values as high as 42 m s^{-1}, and the maximum daily mean value was $\approx$21 m s^{-1} (assessed from ECMWF grid, on 7 February 2013). After 1 February the whole Adriatic was practically influenced by strong wind, which is rare according to *Ivančan-Picek and Tutiš* [1996].

[17] Moreover, the episode described here, lasted ~21 days (see e.g., *Mihanović et al.*, [2013], for a detailed description of this Bora event), that is 3–4 times longer than the average duration. In this sense, the wind activity recorded over the whole Adriatic basin during winter 2011/2012 seems unprecedented in the region.

3.2. Thermohaline Variability in the Southern and Middle Adriatic During Recent Years With Emphasis on Winter 2011/2012

[18] In the Adriatic Sea, thermohaline changes are driven by interactions with the water masses of the Eastern Mediterranean [see e.g., *Gačić et al.*, 2010] as well as by the variability of local air-sea interactions and river runoff [see e.g., *Gačić et al.*, 2002; *Cardin and Gačić*, 2003].

[19] In February 2012, the overall salinity in the Northern Adriatic experienced a large increase in concomitance with the long-lasting episode of Bora wind described above. This change should be comprehended in the frame of a large-scale low frequency temporal variability. Indeed, the time-depth diagram obtained from the float data in the Pomo pit along its track between 1 January 2011 and 1 January 2013 (Figure 3) reveals that, in late autumn 2011, the salinity in the Pomo pit suddenly increased by a value of 0.2 (average values of the water column changed from $\approx$38.50 to $\approx$38.70), thus reaching values similar to those observed further south, at the E2M3A, at 350 m depth (Figure 4).

[20] However, the salinity in the SAP experienced a general decrease in the layer, down to 800 m depth. This started in 2008 and has continued at least until winter-spring 2012. In particular, after 2010, the salinity values observed were not larger than 38.71 down to 400 m depth [see Figure 4, and see also *Cardin et al.*, 2011, for a detailed description of the long-term variability in the SAP from 1990 until 2010]. This variability has been widely ascribed to a periodical reversal of the circulation in the Northern Ionian Sea, the so-called BiOS [see e.g., *Gačić et al.*, 2010; *Cardin et al.*, 2011; *Gačić et al.*, 2011; *Bensi et al.*, 2013a].

[21] However, we cannot exclude that spatially limited branches of salty waters (with at least $S > 38.75$), confined in the eastern side of the SAP, were able to reach the

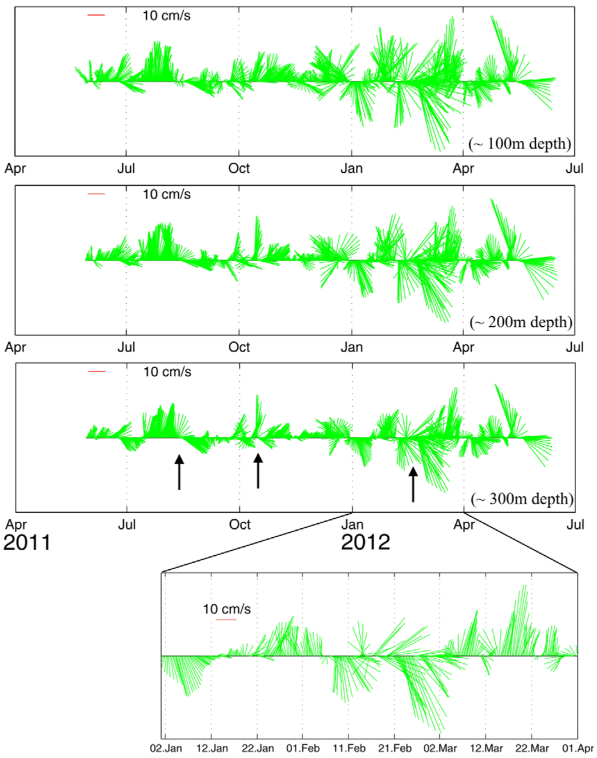

Figure 8. Current time series obtained from the up-looking ADCP at the E2M3A from May 2011 to May 2012 at 100, 200, and 300 m depth. The bottom plot shows a zoom of the 300 m depth time series between 1 January and 31 March 2012. Black arrows indicate the passage of cyclonic eddies.

