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# A study of the hydrographic conditions in the Adriatic Sea from numerical modelling and direct observations (2000–2008)

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**Abstract.** The inter-annual variability of Adriatic Sea hydrographic characteristics is investigated by means of numerical simulation and direct observation. The period under investigation runs from the beginning of 2000 to the end of 2008. The model used to carry out the simulation is derived from the primitive equation component of the Adriatic Forecasting System (AFS). The model is based on the Princeton Ocean Model (POM) adapted in order to reproduce the features of the Adriatic. Both numerical findings and observations agree in depicting a strong inter-annual variability in the entire Adriatic Sea and its sub-basins. Nevertheless, two model deficiencies are identified: an excessive vertical/horizontal mixing and an inaccurate representation of the thermohaline properties of the entering Mediterranean Waters. The dense water formation process has been found to be intermittent. In addition to inter-annual variability, a long-scale signal has been observed in the salinity content of the basin as a consequence of a prolonged period of reduced Po river runoff and high evaporation rates. As a result, the temperature and salinity of the northern Adriatic dense water vary considerably between the beginning and the end of the period investigated.

## 1 Introduction

The hydrographic characteristics of the Adriatic Sea (Fig. 1) are known to be subject to great spatial and temporal (both seasonal and inter-annual) variability. The nature of this variability is related to the characteristics of its geometry, its geographical position, the geography of the surrounding areas and, clearly, to the surface and lateral forcing functions acting on the basin. The Adriatic Sea extends northwest from 40° to 45°5′ North, with an extreme length of about 800 km and an average width of about 160 km. The southern limit is delimited by the Strait of Otranto, which connects it to the south with the Ionian Sea.

The northern part is characterised by a shallow mean depth (about 30 m) with a very weak bathymetric gradient (Russo and Artegiani, 1996). The central part of the basin, spanning approximately from the 100m contour to the Palagruža sill (about 170 m depth), is characterised by two depressions, the Pomo (or Jabuka) Pits, having a maximum depth of about 270 m. The southern part of the Adriatic Sea extends from the Palagruža sill to the Otranto sill; both western and eastern coasts have a narrow continental shelf and a steep continental slope reaching a maximum depth of 1270 m (often referred to as the south Adriatic Pit) (Russo and Artegiani, 1996).

The river runoff is a significant component of the basin hydrological cycle and is responsible for its net freshwater gain (Raicich, 1994, 1996), implying an average estuarine thermohaline circulation. The freshwater discharge is concentrated particularly in the northern sub-basin, where the river Po constitutes the main freshwater source. However, in the southern basin, Albanian and Croatian rivers provide a significant freshwater input (Raicich, 1994; Oddo et al., 2005). The total evaporation ranges from 0.98 to 1.34 m yr$^{-1}$ (Raicich, 1996), the seasonal oscillation reaches the maximum values during October–February period and minima during April–September. The annual cycle of precipitation exhibits a maximum in autumn and a marked minimum in summer, values ranges from 0.7 to 1.02 m yr$^{-1}$ depending on the dataset and methods used (Raicich, 1996).

Prevailing wind regimes are the Bora (northeast), the Sirocco (southern) and Maestral (western). The Sirocco wind, characterized by a high humidity content, blowing from the southeast drives the sea level of the north Adriatic Sea. The Bora wind, which can be dry, cold, and strong,

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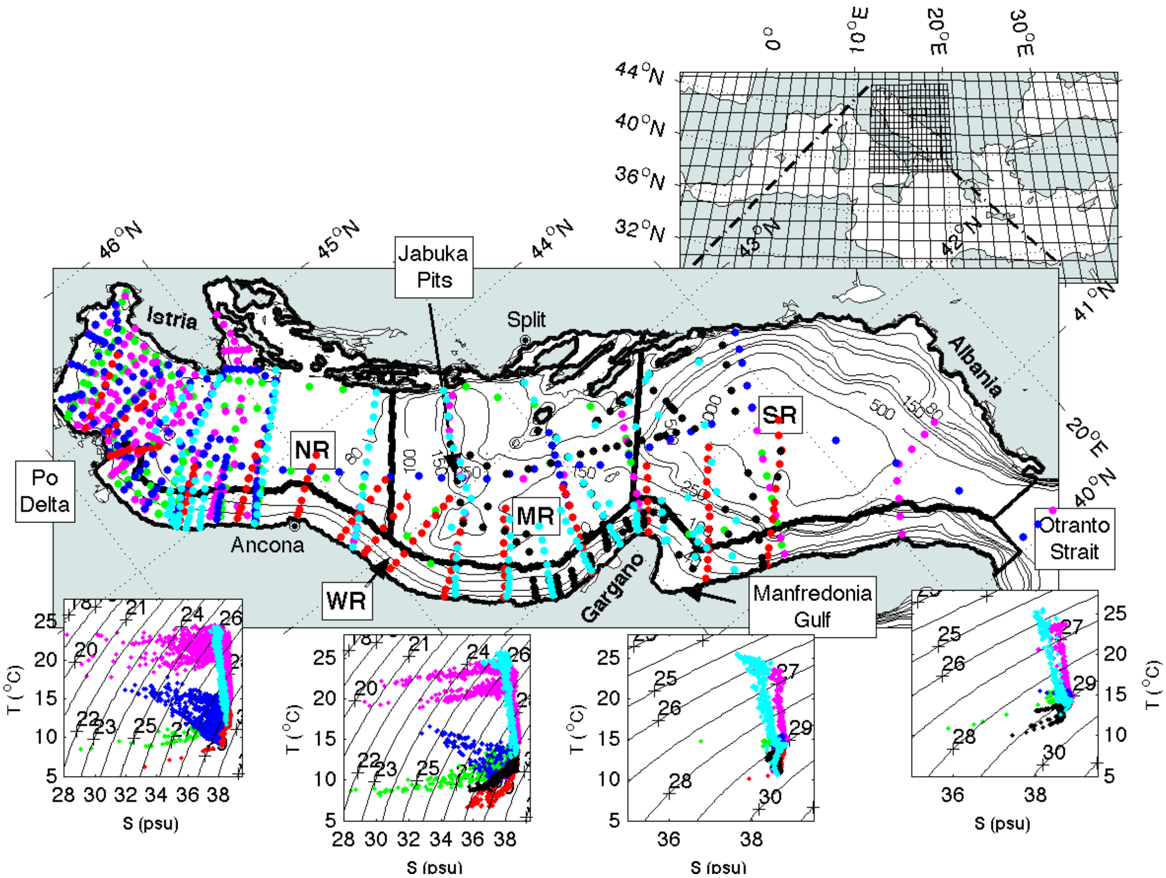


**Fig. 1.** Adriatic coastline, bathymetry and sub-region boundaries are shown (WR = WACC region; NR = Northern Adriatic Region; MR = Middle Adriatic Region, SR = Southern Adriatic Region). Locations of CTD sampling are also shown. Green dots indicate CTD positions for the 2001 cruise; magenta dots the 2002 cruise; blue dots 2003; red, black and cyan dots indicate first, second and third 2006 cruises, respectively. Exact dates are listed in Table 1.

blows over the Adriatic Sea from the north and north-east. In summertime, besides local breezes, the dominant wind – the Maestral – comes from the northwest.

The climatological annual heat budget of the Adriatic basin is negative. Several values have been proposed in the literature; these vary as a consequence of different methodologies used and different periods investigated. Mantziafou and Lascaratos (2008) found values ranging between $-6$ to $-34\,\mathrm{W m^{-2}}$; similar values have also been suggested by Cardin and Gacic (2003); Maggiore et al. (1998) suggest values in the range between $-5$ and $-10\,\mathrm{W m^{-2}}$; Chiggiato et al. (2005) by comparing different data source and different computational methods found values in the range of $-18$ and $-54\,\mathrm{W m^{-2}}$. All the authors agree in suggesting that the total heat flux exhibits a strong inter-annual variability, particularly marked during the periods of negative heat budget (autumn–winter).

The resulting general circulation of the Adriatic Sea is cyclonic and highly variable according to the season (Artegiani et al., 1997a, b; Malanotte-Rizzoli and Bergamasco, 1983; Zavatarelli et al., 2002; Zavatarelli and Pinardi, 2003). The climatological circulation pattern is composed of well-known currents and gyre structures (Artegiani et al., 1997b; Poulain, 2001; Zavatarelli et al., 2002; Zavatarelli and Pinardi, 2003). The three main gyres (Southern, Middle and Northern Adriatic Gyre, Artegiani et al., 1997b) are interconnected (with seasonally varying characteristics) by two coastal currents, one flowing southward along the Italian coast from the Po delta to the Strait of Otranto (Western Adriatic Coastal Current or WACC), the other flowing northward from the Strait of Otranto along the eastern coast and reaching the central Adriatic (Eastern Southern Adriatic Current or ESAC) (Oddo et al., 2005).

The Adriatic Sea is usually divided into four sub-basins (Artegiani et al., 1997a, 1999): the WACC region, between the Po delta and Strait of Otranto along the Italian coast; the Northern region, delimited by 100 m bathymetry north of the Jakuba Pit; the Middle Adriatic region, with the southern boundary across the basin starting from the Gargano Peninsula; and the Southern Adriatic region. The limits of these sub-regions are depicted in Fig. 1.

The Adriatic Sea has been the main source of dense water masses for the Eastern Mediterranean basin for many decades, until the late nineteen-eighties, when the Aegean Sea became the main supplier of Eastern Mediterranean Dense Water (EMDW) (Roether et al., 1996). Nevertheless, it has been demonstrated that although the Adriatic contribution to EMDW might have been temporarily reduced, it has never ceased (Klein et al., 2000; Nardelli and Salusti, 2000; Sellschop and Alvarez, 2003).

Dense waters are formed locally in the Northern, Middle and Southern Adriatic. However, while the formation of the dense water mass in the Southern and Northern sub-basins is reasonably well detected in the hydrographic observations, the local formation process in the Middle sub-basin is not well documented from in-situ data (Bergamasco et al., 1999). The Northern Adriatic dense waters (hereafter NAdw) are formed in winter during outbreaks of the bora winds that provoke strong surface cooling and evaporation processes (Bergamasco et al., 1999), and are also at the same time under the influence of the large Po river runoff. NAdw are thus characterized by a wide range of temperatures and salinities depending on the surface forcing characteristics of the formation period, and sigma-*t* is usually considered to be higher than 29.2 kg m$^{-3}$. Temperature ranges between 8 and 12.8 °C, while salinity can vary between 38.1 and 38.5 psu (Supic and Vilibic, 2006; Hendershott and Rizzoli, 1976; Artegiani and Salusti, 1987; Zore-Armanda, 1963; Artegiani et al., 1997a). This dense water mass is known to move southward along the Italian coast (Artegiani et al., 1989) and exits from the Strait of Otranto into the Ionian Sea (Bignami et al., 1990).

