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Dense-water generation episodes in the Northern Adriatic

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Summary. — The generation of North Adriatic Dense Water (NAdDW) has been documented in the paper, by analysing three generation episodes occurred in winters of 1981, 1987 and 1989. Temperature, salinity and density collected at the Po Delta-Rovinj transect before, during and after NAdDW generation were analysed and discussed. Furthermore, monthly surface heat, water and buoyancy fluxes were computed for the respective time intervals, coupled with Po River discharge rates. The decrease in the Po River runoff in the preceding 4 months is common characteristics for all of three NAdDW generation episodes. Nevertheless, NAdDW generated in winter of 1989 was the result of extremely lowered water fluxes that preceded to the generation, producing extremely saline dense water. In contrary, winters of 1981 and 1987 were characterized by extensive heat losses in January/February therefore resulting in very cold NAdDW. NAdDW density in all of the cases surpassed 29.7, being dense enough to influence wider area and bottom layers of the whole Adriatic, changing a lot its physical and chemical properties.

PACS 92.10.Bf – Physical properties of seawater.
PACS 92.10.Kp – Sea-air energy exchange processes.
PACS 92.10.Mr – Thermohaline structure and circulation.

1. – Introduction

The Adriatic Sea (fig. 1) is an elongated (about 800 km long and 150 to 200 km wide) semi-enclosed basin situated in the north part of the Mediterranean Sea, and is connected with the Ionian Sea (4000 m deep) through the Otranto Strait (about 800 m deep). Its northern part is a broad shelf with depths smaller than 100 m. Hydrographical characteristics of the North Adriatic are generally under the influence of air-sea fluxes and Po River discharge (*e.g.*, [1, 2]). At the air sea interface the North Adriatic gains heat from March to August and water almost during the whole year. Seasonal cycle of buoyancy flux depends almost entirely on surface heat exchange. Very high buoyancy

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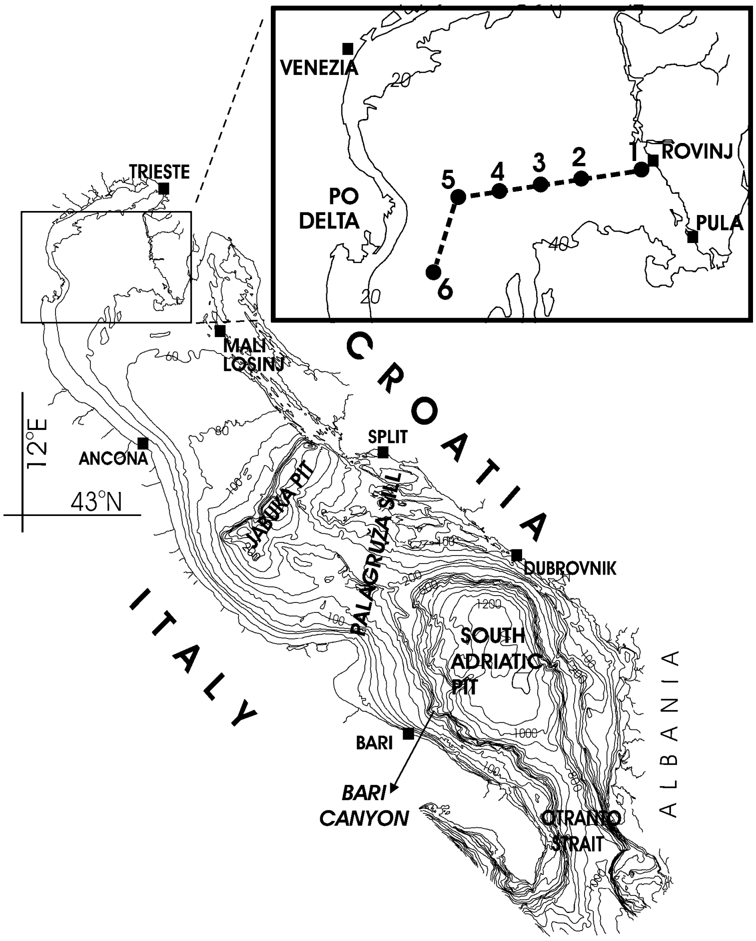