Northern Adriatic during this general low salinity phase that has characterized the SAP in recent years. These findings, together with the results of different observations carried out recently both in the Southern and the Northern Adriatic [see e.g., *Gačić et al*., 2010; *Cardin et al*., 2011; *Mihanović et al*., 2013; *Vilibić and Mihanović*, 2013; *Bensi et al*., 2013a] pave the way to two different complementary scenarios. In the first one, the observed salinity increase in the Northern Adriatic seems to have been due—at least partly—to the effect of the Bora event (strong evaporation and local circulation limiting offshore freshwater propagation). In the second, the advection of very saline water from the south, due probably to a vein of saltier water from the Ionian Sea confined in the easternmost part of the SAP, could have played a major role in producing the observed salinity increase in the Middle and Northern Adriatic.

[22] The analysis of the CTD profiles collected by the floats in the Pomo pit and in the SAP, together with the data recorded at the E2M3A site, helps to understand aspects of the spreading of dense water from the Northern shelf toward the Southern Adriatic after the convective phase of February 2012. Note to this regard that *Bensi et al*. [2013a] pointed out the existence of a large correlation between T and S values observed at the E2M3A site and T and S observed within the deep part of the SAP.

3.2.1. Thermohaline Variability Induced by Dense Water Spreading in the Middle and Southern Adriatic: The 2012 Episode

[23] In this paper, we consider particularly the thermohaline characteristics of the deep layers of the Pomo pit (100 m thickness above bottom) and of the SAP (200 m thickness above the bottom), as these regions are those most profoundly influenced by the signal of NAdDW.

[24] In order to compare the overall characteristics of the bottom layer in the Pomo pit after the end of the mixing (autumn/winter) and spreading (end winter/spring) phases with the corresponding characteristics existing before the strong convection occurred in 2012, we first of all analyzed all float profiles collected in the central and deepest part of the Pomo pit during summer 2011 and 2012 (July and August). Figure 5 reveals that, in summer 2011, the NAdDW entrapped in its deepest part was characterized by the following average properties: $\theta = 13.14 \pm 0.26°C$, $S = 38.40 \pm 0.03$, and $\sigma_\theta = 29.00 \pm 0.04$ kg m^{-3}. At the beginning of February 2012, the bottom layer in the Pomo pit underwent abrupt thermohaline changes, which resulted in the following average properties observed during summer 2012: $\theta = 12.06 \pm 0.86°C$, $S = 38.69 \pm 0.02$, and $\sigma_\theta = 29.44 \pm 0.16$ kg m^{-3}. These changes were mainly caused by the massive arrival of NAdDW, formed under the effects of the strong and long-lasting Bora event investigated above. Signals of the arrival of the said water mass were locally captured by a sequence of several float profiles collected close to each other in the Middle Adriatic (Figure 5d).

[25] Despite the rather moderate temporal (5 days) and horizontal spatial (about 9 km) resolution of the float profiles, we are confident that this data set can yield valuable information on the spreading of the NAdDW toward the Middle and Southern Adriatic pits, particularly regards major thermohaline variability [see also *Vilibić and Mihanović*, 2013].

[26] Indeed, the data from the floats provide the first indication of the presence of a very dense bottom layer (maximum value of $\sigma_\theta = 29.65$ kg m^{-3}) on 19 February (Figure 6) in the northwestern edge of the Middle Adriatic (depth $<$ 100 m). Note that this CTD profile covers only part of the water column, from 65 to 92 m. The fact that the following two profiles (acquired on 29 February and 25 March, respectively) do not show the same signal of dense water reveals that probably, at that time, the NAdDW still occupied a very narrow near-bottom area. Afterward, the first clear occurrence of NAdDW in the deepest layer of the northwestern part of the Pomo pit is given by a float profile collected on 4 April 2012, when the average properties of the bottom layer were $\theta \approx 9.56°C$, $S \approx 38.63$, and $\sigma_\theta \approx 29.87$ kg m^{-3}.