In the Middle Adriatic, a winter convective overturning process mixes the cold and fresh NAdw with the warm and salty Modified Levantine Intermediate Waters (MLIW) intruding in the basin. This mixing process forms the Middle Adriatic dense water (MAdw). MAdw characteristic temperature and salinity range between 11–12°C and 38.1–38.62 psu (Zore-Armanda, 1963; Artegiani et al., 1997a; Vilibic and Orlic, 2002). However, the penetration of convection all the way to the bottom of the pit is not clear from the observations, and does not appear to occur regularly every winter (Bergamasco, 1999). Thus, in addition to the intensity of winter cooling, the stratification characteristics of the intermediate and deep water masses may play a very important role in the dense water mass characteristics of the central basin (Bergamasco, 1999).

The Southern Adriatic dense waters (SAdw) are formed in the SA gyre, where deep open ocean convection occurs to depths of about 750 m (Ovchinnikov et al., 1985). They are mainly formed by the mixing of the surface waters with the relatively warmer and more saline MLIW and with the colder and fresher waters generated in the northern sub-basins. Thus, the SAdw temperature and salinity are generally in the range between 12.7–13.5 °C and 38.5–38.7 psu, respectively (Zore-Armanda, 1963; Artegiani et al., 1997a; Vilibic and Orlic, 2002; Mantziafou and Lascaratos, 2008). SAdw are recognized as one of the major contributors to the ventilation of deep waters in the whole Eastern Mediterranean (Roether and Schlitzer, 1991; Steinfeldt, 2004; Vilibic and Supic, 2005). The dense-water formation processes in the Southern Adriatic show a significant inter-annual variability (Gacic et al., 2002b; Mantziafou and Lascaratos, 2008).

Formation rates of the Adriatic dense water have been investigated in several studies (Artegiani et al., 1989; Artegiani and Salusti, 1987; Vested et al., 1998; Mantziafou and Lascaratos, 2004, 2008). Numerically- and observationally-based estimates of NAdw formation rates suggest values of about 0.03–0.07 Sv; similar derivations for the MAdw are about 0.06–0.07 Sv, whereas in the Southern Adriatic, dense water formation rate ranges from 0.18 to 0.64 Sv. In all three sub-basins, large inter-annual variability in the dense water formation rate has been observed (Mantziafou and Lascaratos, 2008; Vilibic and Supic, 2005).

The water exchange through the Strait of Otranto between the Adriatic and the Ionian Sea has been the subject of a series of experimental investigations and also of some numerical studies, proposed literature data for Strait of Otranto transport are variables depending on the data and methods used in the computation, however recent estimates suggest values of about $1\times10^6$ m$^3$ s$^{-1}$ leading to a turnover time of the order of 1 yr (Franić, 2005).

This work explores the inter-annual variability of the Adriatic Sea hydrographic conditions connected to atmospheric forcing through the analysis of numerical simulation results and direct and remote observations. We concentrate on the period 2000–2008, during which several dedicated oceanographic cruises extensively monitored the Adriatic Sea, and satellite-derived Sea Surface Temperature data were also available. The Adriatic Sea hydrodynamic is simulated by a three-dimensional model already used by Oddo et al. (2005) to investigate the response of the Adriatic Sea circulation to variable atmospheric forcing; this was later implemented in the operational chain of the Adriatic Forecasting System (Oddo et al., 2006) and continuously developed within the framework of international projects (Guarnieri et al., 2010). The version of the model used in this work has been developed within the ECOOP (European COastal sea OPerational observing and forecasting system) project. Section 2 gives a general description of the model's implementation. In Sect. 3 data and methods are presented, in Sect. 4 the model results and available observed data are discussed. Summary and conclusions are offered in the last section.

## 2 Model description

Numerical integration was carried out using a pre-operational version of the Primitive Equation module of the Adriatic Forecasting System (AFS, http://gnoo.bo.ingv.it/afs, Oddo et al, 2006). This model is based on the Princeton

Ocean Model (POM, Blumberg and Mellor, 1987), and was implemented with a regular horizontal grid having approximately 2.2 km resolution (1/45° of latitude and longitude) and 27 sigma layers in the vertical. The model lateral open boundary is south of the Strait of Otranto along the 39° parallel. The bathymetry was obtained from US Navy data (horizontal resolution 1/60°); the minimum depth is 10 m and between 0 and 10 m depth the topography slope was flattened (that is, the modelled Adriatic has a realistic coastline).

The surface fluxes are interactively computed using model predicted sea surface temperature and realistic atmospheric data. The model uses the same bulk formulae to compute surface fluxes as described in Oddo et al. (2005). The atmospheric data (air temperature, relative humidity, cloud cover, mean sea level pressure and both wind components) are analyses with 0.5° horizontal resolution and 6 h frequency provided by the European Centre for Medium-Range Weather Forecasts (ECMWF).

Real freshwater input was used in the surface boundary condition for the vertical velocity, which reads:

$$w|_{z=h} - \left(\frac{\partial h}{\partial t} + \overline{v}\cdot\nabla h\right)\Big|_{z=h} = (E-P-R)$$

where $w$ is the vertical velocity, $h$ is the surface elevation, $E$ is the evaporation, $P$ is the precipitation and $R$ indicates the river runoff. The two critical components of the water flux are the precipitation and the runoff. For precipitation we use the climatological monthly mean values from Legates and Wilmott (1990) according to the operational procedures. For river runoff, daily observed values are used for the Po while only monthly climatological values are considered for the other forty-eight sources (31 rivers and springs) (Raicich, 1994). Following the hypothesis made in Oddo et al. (2005) concerning a possible overestimation of these climatological values in the past ten years, we reduced the prescribed data for the Croatian part by a factor of 0.3 (this factor derives from sensitivity studies).

The Po runoff is specified daily taking the values at the closing point of the drainage basin (Pontelagoscuro) and partitioned over several grid points approximately representing the proportion of the fresh water discharge through the different branches of the delta (Provini et al., 1992).

Thus, inter-annual variability of the surface water (and consequently salinity) flux is driven only by variation in the evaporation flux and in Po river regimes (which, however, is more than 1/3 of the total runoff of the Adriatic Sea).

A further difference with the previous POM simulations in the Adriatic Sea (Oddo et al., 2005, 2006; Zavatarelli et al., 2002; Zavatarelli and Pinardi, 2003) is related to the advection scheme. A flux limiting advection scheme (MUSCL, Monotonic Upwind Scheme for Conservation Laws, Van Leer, 1979) was implemented, allowing a better reproduction of the horizontal and vertical gradients.

In order to reduce the pressure gradient error associated with sigma coordinates, a horizontally averaged density is subtracted before computing the baroclinic integrals (Mellor et al., 1998).

For initial and lateral boundary conditions (temperature, salinity and velocity fields), data are taken from a 1/16° horizontal resolution operational analysis of the Mediterranean Forecasting System (MFS, Tonani et al., 2008). The lateral boundary data are provided daily. The definition of the nested open boundary conditions is based on Oddo et al. (2005) and Oddo and Pinardi (2008).

The simulation spans the period from January 1999 to December 2008; results for the year 1999 are not shown as this year is considered to represent the model spin up.

## 3 Data and methods

Based on the simulated and observed oceanographic characteristics of the Adriatic Sea (Artegiani et al., 1997a and b), 4 regions were defined and analysed separately: the WACC region, between the Po delta and Strait of Otranto along the Italian coast; the Northern region, delimited approximately by 100 m isobaths north of the Jabuka Pit; the Middle region, with the southern boundary across the basin starting from the Gargano Peninsula; and the Southern Adriatic region. The limits of these sub-regions are depicted in Fig. 1. It has to be stressed that the WACC region is defined here as a relatively wide area along the Italian Peninsula potentially also including the western limbs of the cyclonic gyres. This definition is similar to that adopted by Poulain (2001) but differs from that used in Artegiani et al. (1999) and Hopkins et al. (1999).

In addition to satellite-derived Sea Surface Temperature (Marullo et al., 2007), a total of 1617 CTD stations, collected between January 2001 and August 2006, were used to support the model results. However, as hydrographic observations are sparse in space and time (Table 1 gives the total number of CTD casts per region and per year, while in Fig. 1 the sampling positions are shown), direct calculation of inter-annual variability of basin and sub-basin averages will be affected by a large sampling error. When they were compared, model results were sampled in the grid point nearest to the sampling position and then both observations and numerical results were averaged over the intervals listed in Table 1.

## 4 Results and discussion

### 4.1 Heat and water fluxes

The analysis of the estimated surface forcings for the period under examination shows an important inter-annual variability in both heat (in Fig. 2 the time series of the monthly means total surface heat flux are shown, while in the upper panel of Fig. 3 the advective heat flux at the Strait of Otranto is drawn)

**Table 1.** Number and time intervals of CTD sampling for each year.

| | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|
| WACC | / | 28 Jan–10 Feb (52) | 16 Sep–6 Oct (111) | 28 Apr–2 May (37) | / | / | 15–27 Jan (59)<br>3–21 Mar (81)<br>14–27 Aug (75) | / | / |
| North | / | 28 Jan–10 Feb (162) | 16 Sep–9 Oct (489) | 27 Apr–4 May (159) | / | / | 14–20 Jan (44)<br>14–18 Aug (45) | / | / |
| Middle | / | 4 Feb–7 Feb (24) | 20 Sep–10 Oct (25) | 27 Apr (17) | / | / | 19–22 Jan (24)<br>5–22 Mar (44)<br>17–29 Aug (39) | / | / |
| South | / | 5 Feb–6 Feb (13) | 19 Sep–11 Oct (24) | 26–27 Apr (12) | / | / | 25–27 Jan (22)<br>2–22 Mar (33)<br>16–26 Aug (19) | / | / |