Fig. 1. – Adriatic bathymetry (in meters) with oceanographic stations (1 to 6) and major topographical features indicated. The transect line is indicated too.

gain occurs in November and December due to very intense surface cooling while a large heat gain induces very high buoyancy loss in May, June and July [3]. During the wintertime, freshened Po-influenced waters are generally confined to the western coast, while the Po River affects the waters over larger areas of the Northern Adriatic during spring and summer seasons. Consequently, water column is well mixed during winter and highly stratified during spring and summer seasons [1, 4].

Seasonal and year-to-year changes of hydrographic conditions in the surface layer are mainly driven by changes in surface buoyancy fluxes and by changes in fresh-water inputs. Corresponding changes in the bottom layer seem to be primarily controlled by the processes of vertical mixing [5]. The main dynamic process that affects a considerable part of the Adriatic Sea is the generation of shelf-type North Adriatic Dense Water (NAdDW [6-9]) during the wintertime. As the North Adriatic is open to the winter cold-wind outbreaks, NAdDW is formed under the influence of enhanced surface buoyancy losses and cold river runoffs (primarily related to the Po River) acting together.

NAdDW can have temperature as low as 7°C and density (sigma-t) as high as 29.9 [10]. Air pressure gradient over the Adriatic can also be of importance to the dense-water formation in the North Adriatic, as the inflow of saline Levantine Intermediate Water (LIW) into the Adriatic is correlated to it [11].

NAdDW, generated during the winter on the North Adriatic shelf, fills the bottom layer and then flows close to the western flank as a subsurface vein of dense water [10,12] towards the Middle Adriatic. Sigma-t values higher than 29.8 were measured in the Jabuka Pit (winter 1980/1981 [13]). As it is a depression (maximum depth of 280 m), a portion of NAdDW is accumulated there [10, 14-16], while the rest proceeds to flow further southeast [10,17] over the Palagruža Sill (approximately 160 m deep) towards the circular South Adriatic Pit (1200 m deep). The South Adriatic Pit is well documented as a place where deep convection is known to occur and Adriatic Deep Water (ADW) is generated [18-21], yet another important feature is a subsurface dense current (NAdDW current) occurring at the Italian shelf break during the spring season. The current can be traced on the shelf break up to the Bari Canyon [22]; then, violent mixing and sinking of NAdDW take place in the canyon [23-25]. A portion of NAdDW can be directly traced in the South Adriatic and Otranto Strait, while the rest is transformed to ADW during the deep-convection processes occurring there. ADW, together with modified NAdDW, flows out of the Adriatic through the Otranto Strait afterwards [26-28], towards the bottom layer of the Ionian Sea [29, 30]. Vilibić and Orlić [31] estimated direct contribution of NAdDW to the bottom outflow in the Otranto Strait to be 4-6% of total deep-water outflow in 1975; but indirect contribution (conversion to ADW) is at least twice as big as the direct contribution. Nevertheless, the percentage of outflowing NAdDW, as compared to ADW in the Otranto Strait, could probably be even larger, in particular during extreme dry and cold periods such as 1980-1983. NAdDW fraction reached average values higher than 20% in the South Adriatic Pit at that time, being preserved in 1985-1989 interval [22].

This papers endeavours to figure out the generation of NAdDW, by analysing three case studies: 1) winter 1981, followed by rather strong dense-water flow documented on the bottom of the Middle Adriatic [13], 2) winter 1987, when strong Bora event was recorded in January [32], and 3) winter 1989, when extremely high salinities occurred both in the South [22] and North [5] Adriatic.