[27] In the SAP, data collected at the E2M3A show a sudden decrease in T (from ≈13.07 to ≈12.92°C) and S (from ≈38.735 to ≈38.72) close to the bottom, which started approximately after 10 March 2012 (Figure 7). This resulted in a density increase of ≈0.02 kg m^{-3}. We interpret this signal as the arrival of NAdDW in the abyssal part of the Southern Adriatic. Since its propagation time appears much faster than what usually reported in the literature (1.5 months against the 2–3 months usually reported) [see e.g., *Vilibić*, 2003] we cannot exclude that this first signal of dense waters belongs to those originated along the Croatian

Table 1. Thermohaline Properties of the Core of Adriatic Waters (Usually Confined in a 100 m Thick Bottom Layer) Outflowing the Strait of Otranto Between 2003 and 2012[a]

Year/Month	Cruise	θ (°C)	S	σ_θ (kg m^{-3})
2003/May	POSEIDON 298	13.47/13.57	38.70/38.74	29.16/29.18
2006/Nov	VECTOR-AM1	13.36	38.75	29.22
2007/Jan	M 71/3	13.32	38.75	29.24
2008/Oct	SESAME-IT7	13.25/13.30	38.71/38.72	29.22
2009/Oct	MSM-132	13.26/13.30	38.72	29.22
2010/Jul	MSM-154	13.29/13.42	38.72	29.19/29.22
2011/Jun	P-414	13.27	38.72–38.73	29.22/29.23
2012/Jul	Argo float 6901040	13.08	38.71	29.25

[a]Data are retrieved from punctual CTD casts (hydrographic surveys and floats). Ranges are given when a large variability between adjacent stations was encountered.

coast and not in the northernmost part of the Adriatic Sea. This would substantially reduce its traveltime toward the abyssal part of the SAP.

[28] At 1000 m depth, and likely also at 750 m (unfortunately, the time series at 750 m was interrupted on 5 March 2012) a phase characterized by an increase in T and a decrease in S, made of a rather irregular series of strong pulses, was observed from 22 February to ~15 March (Figures 7b and 7c). It was followed by another phase characterized by a decrease of both T and S. During this last phase the short-term variability at 1000 m did not substantially differ from that at 1200 m. Thus, the deep layer of the SAP was influenced by a coherent signal of NAdDW after mid-March 2012. Note also that, from the beginning of April 2012, a tendency was found toward a homogenization in S between 1000 and 1200 m water depth which was not accompanied by a corresponding homogenization in *T*. Although the available data do not allow for an exhaustive investigation of the said phenomenon, we believe that it can be explained by differential mixing acting on the pre-existing stratification. Since S at 1200 m was larger than that at 1000 m before the arrival of the newly formed, colder, and fresher, dense water of Northern Adriatic origin, while T at 1200 m was lower than that at 1000 m, mixing of S was likely more effective near the bottom and tended to restore the "classical" negative S vertical gradient in the deep layer of the SAP, where S usually decreases with depth.

[29] Thermohaline variability in the upper part of the water column is influenced both by mixing induced by open-ocean convection and by lateral advection. In particular, at 550 m depth, a sudden decrease in S was recorded after 22 February (Figure 7c). Intriguingly, such variation was not accompanied by a similar variation in T (Figure 7b). At the same time, increased southward currents were registered in the layer 100–300 m by the ADCP, with peak values larger than 30 cm s^{-1} (Figure 8). Probably, these signals are linked to the passage of coherent mesoscale vortices spanning from the near-surface to deeper layers or even to the bottom, which seem not infrequent in the area (see Figure 8) [e.g., *Burrage et al*., 2009; *Ursella et al*., 2011; *Bensi et al*., 2013a]. Also the 2011/2012 E2M3A time series analyzed here shows three passages of different vertically coherent mesoscale cyclones (e.g., in August 2011, October 2011, and February 2012, indicated by black arrows in Figure 8). They forced a major upward displacement of deep waters, causing a sudden density increase throughout the water column (see Figures 7d and 8). These features, together with other vortices not captured by the E2M3A, could have been responsible—at least partly—for the advection of water bodies from the boundaries of the SAP toward its central part, producing a local temporary modification of the characteristics of the water column.

[30] Depth-average properties in the SAP, between 200 and 800 m depth in mid-March 2012 were $\theta \approx 13.60$°C, S ≈ 38.70, and $\sigma_\theta \approx 29.14$ kg m^{-3}, while below 800 m depth they were $\theta \approx 13.11$°C, S ≈ 38.71, and $\sigma_\theta \approx 29.25$ kg m^{-3} (see CTD profile on 31 March 2012 in Figure 6). These data identify a signal of newly formed Adriatic dense water. The fate of such water masses is a southward movement toward the Strait of Otranto and their descent into the abyssal Ionian plain [*Hainbucher et al*., 2006; *Bensi et al*., 2013b]. On average, the water volume involved in this cascading is about 0.6 Sv [see e.g., *Hainbucher et al*., 2006], but peaks exceeding 1 Sv have been reported [*Vetrano et al*. 1996; *Yari et al*., 2012]. In spring and summer 2012, the newly formed AdDW arrived in the Strait of Otranto. One float passed through the strait in July (see Figure 6) revealing mean characteristics of the Adriatic outflow that profoundly differ from those observed during the previous years (see Table 1). In particular, T experienced a large decrease in 2012, confirming that the cause of the said change is attributable mainly to the contribution of newly formed NAdDW.