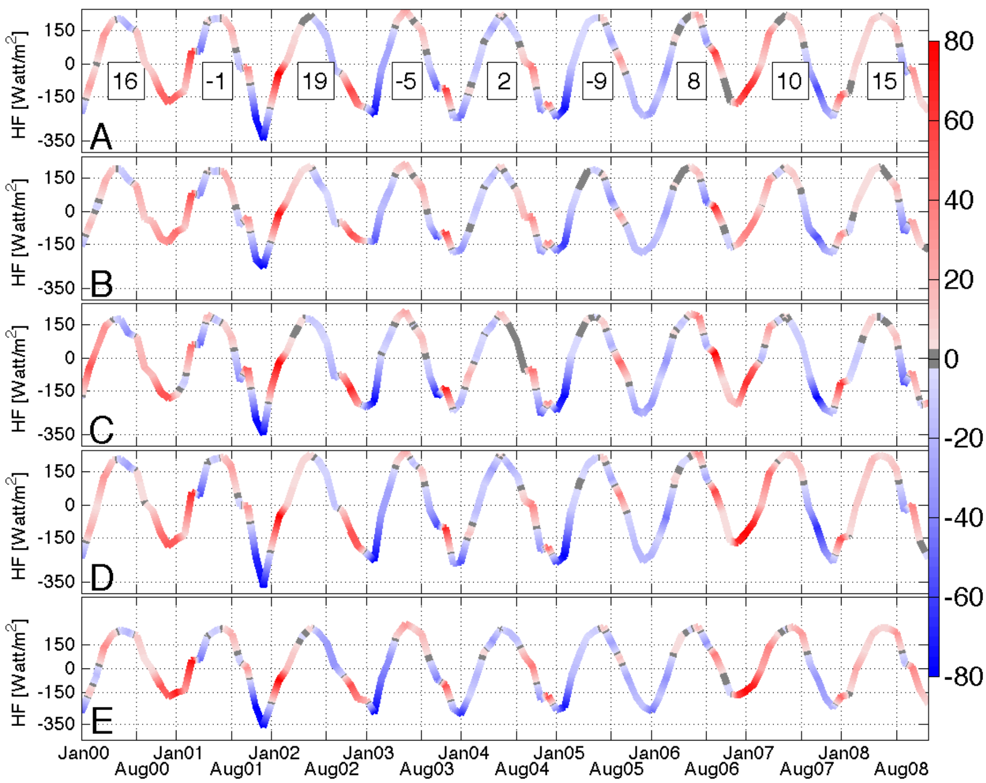


**Fig. 2.** Monthly time series of total Heat Flux, units are W m$^{-2}$. Colour indicates monthly anomaly values. **(A)**: whole Adriatic Sea; **(B)**: WACC region; **(C)**: Northern Adriatic Region; **(D)**: Middle Adriatic Region; **(E)**: Southern Adriatic Region.

and freshwater fluxes (Fig. 3, bottom panel, presents the Po river runoff and Fig. 4 the time series of the evaporation rate).

In the figures, ordinates indicate the monthly values, while colours indicate the amplitude of the anomalies calculated using the monthly climatology obtained from the same simulation. In agreement with previous findings (Oddo et al., 2005; Mantziafou and Lascaratos, 2008) the total surface heat flux anomaly is larger during cooling episodes (from October to March) than in periods of net heat gain. In general, the spring-summer (from May to August) heat gain does not change significantly from year to year having anomalies ranging between ±20 W m$^{-2}$. On the contrary, the autumn and winter cooling exhibits a strong inter-annual variability mainly due to the latent heat flux (not shown) component of the surface heat balance.

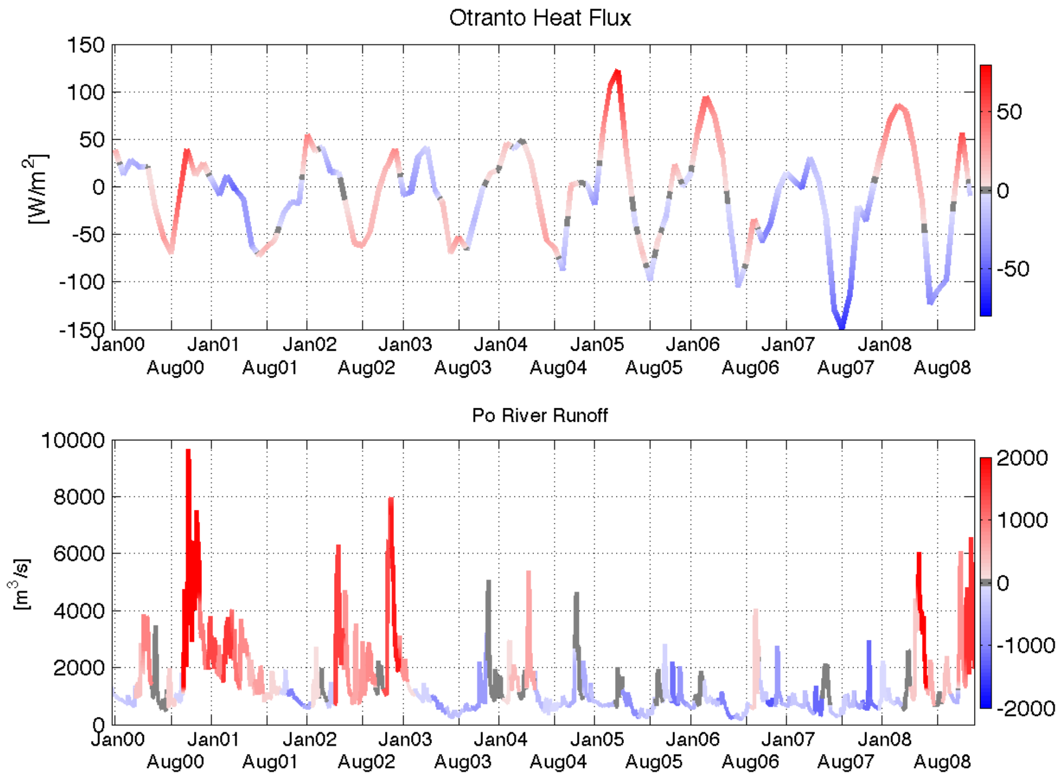


**Fig. 3.** Top panel: monthly time series of advective heat flux through Strait of Otranto, units are W m$^{-2}$ and colour indicates monthly anomaly values. Bottom panel: daily time series of Po river runoff, units are m$^3$ s$^{-1}$, colour indicates monthly anomaly values.

The mean annual surface heat budget of the basin oscillates between negative and positive values (Fig. 2a), varying from $-9$ Wm$^{-2}$ in 2005 to 19 Wm$^{-2}$ in 2003. Unlike previous studies (Gacic et al., 2002a and b; Manca et al., 2002; Maggiore et al., 1998; Chiggiato et al., 2005; Cardin and Gacic, 2003; Mantziafou and Lascaratos, 2008) the surface heat flux averaged over the entire simulated period (January 2000 to December 2008) is slightly positive. There are several possible sources for this difference: primarily, it is worth mentioning that all the previous studies analysed different periods (mostly ranging between 1990 and 1999, with the sole exception of Mantziafou and Lascaratos 2008 who also studied the nineteen-eighties); in addition there are differences in the atmospheric data sets, in the bulk formulae used, in the Sea Surface Temperature (SST) data, as well as possible deficiencies in the model (and its set-up) used in the present study. Unfortunately, the lack of observational field does not allow a direct validation of the model heat budget estimates.

However, the year-to-year pattern is similar in all subbasins, with the WACC region (Fig. 2b) characterized by the smallest amplitude of both seasonal and inter-annual variability.

In all the basins, the largest anomaly is detected in Autumn 2001 (November and December) with a seasonal (seasons are defined according Artegiani et al., 1997. Winter: January to April; Spring: May and June; Summer: July to October; Autumn: November and December) heat loss of about $-295$ Wm$^{-2}$, ranging from $-315$ Wm$^{-2}$ in the Northern region to $-234$ Wm$^{-2}$ in the WACC region. Climatological estimates for the same season are smaller (i.e. Maggiore et al., 1998 suggest values of about $-225$ Wm$^{-2}$). During the same period advective heat flux at the Strait of Otranto (Fig. 3, upper panel) is negative ($-17$ Wm$^{-2}$), thus acting in the same direction as the surface heat fluxes and amplifying the overall cooling of the basin.

Winters between 2003 and 2006 are characterized by large heat losses that are particularly marked during January and February. With the sole exception of the winter 2003, a contemporaneous net positive advective flux at the Strait of Otranto is observed, partially compensating the surface heat losses. Autumns 2005 and 2007 are also characterized by large heat losses but with different dynamics at the Strait of Otranto. During November and December 2005 the advective Otranto contribution to the heat budget is positive (+12 Wm$^{-2}$), while during the same months in 2007 a net heat loss of 20 Wm$^{-2}$ characterizes the model results. The advective contribution can thus strongly influence the thermodynamic of the Adriatic system, amplifying or mitigating the effect of the surface heat exchanges. The period between autumn 2006 and winter 2007 is characterized by weaker heat losses at the surface; in the Northern region

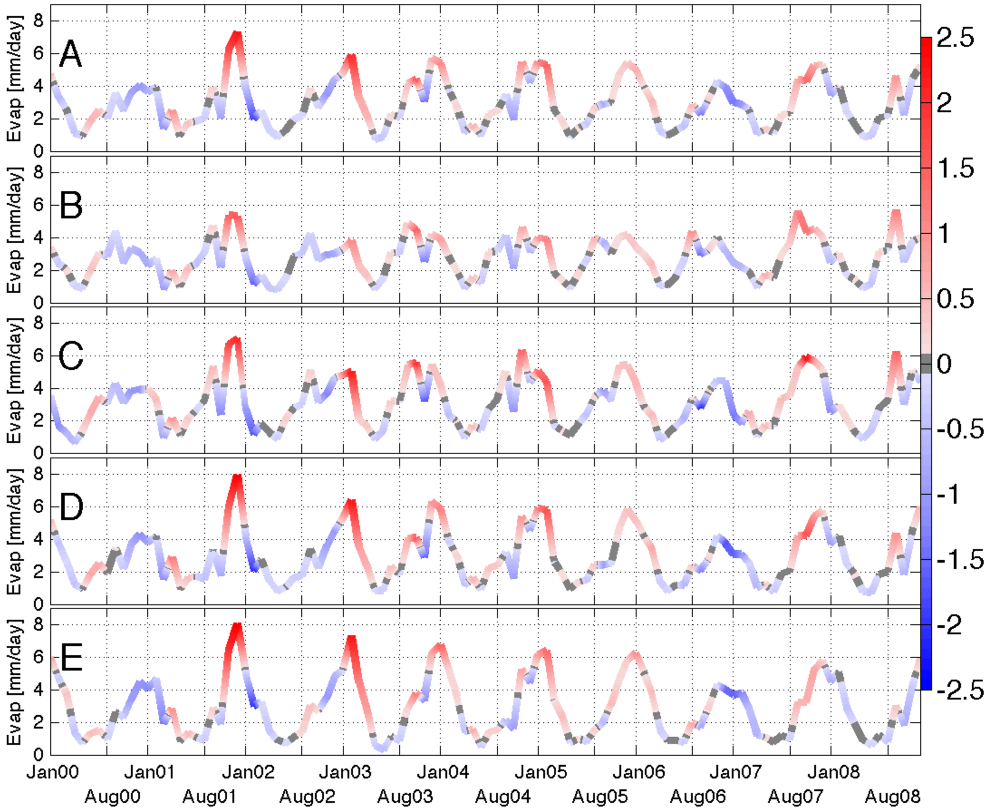


**Fig. 4.** Monthly time series of Evaporation rate, units are mm $day^{-1}$. Colour indicates monthly anomaly values. **(A)**: whole Adriatic Sea; **(B)**: WACC region; **(C)**: Northern Adriatic Region; **(D)**: Middle Adriatic Region; **(E)**: Southern Adriatic Region.

this behaviour is particularly strong in autumn, while in the Middle and Southern sub-basins it is more relevant in winter (2007) and persists until summer.