2. – Materials and methods

The generation of NAdDW has been analysed on the basis of temperature and salinity data collected at stations 1 to 6 of the Po-Rovinj profile (fig. 1) on the monthly to seasonally time scale. The data comprise temperature and salinity measured at standard oceanographic depths (0 m, 5 m, 10 m, 20 m, 30 m, 2 m above the bottom) during the winters of 1981, 1987 and 1989, and also during the preceding summer and spring seasons, in order to explore preconditioning phases of the NAdDW generation.

All the data were collected by the Centre for Marine Research (CMR) of the Ruđer Bošković Institute at Rovinj. Temperature was measured by protected reversing thermometers (Richter and Wiese, Berlin, precision ±0.01°C), whereas salinity was determined using high-precision laboratory salinometers with accuracy of ±0.01. Additionally, surface heat, water and buoyancy fluxes for the Northern Adriatic and Po River discharges for 1980-1981 and 1986-1989 (fig. 2), calculated by [3], were discussed in order to quantify the processes at the air-sea and land-sea discontinuity responsible for the generation of NAdDW. Namely, lower heat and water fluxes lead to higher buoyancy

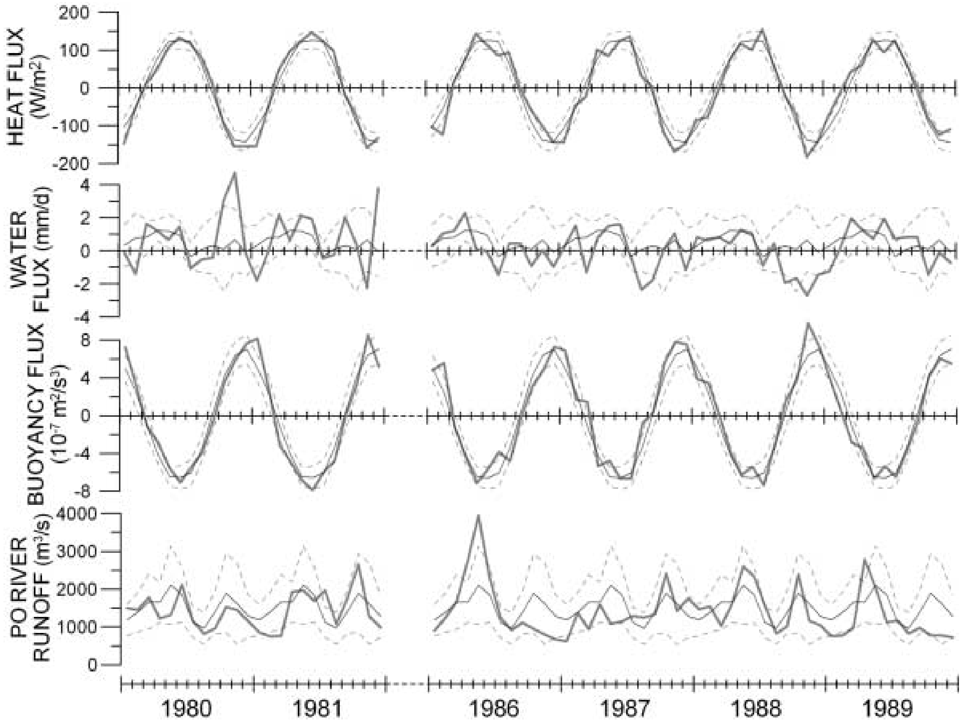

Fig. 2. – Time series of average monthly surface heat, water and buoyancy fluxes and Po River discharge rates during 1980-1981 and 1986-1989 periods (thick gray lines). The average values of all parameters in 1966-1992 period (after [3]) are shown in thin lines with one standard deviation limits given in dashed lines.

gain and result in higher density and larger quantity of the generated NAdDW.