[31] At the beginning of 2013 (January and February), an abrupt increase in T and S was detected by the same float ($\theta \approx 13.94$°C, S ≈ 38.80, $\sigma_\theta \approx 29.14$ kg m^{-3}) in the layer down to 800 m (Figure 6), both in the Strait of Otranto and in the SAP. This fact can be associated with the change of circulation of the North Ionian Gyre [*Gačić et al*., 2011], which led again to an abundant entrance of salty water of Levantine origin into the Adriatic Sea.

4. Conclusions

[32] During winter 2012, abundant and exceptionally dense water (potential density anomaly $\sigma_\theta > 30$ kg m^{-3}) was produced in the northern part of the Adriatic Sea.

[33] According to our analyses, the meteorological and oceanographic conditions of winter 2012 over the Northern Adriatic, which led to such major water formation, can be considered exceptional on the basis of a series of considerations. First, we were not able to identify other years with so

harsh and long-lasting events of Bora wind. Indeed, from 24 January to 14 February 2012, very strong, cold, and dry winds blew over the Adriatic Sea, with a particular intensity and continuity over the Northern basin: peaks larger than 40 m s^{-1} were observed. As far as the heat loss at the air-sea interface is concerned, both January and February 2012 were characterized by exceptionally large negative values in the Northern basin, with monthly integrated values larger than -6×10^8 J m^{-2}. Second, a low discharge of the Po River and low rain rates over the area occurred, which contributes to explain the observed vigorous convective activity, leading to the formation of extremely dense ($\sigma_\theta > 30$ kg m^{-3}) NAdDW [*Mihanović et al*., 2013].

[34] After its generation phase, the NAdDW propagated toward the Middle and Southern Adriatic. Due to its large density difference with adjacent water masses, it spread very quickly toward the south. Its arrival in the Middle Adriatic and in the SAP caused profound variations in the local deep stratification. During summer 2011, the NAdDW entrapped in the deepest part of the Pomo pit (100 m thickness layer above the bottom) was characterized by the following average properties: $\theta = 13.14 \pm 0.26$°C, S = 38.40 ± 0.03, and $\sigma_\theta = 29.00 \pm 0.04$ kg m^{-3}, while in summer 2012 the average values were: $\theta = 12.06 \pm 0.86$°C, S = 38.69 ± 0.02, and $\sigma_\theta = 29.44 \pm 0.16$ kg m^{-3} (see Figure 5). This large decrease in T is related to the formation of cold water during the long-lasting Bora episode. The observed increase in *S*, instead, is likely related, at least partly, to the strong evaporation phase associated with the Bora event and to the advection of salty waters from the SAP.

[35] In the SAP, the signal of newly formed NAdDW appeared at the E2M3A after 10 March 2012, even though we cannot exclude that other parts of the pit, especially those much closer to the Italian slope, could have been reached by dense waters of Northern or Middle Adriatic origin before the said date. The arrival of NAdDW at the E2M3A caused a sudden decrease in T and S (≈0.15°C and ≈0.015, respectively) accompanied by a density increase of ≈0.02 kg m^{-3} in the deep layer (>1000 m), which interrupted the positive T and S bottom trends observed during the last 5 years. This confirms that profound modifications of the deep structure of the SAP occur only when harsh winter conditions enable the production of a high volume of NAdDW denser—or with comparable density but different T and *S*—than those of the previous years.

[36] Eventually, the signal of AdDW (in this case intended as the sum of dense waters produced in the whole Adriatic) reached the Strait of Otranto during July 2012. Its thermohaline characteristics were profoundly different from those observed in the previous 9 years. Hence, the variability induced in the characteristics of the bottom-arrested currents exporting Adriatic deep water could induce, in the next future, a noticeable variability in the structure and circulation of the abyssal layers of the Ionian basin.

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