As in previous studies (Oddo et al., 2005), in the period between August 2000 and March 2001 surface heat fluxes are continuously above the climatological values, with a stronger warming during summer and a weaker cooling in autumn and winter. During these 8 months surface heat flux anomaly is on average 30 $Wm^{-2}$, however the extended length of this episode has largely affected the thermohaline characteristics of the basin inhibiting the winter cooling of the Adriatic waters and the consequent dense water formation process.

Starting from 2005 the seasonal amplitude of the heat flux through the Strait of Otranto grows, reaching values almost twice as high as in the previous period; however, the annual mean does not differ significantly between the two periods. The values of the Otranto mass fluxes (not shown) are slightly higher than previous numerical (Mantziafou and Lascaratos, 2008) and observational (Gacic et al., 1996) estimates, ranging between 1.3 Sv in 2001 and 1.7 Sv in 2008.

The large inter-annual variability depicted in the total heat flux is mainly due to the variations in the latent heat flux component and consequently to the evaporation rate (Fig. 4). The seasonal cycle of the evaporation rate (Fig. 4) is stable over the years simulated, showing the largest inter-annual variability during the autumn-winter period (and thus strongly contributing to the inter-annual variability of the total heat flux). Starting from autumn-winter 2001–2002 and until autumn-winter 2005–2006, a large evaporation rate positive anomaly is diagnosed by the model during all the cool seasons. This anomaly is larger in the Southern basin than in the coastal areas (WACC and Northern regions). However, in terms of water balance, 2001 and 2002 are characterized by a very large Po river runoff (Fig. 3 bottom panel), compensating the large mass loss occurring at the surface. In the period between 2003 and 2007, on the other hand, the Po regime (Fig. 3 bottom panel) is always below the climatological mean.

Water mass exchanges at the Strait of Otranto also play a crucial role in the salinity budget of the Adriatic Sea. The relatively fresh waters formed locally, spilling as bottom density currents through the Otranto sill, are compensated by an inflow at intermediate depths of waters of Mediterranean origin. Among others, the Modified Levantine Intermediate Water is fundamental in conditioning the thermohaline characteristics of the Adriatic Sea (Zore-Armanda, 1969; Malanotte-Rizzoli and Hecht, 1988; Russo and Artegiani, 1996). The Hovmoeller diagram of the modelled salinity

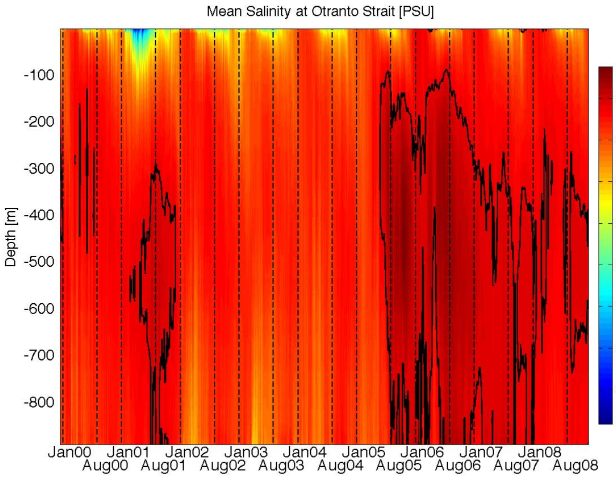


**Fig. 5.** Hovmoeller diagram of modelled mean salinity profile at Strait of Otranto. Y-axis indicates depth in metres; X-axis indicates time and colour indicates salinity in PSU. The solid black line indicates water having salinity content larger than 38.68 psu.

profile zonally averaged along the Strait of Otranto is shown in Fig. 5. The diagram shows low salinity at surface and bottom layers, indicating the outflow of fresh and dense waters, and high salinity at intermediate depths. The black solid line identifies the MLIW and thus a source of salty waters for the Adriatic Sea. The presence of the salty MLIW is irregular. During summer 2000 a small quantity of MLIW is found between 200 and 400 m depths; during summer 2001 a larger amount of MLIW is present at deeper layers. Starting from winter 2002 and until summer 2005 MLIW is absent. Summers 2005 and 2006 are characterized by a noticeable presence of very salty MLIW reaching 800 m depth. Later in 2006 the signal weakens, having a less pronounced salinity maximum, and it tends to disappear in late winter 2008. The described inter-annual variability can be ascribed to the dense waters productions in the Aegean Sea and their effect on the pathway of the LIW (Malanotte-Rizzoli et al., 1999). It is worth mentioning that lateral boundary data are provided by the MFS operational system (Tonani et al., 2008), and thus the number and position of assimilated data, which strongly influence the quality of the operational products, can vary considerably from year to year. However, as will be discussed in the following section, there is observational evidence of MLIW intrusion during late summer 2002.

Again, it is worth to point out that the inter-annual variability in the water budget includes only Po river runoff, evaporation rate and Otranto mass exchanges, since all the other components (precipitation and all the other rivers) are climatological.

## 4.2 Sub-basin temperature and salinity

The time series of volume averaged temperature for each sub-region and for the whole basin are shown in Fig. 6. As with Figs. 2–3 and 4, the abscissa indicates monthly values, while colours indicate the monthly anomalies computed against the monthly climatology obtained from the simulation.

Starting from late summer 2000 and until winter 2003, the basin-averaged volume temperature is constantly higher than the climatological values. This permanent anomalous condition strongly depends on the high warming rate simulated during spring 2000 and the missing cooling in the autumn-winter 2000–2001 seasons (Oddo et al., 2005). The basin volume temperature rise between the two annual minima in 2000 and 2001 (0.8 °C) is large enough to mitigate the effect of the strong cooling depicted during autumn 2001 and the volume-averaged temperature persists above the climatological values until spring 2003. Year 2003 is a transition period between almost 3 consecutive years of positive anomalies and 3 yr of negative anomalies. The first positive period is characterized by relatively short intervals of strong anomalies in the surface fluxes, on the other hand the second period (2004–2006), characterized by negative anomalies, is stable with minor year-to-year differences. Like 2000–2001, the period spanning from autumn 2006 to summer 2007 is characterized by weak cooling and strong warming, and thus the volume-averaged temperature minimum in 2007 (occurring on February) and maximum (occurring in late August) are similar to those occurring in 2002.

The described inter-annual variations are strongly modulated in the different Adriatic sub-basins. The sub-basin time-series obtained from the model simulation and the comparison between available observations and model results are shown in Fig. 6 (panels b-c-d and e). Model results were first sampled in the observational positions and then both simulated and observed values were grouped by region and averaged in time according to the intervals listed in Table 1.

The WACC region (Fig. 6b), extending from North to South and characterized by relatively shallow depths, reacts faster than the deeper regions to the surface fluxes. Differently from the entire Adriatic basin, this region is characterized by an alternation of positive and negative anomalies. The largest inter-annual variability is found in correspondence with the minima of the annual cycle; this is particularly pronounced during two episodes also detected in the whole Adriatic average: the warm autumn-winters 2000–2001 and 2006–2007. As also discussed for the whole basin, the successive summers are also warmer than the climatology. A general good agreement characterizes the comparison with the available observations, particularly during the autumn-winter seasons. During summer a warm bias characterizes the model results. Analysing the vertical structure of the water column (Fig. 7), it is evident that the summer bias (magenta for September–October 2002 and cyan for August

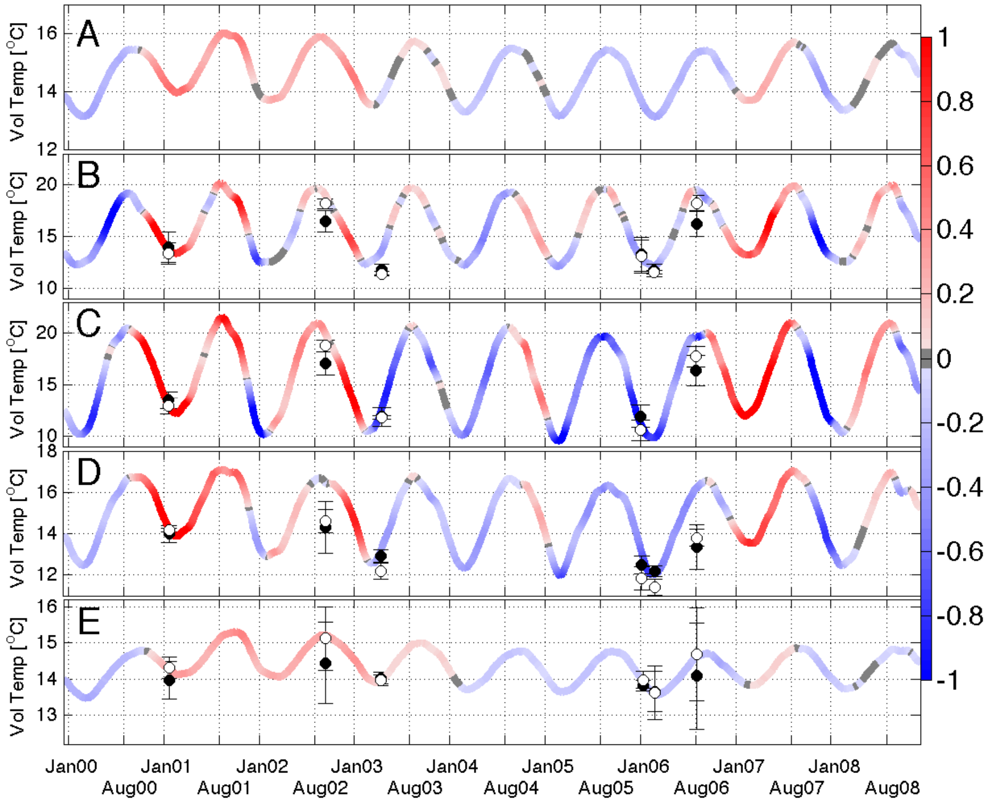


**Fig. 6.** Monthly time series of volume-averaged temperature, units are °C. Colour indicates monthly anomaly values. **(A)**: whole Adriatic Sea; **(B)**: WACC region; **(C)**: Northern Adriatic Region; **(D)**: Middle Adriatic Region; **(E)**: Southern Adriatic Region. In panels **(B, C, D)** and **(E)** dots indicate the vertically- and spatially-averaged values of observations (black dots) and model results (white dots). Dates of the sampling are listed in Table 1; positions of the sampling are displayed in Fig. 1. The model results were sampled in the same position and at the same time as the observation before averaging.

2006) is due to an excessive vertical mixing. The model reproduces the surface values well but between 20 and 50 m depth the simulated thermocline is weaker than observed. During winters the surface waters are generally cooler than the bottom layers, thus requiring a compensation effect from salinity in order to maintain the water column stable.