3. – Results and discussion

Let us start with winter 1981. Two cruises were carried out on the Po-Rovinj transect, namely on 10 February and 25 March 1981. Temperature, salinity and sigma-t fields are displayed in fig. 3. The winter was characterized by rather strong heat loss and buoyancy gain in January (heat and buoyancy flux departured for 2 standard deviations from the mean, see fig. 2), favouring the generation of NAdDW, but the preceding and subsequent months were typified by the moderate values. The Po River runoff was a bit reduced than normal at that time, so that the fresh waters were probably pushed close to the western coast and did not influence the open North Adriatic. Large heat losses in January were the result of the position of pressure systems over Europe (fig. 4); namely, a low-pressure centre was situated over the Eastern Mediterranean whereas high pressure was spread over the Western Europe. As a result, very strong flow of cold and dry air occurred over the Adriatic, both from the North Europe and Siberia. Moreover, heat losses over the Adriatic were additionally intensified by the Bora wind which is usually linked to such distribution of pressure systems over Europe. So that, the cooling and homogenizing the water column were in progress at that time. In February salinity was

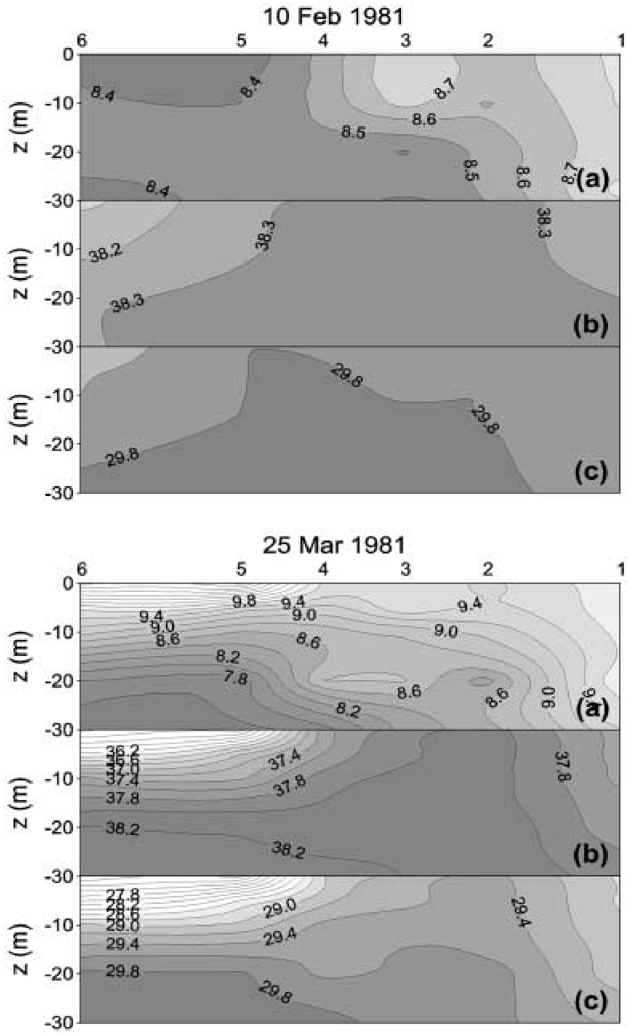

Fig. 3. – Vertical profiles of (a) temperature in °C, (b) salinity and (c) sigma-t values measured at the section Po-Rovinj on 10 February and 25 March 1981. Station numbers are marked on horizontal axis. Note that the transect changes its direction between stations 5 and 6.

a bit lower at station 6 than on the rest of transect, whereas distribution of sigma-t field clearly depicts cyclonic circulation (confirmed by computation of geostrophic currents, not shown). Warmer but not more saline waters were advected from the southeast along the eastern part of transect; therefore, there was probably no strong inflow of saline LIW in the Middle and North Adriatic previously.