The northern region, as a consequence of the very shallow bathymetry, is characterized by the largest amplitude of the volume-averaged temperature seasonal cycle (Fig. 6c) with minimum values below 10 °C and summer maxima exceeding 21 °C. The anomaly pattern is similar to that depicted for the whole basin, with prolonged periods of positive and negative signs. Moreover, the amplitude of the anomalies is the highest recorded in all the sub-basins. The cooling event occurring in autumn 2001 strongly influences the mean temperature of this region as a consequence of its shallow depth. In fact, even though the previous summer (2001) is characterized by temperature values higher than the climatology, autumn 2001 and early winter 2002 sub-basin-averaged temperatures are approximately 10 °C (similar to other years, excluding 2001 and 2007). Summers 2001 and 2007, both preceded by anomalous warm autumns and winters, are characterized by values significantly higher than 20 °C. The vertical structure of the water column (Fig. 7) is similar to that observed in the WACC region, but vertical gradients are weaker. In this region too the positive summer bias is due to an overestimation of the vertical mixing during the stratified season and below 20 m depth the model produces temperature higher than the observation. During winter the model slightly underestimates temperature but is capable of reproducing the vertical shape of the observed profiles and the inter-annual variability.

The Middle Adriatic volume-averaged temperature (Fig. 6d) ranges between 12 and 17 °C. The large heat flux anomaly occurring between summer 2000 and spring 2001 determines temperature minima during February 2001 to be almost 2 °C higher than the climatological values. The strong cooling event occurring in autumn 2001 produces an abrupt decrease in temperature but not enough to bring the successive winter values close to the climatological estimates. This sub-basin requires a longer time to recover from the anomalous condition occurring in 2000. Starting from summer 2001, there is a progressive decrease in volume-averaged temperature that persists until summer

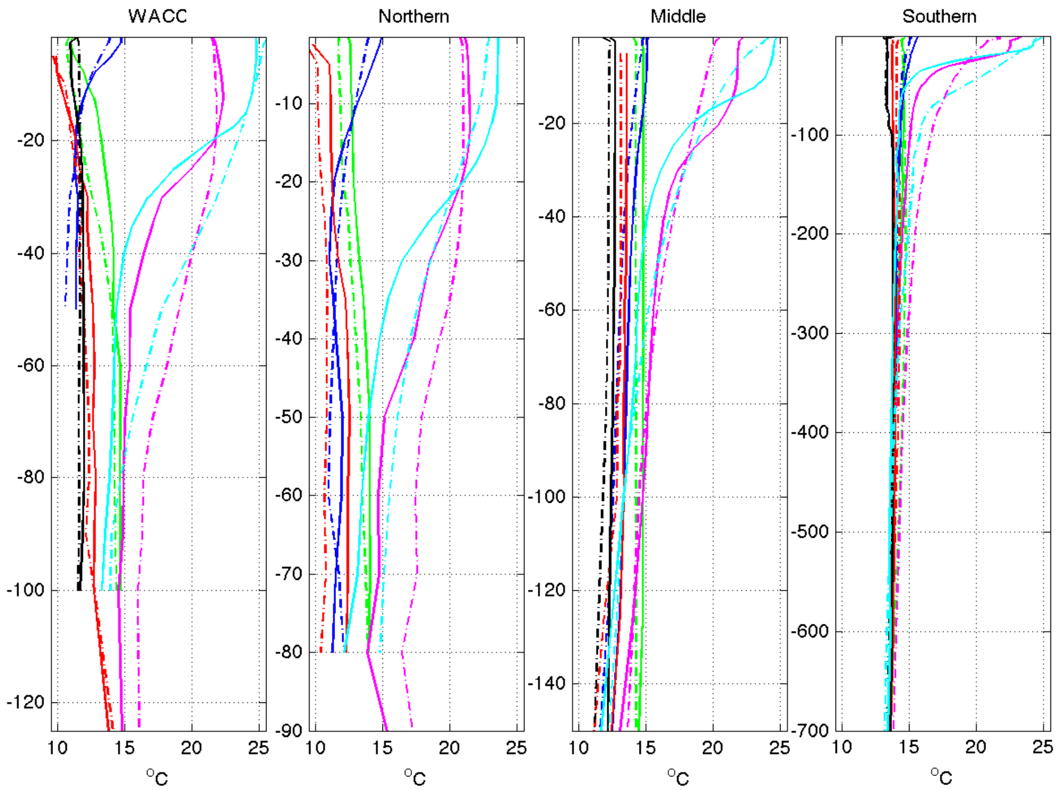


**Fig. 7.** Temperature vertical profiles obtained averaging both observations (solid lines) and corresponding model results (dashed lines) spatially and temporally . Colours indicate different cruises listed in Table 1 following Fig. 1.

2006. Unlike the WACC and the Northern regions, temperature vertical profiles (Fig. 7) are always characterized by a negative gradient from top to bottom (even though it becomes very small during winters as the water column is very well mixed).

The large inter-annual variability predicted by the model simulation is also confirmed by the observations. The model predicted difference between winter 2001 (the warmest) and winter 2006 (the coolest) matches the observational (green and red respectively) evidence. Both model and observation depict a well-mixed water column with a nearly constant temperature that during 2001 is of 13.5 °C and in 2006 is about 14.7 °C. During late summer 2002 (magenta line in Fig. 7) the model fails to reproduce the observed mixed layer, which extends from the surface to 20 m depth; whereas below the mixed layer modelled and observed temperature agree.

The Southern Adriatic volume is approximately 24 500 $km^3$ (77 % of the entire basin). As a consequence of this large volume, the sub-basin responses to surface and lateral fluxes are slower than in the rest of the basin and the amplitude of the seasonal and inter-annual variability signal is smaller than in the other sub-basins. In particular, in contrast with the other sub-basins, the positive anomaly characterising winter 2007 is less pronounced. The 2000–2001 anomalous surface heat fluxes increases the sub-basin volume-averaged temperature of about 0.5 °C, and this region persists in its positive anomalous condition until the beginning of 2004. The highest summer temperature is recorded in 2001. As supported by a cross analysis of Figs. 2e, 6e and of the upper panel of Fig. 3, the successive strong cooling occurring during autumn is partially compensated by the advective flux through the Strait of Otranto (Fig. 3, upper panel), and thus temperature minima in winter 2002 are similar to the previous year. Only in 2003 the combined effects of surface (Fig. 2) and lateral (Fig. 3) fluxes start bringing the volume-averaged temperature back to climatological values, which are reached at the beginning of 2004.

Observed values (Fig. 7) show that most of the seasonal cycle signal is confined to the upper 50–60 m of the water column, while the model produces a weaker thermocline and tends to overestimate vertical mixing, propagating down to 100 m the seasonal warming cycle. Below 200–250 m depth model results and observations agree, having values of about 13.5 ± 0.1 °C during all the periods sampled. At these depths, observed and predicted temperatures depend more on the inter-annual variability than on seasonal oscillation. Observed and modelled temperature differences, in the upper layers, in winter 2001 and 2006 are almost 1 °C (green and red lines, respectively).

Analysed and modelled sea surface temperatures (Fig. 8) are both characterized by a large inter-annual variability that differs from the volume-averaged temperature analysed series. In general, the model is able to reproduce the observed inter-annual variability. The agreement between the two datasets is very good, having a Nash-Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970) of about 0.95 considering the entire signal, and about 0.8 after removing the monthly climatology. The model results are characterized by a negative bias, which is more pronounced during summer seasons. The largest anomaly is observed during summer 2003 by both modelled and observed datasets. As already noted by Grbec et al. (2007), the spring/summer 2003 period was extremely warm and the response of the sea was remarkable. It is interesting to note that this anomalous warm summer has a very weak signal in the volume-averaged temperature. The anomalous warm winter 2001 and 2007 signal is also present in the SST time-series, with temperatures 1 °C higher than the corresponding climatological monthly mean.

During the period under investigation, the inter-annual variability of the volume-averaged salinity (Fig. 9) is larger than the seasonal oscillations. From January 2000 until summer 2003 the values oscillate seasonally around 38.5 psu. From summer 2003 to winter 2006 a constant increase in salinity content of the basin is observed; in late winter 2006 a new plateau is reached and basin-averaged values are constantly slightly higher than 38.6 psu. Large sea surface salinity values during summer 2003 have been detected in previous studies analysing observed data collected in the Middle Adriatic (Grbec et al., 2007). This progressive salinification of the basin is strongly driven by the Po runoff inter-annual variability (Fig. 3, bottom panel). In fact, from January 2003 to spring 2008 the Po regime is always below its climatological values. The effect of the missing freshwater input from the Po is also amplified by the concomitant high evaporation rates simulated by the model during winters 2003-2004-2005 and 2006 (Fig. 4). The surface fluxes compensate the missing intrusion of MLIW at the Strait of Otranto that becomes significant only in summer 2005 (Fig. 5) (the MLIW effect, during this period, has been also recently analyzed by Cardin et al., 2011).

In the WACC and Northern regions, the effects of the large Po runoff (Fig. 3 bottom panel) occurring during autumn 2000 and continuing until spring 2001 are evident, and a freshening of about 0.5 psu is observed in both the sub-basins during this period (Fig. 9b and c). Within the WACC region observational and modelled data are consistent. As already discussed for temperature data, model results are affected by an excessive vertical mixing (Fig. 10) in the upper layers of the water column. However, the inter-annual variability signal detected in the observations is reproduced well by the model simulation. The winter 2001 data (green) are those with lower salinity values at the surface, as a consequence of the large Po runoff, with values lower than 36.0 psu in both the datasets.

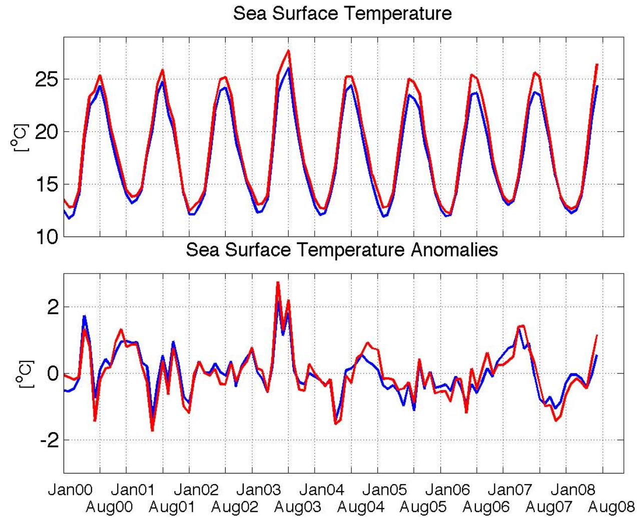


**Fig. 8.** Top panel: monthly time series of satellite (red line) and modelled (blue line) Sea Surface Temperature. Bottom panel: monthly time series of satellite (red line) and modelled (blue line) Sea Surface Temperature anomalies.

Observed and modelled stratification progressively decrease as a consequence of the reduced input from the Po and simultaneous large evaporation rates. These conditions, persisting for several years, strongly modify the salt content of the WACC region especially in the upper layers, reducing stratification (Fig. 10).