A month later (25 March 1981, fig. 3) the situation changed completely. The Po River runoff increased in March, extending warmer and less saline waters over the surface of the western part of transect. At the same time, the eastern part of the transect is still characterised by saline waters, extending in the bottom layers towards the western coast. The densest (the most cold and most saline) water was observed at station 6 what

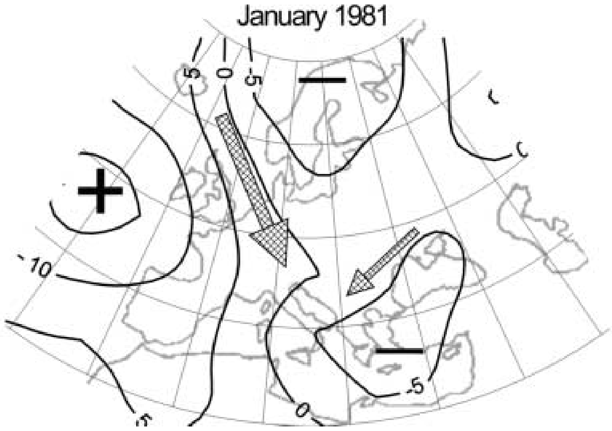

Fig. 4. – Monthly surface air pressure anomaly in hPa (departure from average values) over Europe computed from regular meteorological stations for January 1981 (after Deutscher Wetterdienst [33]). The arrows indicate pathways of air masses being transported as a result of air pressure gradient force. The centres of high (+) and low (−) pressure anomaly are marked too.

indicates that dense NAdDW waters were leaving the area following the Italian shore, being replaced by warmer waters advected from the southeast along the Croatian coast. Advected waters are warmer in general as the cooling in January produces colder water on the North Adriatic shelf than in the deeper Middle Adriatic [9, 14].

The situation in winter 1987 was different a bit, namely January and March were characterized by rather high heat loss and buoyancy gain fluxes (fig. 2), while Po River discharge was again lower than the usual. Herein the temperatures in early February were for almost 1°C lower at the western part of transect compared to the eastern part (fig. 5), whereas the isopycnals reveal dominantly anticyclonic circulation in the area. The densest water can be found near the bottom of the western side, denoting the leakage of freshly generated NAdDW in January towards the Middle Adriatic, as already found by [10]. A month later (24 March 1987), the situation was more complex. The computation of geostrophic currents (not shown) reveal coupled cyclonic-anticyclonic circulation, of which cyclonic gyre was positioned off the Po River delta. Surface layer was largely occupied by the Po River fresh water, whereas the intermediate layer (10–15 m) was filled by very cold ($t < 7.4$°C) but not saline ($37.0 < S < 37.6$) water mass. This water mass was probably formed in the early March during the strong cold outbreaks which took place at that time, while a bit lower salinity is a result of somewhat higher freshwater inflow occurring in February. Bottom layers of the western part of the transect were still occupied with the saline ($S > 37.8$) and very cold ($t < 7.4$°C) waters that were formed in January, while at the same time the advection of even more saline ($S > 38.0$) and warm ($t > 8.0$°C) waters can be found at the very bottom of the eastern part of transect.

Let us start the analysis of thermohaline properties in spring (fig. 6), when thermocline starts to develop rapidly in the North Adriatic. Just to point out, the development and seasonal changes of the thermocline (pycnocline), which can be seen here in temperature, salinity and density series, are the result of seasonal changes in heat fluxes and river discharges, which are the major driving forces on the seasonal scale in the North Adriatic [2,3]. Po River fresh waters can flood surface layers of the entire North Adriatic,