In the Northern region the evaporation rates (Fig. 4c) strengthen the effects of the reduced Po river regime (Fig. 3, bottom panel) and a strong inter-annual variability signal characterizes this sub-basin. Differences between minimum and maximum values modelled during the simulated period are larger than 1 psu. Agreement between observed and modelled values is weaker than in the WACC region; however, the long-period trend seems to be reproduced well by the model. The high salinity values diagnosed by the model, starting from summer 2003, are partially confirmed by observational evidence in 2006. Similarly to the WACC region, the salinification resulting from the reduced river input and large evaporation rate produces a weaker stratification (Fig. 10) with the surface layers significantly saltier during 2006 (red) than 2001–2002 and 2003 (green, magenta and blue lines respectively). The difference between modelled and observed values seems to be a consequence of an excessive vertical, and probably horizontal, mixing simulated by the model. Unlike the WACC region, the lowest surface salinity values were observed during the 2003 cruise (Fig. 10 blue line), while the 2000 Po signal is confined to a very thin surface layer (Fig. 10 green line). The general positive model bias could be a consequence of the only partially resolved water budget deriving from the usage of climatological river input (except for the Po) and precipitation rate.

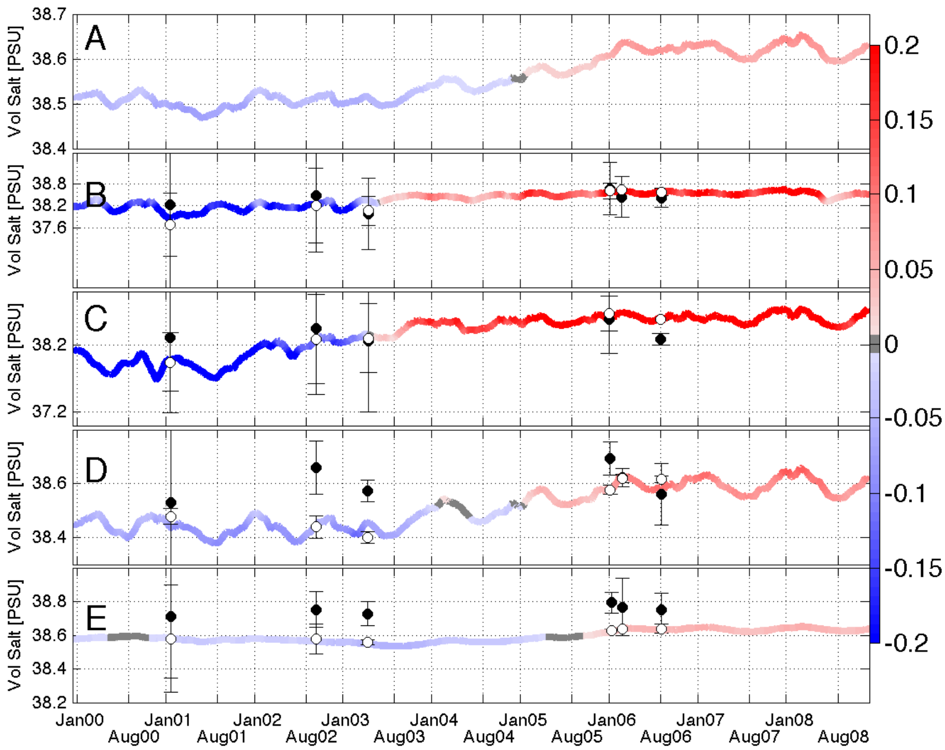


**Fig. 9.** Monthly time series of volume averaged salinity, units are PSU. Colour indicates monthly anomaly values. **(A)**: whole Adriatic Sea; **(B)**: WACC region; **(C)**: Northern Adriatic Region; **(D)**: Middle Adriatic Region; **(E)**: Southern Adriatic Region. In panels **(B, C, D)** and **(E)** dots indicate the vertically- and spatially-averaged values of observations (black dots) and model results (white dots). Dates of the sampling are listed in Table 1; positions of the sampling are displayed in Fig. 1. The model results were sampled in the same position and at the same time as the observation before averaging.

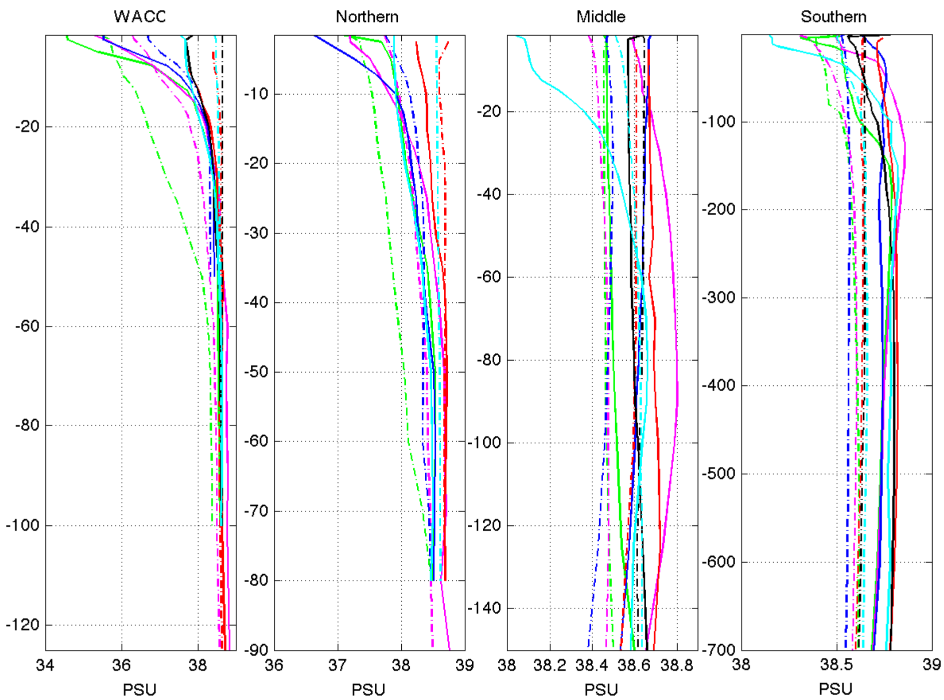


**Fig. 10.** Salinity Vertical profiles obtained averaging both observations (solid lines) and corresponding model results (dashed lines) spatially and temporally. Colours indicate different cruises listed in Table 1 following Fig. 1.

Similarly to the volume averaged temperature, the amplitude of the inter-annual variability signal decreases increasing the volume of the analysed sub-basin. In the Middle Adriatic differences between maximum and minimum salinity values are smaller than 0.3 psu. With the sole exception of August 2006, in this region model results are characterized by a negative bias. We can thus argue that the model overestimates the exchanging processes (both advective and diffusive) between the Northern and Middle sub-basins, the former being characterized by a positive bias.

The low salinity values characterizing the model simulation in 2001 (green lines in Fig. 10) are in good agreement with observations from surface to about 100 m depth; in the deeper layers the model underestimates salinity content by about 0.1 psu. The largest difference between modelled and observed data is probably that recorded in 2002 (magenta lines). During this year there is a clear observational evidence of MLIW intrusion in the intermediate layers of the Middle Adriatic. In addition to the small amount of MLIW present at the Strait of Otranto (Fig. 5) during this period, the missing reproduction of this intrusion can be amplified as a consequence of the excessive mixing described above. During this period the model results are characterized by a strong negative bias with salinity values that are systematically lower than the observations. However, modelled and observed differences between the years 2002 and 2003 (magenta and blue lines, respectively) are similar. During 2003 MLIW intrusion is absent and a general freshening of the sub-basin is observed.

In agreement with recent studies (Cardin et al., 2011), starting from summer 2003 and until winter 2007 a net increase in salinity content of the basin is observed, This behaviour is partially confirmed also by the observational dataset used in the present study, with the exception of the August 2006 cruise (cyan). Data obtained from this cruise are characterized by a marked surface minimum that the model fails to reproduce. However, the sampling positions (Fig. 1) suggest that the major model deficiency is in the representation of the river runoff along the East coast and probably during this period the climatological values used are not representative of the real freshwater input.

Inter-annual variability in the Southern sub-basin is very small; volume-averaged salinity values oscillate around 38.6 and difference between maximum and minimum recorded values is about 0.1 psu. Similarly to the Middle Adriatic, the model results are characterized by a negative bias, which is constant below 200 m depth (Fig. 10). The differences between modelled and observed values in the upper layers seem to be related to the sampling positions (Fig. 1) and can be ascribed to the only partially resolved inter-annual variability in the surface water fluxes.

At intermediate depths, in addition to the MLIW intrusions occurring in late summer 2002 (magenta line in Fig. 10) and found also in the Middle sub-basin, a subsurface salinity maximum not detected in the Middle Adriatic is observed in spring 2003 (blue line) characterized by an unusual uplifted horizon that may be ascribed to MLIW intrusion. The model fails to reproduce both the MLIW intrusion episodes, since this peculiar subsurface salinity maximum cannot be detected in the corresponding model results.

In the bottom layers, the increased salinity content is also confirmed by observations. During 2006 cruises (red, black and cyan lines in Fig. 10) bottom salinity is 0.1 psu larger than the previous years and model results confirm this finding. Unlike the other sub-basins, the Southern Adriatic mean salinity does not show a marked increase between 2003 and 2006. Instead, the salinity content grows in late summer 2005 as a consequence of the intrusion of the MLIW (Fig. 5). This salinification, both observed and modelled, may probably have been strengthened as a consequence of the missing freshwater input in the Northern sub-basins and the consequent formation of dense waters saltier than usual filling the deep part of the Southern Adriatic sub-basin later.

### 4.3 Dense waters

Dense Water (hereafter DW) volume (km$^3$) and formation/dissipation rate (Sv) are investigated here for each sub-basin with the sole exception of the WACC region. The WACC region is omitted from the calculation since preliminary analysis has shown that in this region dense water is only poorly present and is not formed locally. The analysis was performed on a daily basis setting the threshold sigma-$t$ limit to 29.2 in all the sub-basins and results are shown in Fig. 11. In addition, mean characteristics (temperature and salinity) of the newly-formed water masses are presented in Fig. 12. Positive values of formation rate indicate new DW locally formed or advected into the sub-basin; negative values, on the other hand, indicate the occurrence of local processes acting in the direction of decreasing density (positive buoyancy fluxes) or advective processes removing dense water from the sub-basin under investigation. The formation rate is computed as the local tendency of the volume of dense water having sigma-$t$ larger than the threshold on a daily basis. This definition of formation rate differs from others presented in the literature in which the amount of volume of dense water is divided by the seconds elapsed in the entire year; we will refer to the values computed using this method as "seasonal".