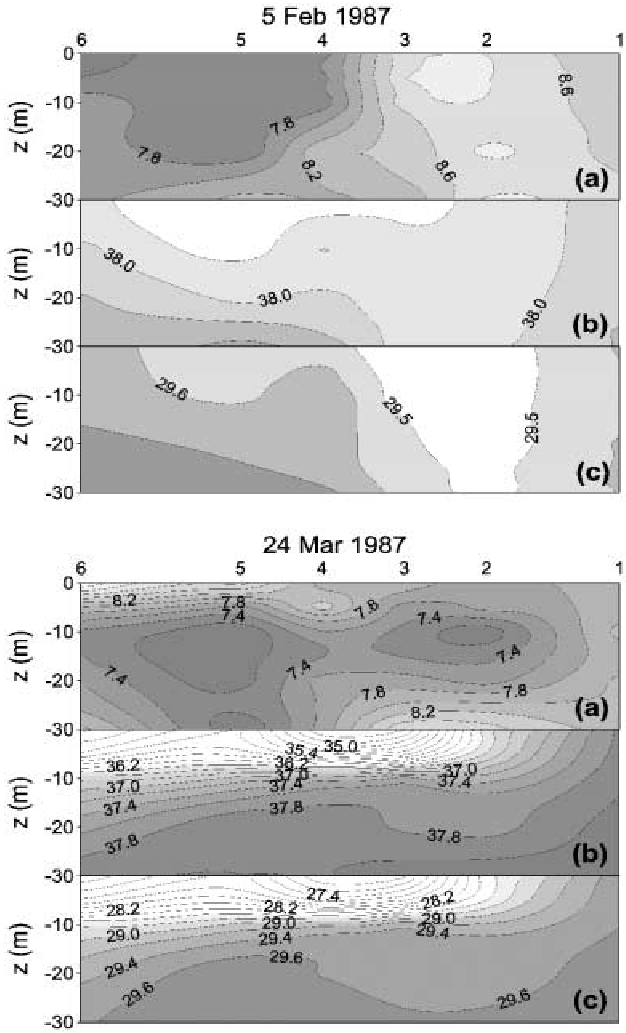

Fig. 5. – Vertical profiles of (a) temperature in °C, (b) salinity and (c) sigma-t values measured at the section Po-Rovinj on 5 February and 24 March 1987. Station numbers are marked on horizontal axis.

as happened in spring 1986 when discharge rates were rather high (about 2 standard deviations, see fig. 2), decreasing salinity to less than 35.0 on the whole transect. In the meanwhile, thermocline has been developed and deepened, with a bit higher values but also stronger vertical gradients at station 5 (not shown). Such situation remained till October at station 5, when the homogenisation of water column took place, bringing less saline and warmer waters to the bottom ($t \approx 16$°C, $S \approx 37.0$) near the Po River mouth. On the contrary, the homogenisation did not bring less saline waters to the bottom at station 2 (fig. 6), where salinity even increased a bit ($S \approx 37.9$), while temperature increased to about 16°C keeping a weak vertical stratification. After that, in December, the Po waters were pushed to the Italian coast, while the cooling brought down the

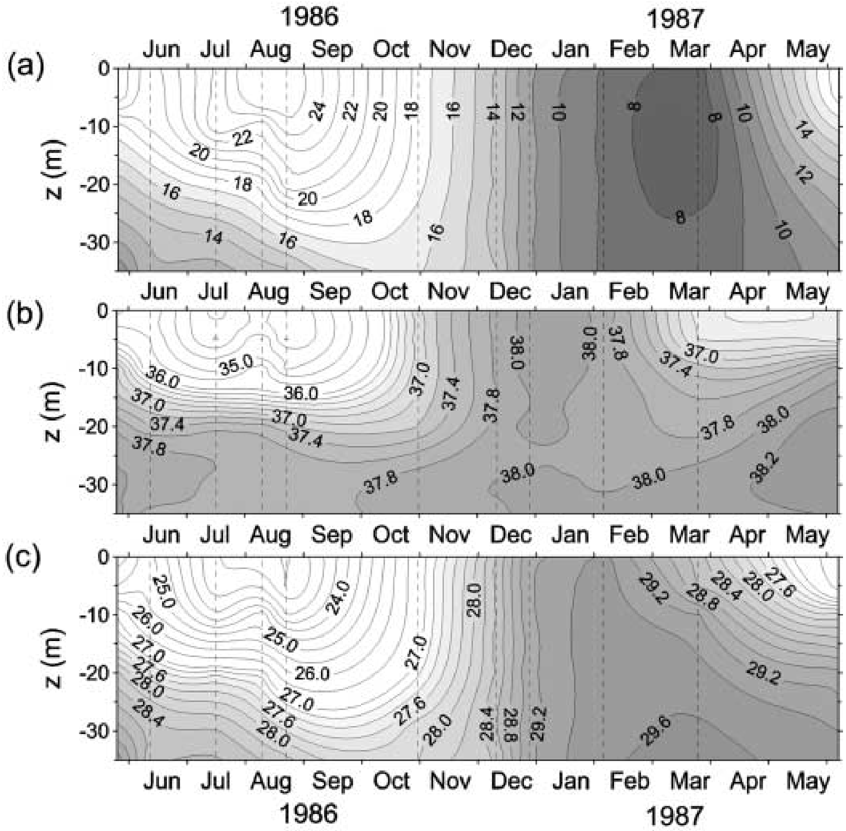

Fig. 6. – Time series of (a) temperature in °C, (b) salinity, and (c) sigma-t values measured at station 2 in the period May 1986-June 1987. Vertical dashed lines stand for the times when the data were collected at the station.

temperature to 8°C at the station 2 and to even 7°C at the station 5. In February, as stated before, the Po River increased its outflow from low to moderate one, flooding the surface layers of the whole transect. Nevertheless, high sigma-t values persisted in the forthcoming months near the bottom (29.4-29.6 in May/June), almost 1.0 higher than the ones observed on May/June of the previous year (28.6-29.0).

The last example (winter 1989) is characterized by rather high salinity that persisted at least since the previous spring season. Figure 7 shows temperature, salinity and sigma-t values between May 1988 and June 1989. Spring maximum of Po River runoff was moved for a month (May-July), affecting only the surface layer (up to 10 m depth), but persisting till November/December. Bottom layer was occupied with relatively saline waters at that time ($S = 37.8$–38.4), while quite sharp halocline stretched at 5–10 m depth. Therefore, even large heat losses in October (anomaly of about 2 standard deviations) did not destroy vertical salinity gradients, whereas temperature followed usual dynamics as documented for the previous case study (winter 1987). Salinity even increased its values in the subsequent months (December-January), particularly on the eastern part of the transect (fig. 7), as a result of advection of extremely saline waters from the southeast. In addition, water flux was directed towards the atmosphere (mean water flux was lower