DWs are formed in the Northern sub-basin (Northern Adriatic dense water, NAdw) in all years with the sole exception of 2000–2001; however, daily values of formation rate (Fig. 11) and mean properties (Fig. 12) differ from year to year as a consequence of the surface and river buoyancy fluxes discussed. Seasonal formation rates (not shown) are in good agreement with previous numerical findings. This "seasonal" formation rate is on average about 0.04/0.05 Sv, as already found by Mantziafou and Lascaratos (2008). At seasonal scales, inter-annual variability of the formation rate is small. In other words, when NAdw are formed, the

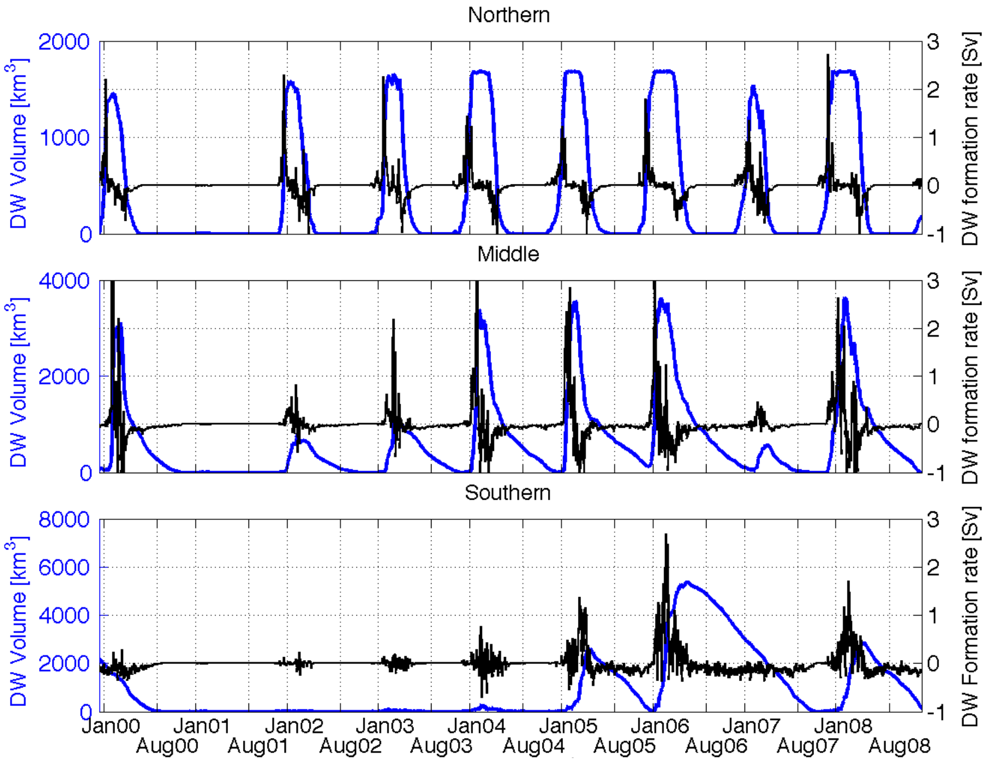


**Fig. 11.** Daily time-series of total volume of water (km$^3$) with sigma-$t$ > 29.2 (blue line and left Y-axis) in Northern, Middle and Southern sub-basins, together with the relative formation/dissipation rate expressed in Sv (black line and right Y-axis).

maximum volume of DW formed is similar (1450 km$^3$ in 2000, 1670 km$^3$ during 2006) in all the years investigated. However, the duration and the intensity of the formation processes differ from year to year as well as the advective processes and the positive buoyancy fluxes. Maximum formation rate occurs between the end of December and the beginning of January with values varying from year to year; the maximum formation rate is higher than 2.7 Sv in December 2007 while it is about 1.2 Sv during January 2005.

The occurrence and the intensity of the NAdw formation process are directly related to the amplitude and timing of the negative surface heat flux modulated by the Po regime. The anomalous large Po river runoff together with the missing cooling during both autumn 2000 and winter 2001 have prevented DW formation in winter 2000–2001. The two strong cooling events occurring in autumn 2001 and 2007 (Fig. 2c) produce large formation rates, both higher than 2 Sv. However, even though cooling was stronger in the 2001–2002 formation process, the high Po runoff input compensated the overall buoyancy flux mitigating the maximum NAdw formation rate, which is, during this period, significantly lower than in 2007–2008. Thus temperature and salinity characterizing these newly formed NAdw strongly differ between the two formation processes. The NAdw formed in 2001–2002 are characterized by very low salinity values, ranging between 37.6 and 38.3 at the beginning and at the end of the formation process respectively. Those values are significantly lower than corresponding values reported in literature, which range between 38.3 and 38.5 psu (Zore-Armanda, 1963; Artegiani et al., 1997b; Vilibic and Orlic, 2002). In 2007–2008 the Northern sub-basin is strongly saltier than the previous period and the NAdw formed also has a salinity content higher than 38.6. As a consequence waters with sigma-$t$ larger than 29.2 start to be produced even when associated temperatures are higher than 12 °C. Moreover, the 2001–2002 NAdw formation process is followed by a period characterized by negative values of NAdw formation rate as a consequence of a strongly positive surface buoyancy flux.

Despite the fact that autumn 2006 and the successive winter are characterized by a weak cooling at the sea surface similar to the 2000–2001 anomaly, NAdw formation process occurs during this period. This is clearly related to the high salinity values that characterize the Northern sub-basin in this year. In fact, the NAdw temperature is about 12 °C, significantly higher than the 10.6 °C indicated by Vilibic and Orlic (2002), or 11.3 °C as suggested by Artegiani et al. (1997a), and associated salinity is higher than 38.5 psu. All the other NAdw formation processes are characterized by similar behaviour, with salinity slightly increasing from year to year prolonging the NAdw formation period and consequently allowing an increase in the associated maximum temperature values (Fig. 12). It is interesting to note that

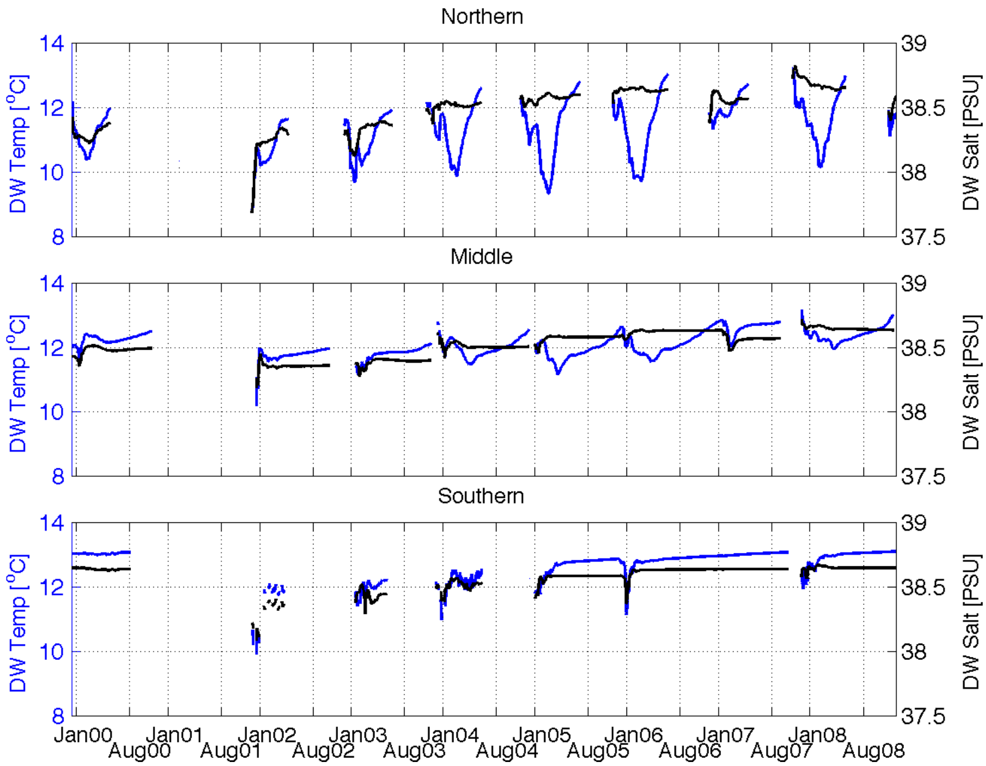


**Fig. 12.** Daily time-series of mean Temperature (blue lines, left Y-axis) and Salinity (black lines, right Y-axis) of waters masses having sigma-$t > 29.2$ in the Northern, Middle and Southern sub-basins.

a reversal of this tendency is diagnosed by the model simulation at the end of 2008, associated with the Po regime, which is back to climatological values. A similar behaviour has been recently observed for the southern basin analyzing observational dataset (Cardin et al., 2011).

Inter-annual variability of DW formation in the Middle Adriatic (Middle Adriatic Dense Water, MAdw) is very large. In addition to the absence of formation in 2001, 2002–2003 and 2007 are also anomalous, and "seasonal" formation rates are smaller than other simulated years. The "seasonal" formation rate varies from 0.02 Sv in the above years to 0.1 Sv in 2000-2004-2005-2006 and 2008. The values and the inter-annual variability computed at seasonal scales are in agreement with previous findings in Mantziafou and Lascaratos (2004) and Mantziafou and Lascaratos (2008). Maximum daily formation rates occur during January–February, ranging from 0.7 Sv during 2002 to about 3.1 Sv during 2000, 2004 and 2006 (Fig. 11).

In addition to the surface flux activity, the intrusion of the MLIW in the Middle Adriatic is a key factor in determining the occurrence of MAdw formation processes (Bergamasco et al., 1999). The three consecutive (2001-2002-2003) years of missing MAdw formation are due to the concomitant effect of surface buoyancy fluxes and absence of MLIW in the sub-basin. The total volume of MAdw during this period and the corresponding formation rates are significantly small, and the temperature and salinity associated with these waters (Fig. 12) suggest that the DW is advected into the sub-basin from the North. In fact, MAdw temperature (Fig. 12) is significantly lower than 12 °C and the corresponding salinity (Fig. 12) is below 38.5 psu. It is important to mention that the data collected in late summer 2002 (magenta line in Fig. 10) indicate the presence of MLIW and highlight a model deficiency in reproducing this event. The model therefore probably underestimates formation processes in this period.

In agreement with previous findings (Zore-Armanda, 1963; Mantziafou and Lascaratos, 2004, 2008) MAdw formation occurs later in the Middle Adriatic than the same processes do in the Northern sub-basin. Large temperature and reduced input of MLIW during winter 2007 inhibit MAdw formation. MAdw volume and the corresponding formation rate diagnosed by the model in 2004-2005-2006 and 2008 clearly indicate that DW formation occurred locally. The corresponding temperature and salinity (Fig. 12) are also in good agreement with previous estimates (Zore-Armanda, 1963; Artegiani et al., 1997a; Vilibic and Orlic, 2002). However, similarly to the Northern region, modelled and observed (both the observational dataset used in the present study and in-situ data analyzed recently by Cardin et al., 2011) increase in salt content of the basin allows dense waters to be formed with progressively higher temperature. In fact, temperature and salinity characterizing dense water formed during 2000 are the closest to climatological and observed values (Artegiani et al., 1997a).