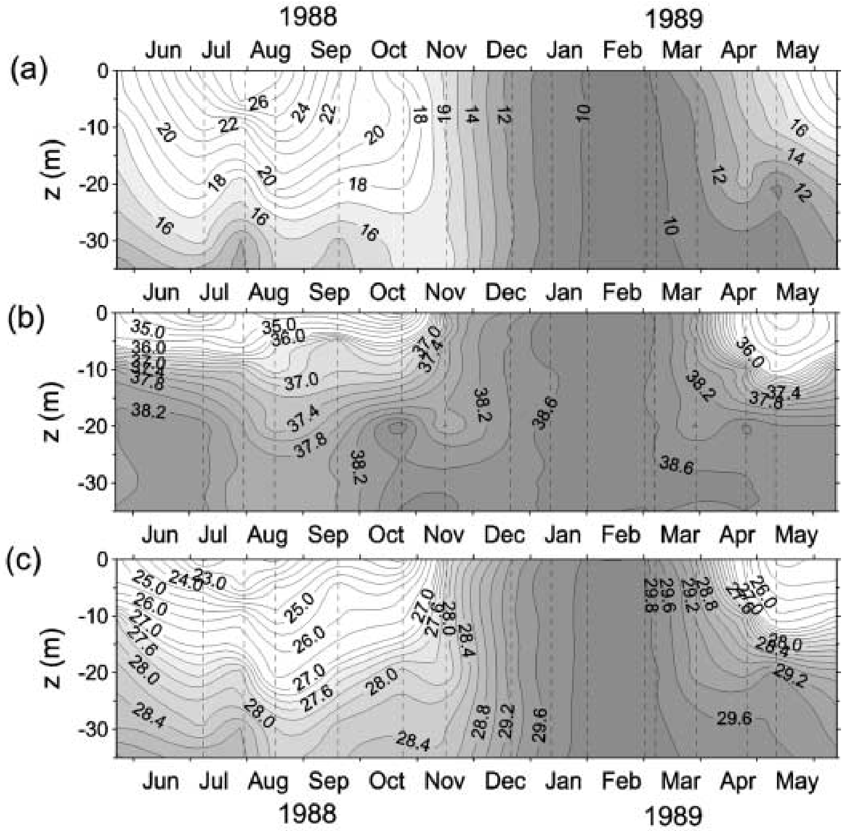

Fig. 7. – As in fig. 6, but for the period May 1988-June 1989.

for 1 standard deviation than average in the period September 1988-February 1989, see fig. 2), enlarging the salinity probably in the wider area. Namely, the period between 1987 and 1989 is characterized with the highest salinities documented in the South Adriatic in the 1967-1990 interval [22], extending its influence towards the Middle and North Adriatic. Therefore, due to the general cyclonic circulation in the Adriatic, these waters were brought to the Middle and North Adriatic, and the maximum in salinity equalled 38.79 (January cruise) on the Po-Rovinj transect. Additionally, atmospheric parameters, in particular air pressure gradient over the Adriatic, are generally correlated to the inflow of LIW in the Adriatic [11], so that it can also be of importance to the dense-water formation in the North Adriatic. The winter 1989 is such a case, but buoyancy gain was rather low during the generative period (January-March). Sigma-t values exceeded 29.8 in February at the station 5 (fig. 7), so very saline ($S > 38.6$) and relatively warm ($t \approx 10°$C) water mass were generated on the shelf. These waters have been probably moved southeastwardly near the bottom close to the Italian shore, reaching the Jabuka Pit where it has been partially accumulated. Such dynamics is generally confirmed by the measurements performed in the Jabuka Pit, as two types of NAdDW were distinguished there [10]: the first one characterized by low temperatures, and the second one typified by rather high salinities, and, naturally, the combination of these two types.

4. – Conclusions

The paper reports on three dense-water generation episodes in the North Adriatic, namely in winters of 1981, 1987 and 1989. The analyses include temporal and spatial profiles of temperature, salinity and density fields, combined with the surface heat, water and buoyancy fluxes computed for the region of interest.

The major element connecting all of the case studies is a decrease in river discharges below the normal values at least 4 months prior to the NAdDW generation, that is the period from September to January/February. Therefore, the impact of Po River waters to the open North Adriatic area is negligible, as the waters are confined very close to the western shore, resulting in somewhat higher salinities in the area and thus preconditioning to the eventual dense water generation during the subsequent winter. The generation usually occurs in January/February, being the result of enhanced surface buoyancy fluxes caused by the strong, dry and cold Bora wind. Such events happened in 1981 and 1987, when January heat losses were anomalous for more than one standard deviation. It should be pointed out that Bora events are of order of a couple of days, when daily heat losses can surpass 800 W/m^2 [3, 21], rapidly cooling and mixing the water column as well as increasing the salinity through the evaporative processes.

Somehow different preconditioning preceded the NAdDW generation in 1989. Herein the decrease in river discharges is coupled with anomalously low average water flux in whole 1987 and 1988, and especially in the period between September 1988 and January 1989, when water flux was lower than one standard deviation during all of 5 months. The consequence is a salinity increase in the whole Adriatic at that time [22], so the very saline waters were advected in the North Adriatic being not destroyed with the river-originated water. Yet, relatively low heat losses occurred in January/February, producing fairly warm but very saline dense water.

To conclude, the different processes acting in the examined years, namely enhanced heat losses and atmosphere-oriented water flux, were efficient in producing very dense water in the North Adriatic. The density (sigma-t) values of newly generated NAdDW in all three cases surpassed 29.7. Consequently, it probably influenced and changed biogeochemical characteristics of a large part of the Adriatic Sea; the denser is NAdDW the higher are changes and the larger is the water volume affected by the changes.

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