The amplitude of the inter-annual variability of the DW formation in the Southern Adriatic basin is highly dependent on the high frequency variability of the atmospheric forcing (Mantziafou and Lascaratos, 2008) and on the effect of lateral buoyancy fluxes (Mertens and Schott, 1998). Moreover, the dimensions of the Southern sub-basin affect the memory of the systems (Mantziafou and Lascaratos, 2004), and as a consequence the missing cooling occurring in 2000 and the absence of MLIW strongly impact DW formation rates calculated until 2005 (Fig. 11).

The small formation rates recorded between 2001 and 2004 (smaller than 1 Sv, Fig. 11) are clearly due to DW advected from the northern sub-basins. This is particularly evident analysing the mean properties of DW. As a matter of fact, during this period DW found in the Southern sub-basin are cool and fresh (Fig. 12).

In winter 2004 the temperature of the basin reverts to standard or climatological values; however, salty waters of Levantine origin are still absent in the basin and the model starts the production of DW again only in winter 2005. This is confirmed both by the amount of DW present in the sub-basin, the formation rate higher than 1 Sv and the associated temperature and salinity.

DW formation is very pronounced in winter 2006 (Fig. 11); DW volume formed in this period is the largest of the entire simulation. The warm period started in autumn 2006 and continuing also in winter 2007, in addition to the reduced amount of MLIW intruding into the basin (Fig. 5), interrupts DW production in the Southern sub-basin. Similarly to 2000–2001, the following autumn is particularly cold and an abrupt drop in temperatures is observed. As a consequence, even though under the influence of a relatively mild winter, DW are formed at the beginning of 2008 (Fig. 11).

During the periods of local DW formation (2005, 2006 and 2008), DW characteristics are similar to previous finding with temperatures of about 13 °C and salinity slightly higher than 38.65 psu (Zore-Armanda, 1963; Artegiani et al., 1997a; Vilibic and Orlic 2002). Similarly to what happens in the Middle sub-basin, the local formation of DW stops in 2007 as a consequence of the surface buoyancy fluxes and of the reduced inflow of MLIW. It is worth mentioning that DW formed in the Southern Adriatic basin can have sigma-$t$ lower than the threshold value of 29.2 used in this work (Gacic et al., 2002b; Mantziafou and Lascaratos, 2004 and 2008), thus formation rates and volumes discussed are indicative only of the denser locally formed waters.

## 5 Summary and conclusions

The inter-annual variability of the Adriatic Sea hydrographic characteristics was investigated for the period 2000–2008 using both numerical simulation results and direct observations. The model used is derived from the Adriatic Forecasting System (AFS, http://gnoo.bo.ingv.it/afs/) and was also developed within the ECOOP project. The primitive equations model was implemented on a regular horizontal grid having approximately 2.2 km of resolution and 27 vertical sigma layers. In order to reproduce the inter-annual variability surface fluxes (both momentum and buoyancy) are interactively computed by means of the model predicted sea surface temperature and the atmospheric variables from the ECMWF operational products. Observational data used in support of numerical findings include CTD casts and satellite-derived sea surface temperature. As per well-known Adriatic characteristics, the basin was divided in four sub-basins (WACC, Northern, Middle and Southern Adriatic) and the data were analysed separately.

Total heat flux during the period under investigation is characterized by a marked inter-annual variability (Fig. 2), which is larger during the cooling periods and mostly due to the variability in the latent heat flux component (Fig. 4).

A remarkable heat flux positive anomaly was detected, in all the sub-basins, during autumn-winter 2000–2001. During the same period the Po river runoff was significantly larger than the climatological values (Fig. 3, bottom panel) and the MLIW absent at the Strait of Otranto (Fig. 5). The basin (and sub-basin) reaction was noticeable in terms of temperature (both volume-averaged and surface, Figs. 6 and 8, respectively), salinity (Fig. 9) and consequent DW production (Fig. 11). The whole basin volume-averaged temperature rise between early winter 2000 and early winter 2001 is almost 0.8 °C. During the same period the SST anomaly is almost 1 °C (Fig. 8). The response of the salinity field to the anomalous Po river runoff and to the missing evaporation is particularly evident in the WACC and Northern basins but, as a consequence of the induced vertical stability, it is mostly confined in a very thin surface layer (Figs. 9 and 10). Consequently, no DW formation occurred in the entire Adriatic Sea.

The river Po continues to supply a large amount of fresh waters to the basin until the end of 2002 (Fig. 3 bottom panel). The successive autumn of 2001 was very cold – the coldest of the entire period under investigation – and was characterized by a strongly negative heat flux (Fig. 2) as a response to the large evaporation rate (Fig. 4). Temperature in the WACC and Northern sub-basins quickly reverted to climatological values in early autumn and was below the climatological values by the end of the year. The relatively large volumes of the Middle and Southern sub-basins mitigate the cooling effect and the corresponding averaged temperature response, which, in the Southern basin, persists above the climatological values (Fig. 6). Volume-averaged salinity in the Northern and Middle Adriatic are now very low as a consequence of the prolonged period characterized by high Po runoff rates. The low temperature reached in the Northern basin allows DW formation process to restart in early 2002 (Fig. 11); the newly formed DW are characterized by very cold and fresh properties (Fig. 12).

The year 2002 was relatively mild (Figs. 2 and 3), this caused the volume temperature to be warmer than climatology again during the entire year and over the entire basin (Fig. 6). The signal is very weak in the sea surface temperature (Fig. 8). The volume-averaged salinity is now stable in all the sub-basins with the sole exception of the northernmost region, which is now slightly saltier than the previous year (Fig. 9). This is due to the fact that the Po runoff, even though above the climatological mean, is significantly reduced compared to autumn 2000 (Fig. 3). During summer there is observational evidence of MLIW intrusion (Fig. 10) in the Middle and Southern sub-basins not reproduced by the model, and thus the salinity content is probably underestimated by the model simulation. The year 2003 starts with a very cold winter characterized by high evaporation rates (Fig. 4); however, the Po river now enters a long prolonged period of very low runoff (Fig. 3), and consequently evaporation effects are remarkable in the salinity content of the basin. The cold winter restores the volume-averaged temperature to climatological values in all the basins with the sole exception of the Southern region. However, as a consequence of the mild 2002 autumn, DW formation occurs only in the Northern sub-basin (Fig. 11). Despite the cold winter, the SST during the summer is the highest recorded in the entire period investigated (Fig. 8). High evaporation and almost absent Po runoff produce a net salinity growth in all the sub-basins except for the Southern where MLIW contribution is still missing (Fig. 5). The concomitant effect of the strong summer stratification amplifies the increased salinity signal at the sea surface (Fig. 10).

The years 2004 and 2005 are both characterized by negative total heat flux anomalies all year round, with the exception of a few months during the late-summer/early-autumn periods (Fig. 2), reduced Po runoff and high evaporation rates. Temperature is generally below the climatological values except in the shallower regions during the warmer period mentioned above (Fig. 6). At the beginning of 2004, the Southern basin temperature is also restored to climatological values and encounters a relatively long period with values constantly below the climatology (Fig. 6). During this two years the volume average salinity continuously grows (Fig. 9). Southern growth only starts in summer 2005 with the arrival of the MLIW at the Strait of Otranto (Fig. 5). DW formation process is now also active in the Middle sub-basin and a small production also starts in the Southern Adriatic in winter 2005 (Fig. 11). The increased salinity content allows NAdw to reach the 29.2 threshold even with warmer temperatures (Fig. 12).

The cold period persists until August 2006. Temperatures are now below, and salinity above, the climatological values over the entire Adriatic Sea. The characteristic freshwater input from the Po river is still absent and a considerable signature of MLIW is observed at the Strait of Otranto. DW volumes formed in this period are the largest of the entire simulation (Fig. 11).

The mild autumn 2006–winter 2007 period (Fig. 2) and the reduced amount of MLIW intruding into the basin (Fig. 6) interrupt DW formation in the Middle and Southern sub-basins. A weak NAdw formation is observed as a consequence of the reduced Po runoff and of the high salinity content characterizing the sub-basin during these years (Figs. 11 and 12). Volume and surface temperatures remain significantly higher than the climatology until spring/early-summer (Figs. 6 and 8). Autumn 2007 is particularly cold and an abrupt drop in temperatures is observed (Figs. 6 and 8) thus, even though under the influence of a relatively mild winter, DW are formed in all the sub-basins at the beginning of 2008 (Fig. 11). In Spring 2008 the Po river runoff reverts to considerable regimes (Fig. 3) and salinity tends to decrease in the WACC, in the Northern, and in the Middle, sub-basins (Fig. 9). The starting of a DW formation process is observed in the Northern basin at the end of 2008 with salinity characterizing the newly-formed water masses that are significantly lower than the preceding years (Fig. 12).

The period investigated shows significant inter-annual variability in all the considered quantities and DW formation processes. However, a long-scale signal has been observed in the basin as a consequence of the reduced river runoff and high evaporation rate. The basin significantly increased the salinity content and the temperature and salinity characterizing DW, especially in the Northern sub-basin, are modified consequently.

In terms of inter-annual variability, the proposed modelling framework enables qualitative studies of the main characteristics of the basin. The nesting procedure, with the operational MFS model, allows for a correct reproduction of the inter-annual variability related to the large-scale flow and the remote influences of the Eastern Mediterranean dynamics.

Even though characterized by a relatively coarse resolution, the atmospheric forcing seems to be adequate for the inter-annual variability investigations.

The weaker modelling components are related to the freshwater balance. The absence of an observational dataset capable of capturing the runoff inter-annual variability of the major Adriatic rivers (with the exception of the Po) seems to affect the quality of the simulation, especially along the east coast. However, the present model configuration allows for an accurate reproduction of the Northern Adriatic sub-basin dynamics, while the inaccuracy of the climatological river data affects mostly the east coasts of the Middle and Southern Adriatic sub-basins. There is a need for further modelling efforts in order to fill the runoff observational data gap.

The study confirmed that the Adriatic variability depends upon many factors: river input, atmospheric forcing and mass exchanges through the Strait of Otranto.

The Po river influence seems to be confined in the Northern and WACC sub-regions, while the Middle and Southern sub-basins seem to be marginally affected by Po river variability. The Middle and Southern sub-basin salinity is strongly dependent on the river regime along the east coast and on the intrusion of the MLIW.

In the Northern Adriatic sub-basin, the freshwater input from the Po determines the characteristics of the locally formed DW, while the occurrence of the DW production processes is totally driven by the surface heat fluxes. In the Middle and Southern sub-basins, however, the key factor in determining the DW production processes is the presence of sufficiently salty water of Mediterranean origin. In fact, even under strong atmospheric conditions the DW formation processes do not start if MLIW are missing.

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