On the bottom density plume on coastal zone off Gargano (Italy) in the southern Adriatic Sea and its interannual variability

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[1] The Adriatic Sea general circulation model (AIM) was implemented to study a bottom density plume found in coastal zone off Gargano (hereafter Gargano bottom density plume) in the southern Adriatic Sea (SAS), Italy, and its interannual variability. The model has been run with realistic wind stress, surface heat flux, and river runoff forcings continuously for a period from 1 January 1999 to 31 December 2002. The study found that the Gargano bottom density plume, typically as found in spring 2000, is a bottom density current driven by a perturbation in density as a result of successive bora cooling events in the northern Adriatic Sea (NAS) from previous autumn and winter. The density current advects cold and less saline Northern Adriatic Deep Water (NADDW) from the NAS to the SAS, and the propagation speed of the plume can reach 0.1 m s^{-1} with a downslope component on the order of 0.05 m s^{-1}. The southward mass and heat transport by the Gargano plume can be calculated to be 0.08 Sv and -30 W m^{-2} at a transect near Gargano Peninsula. These results suggest that about 15% of the NADDW and NAS heat content change produced over previous winter was transported to the SAS by the Gargano plume. One of the most important findings of this paper is that there is a connection between the intensity of Gargano bottom density plume in the SAS and the NADDW production rates in the NAS. The numerical study demonstrated that a continuous heat loss of 175 W m^{-2} from November to January is required to produce adequate volume of NADDW, so that a density perturbation is formed which is large enough to drive a density current that reaches the Gargano Peninsula in the spring. This minimum requirement of heat loss equates to eight consecutive strong bora events in this period. In addition to the autumn and winter surface cooling, summer preconditioning of the NAS density by the lower Po River runoff is another important factor in the Gargano plume generation. A wet summer results in large Po River runoff and decreases the NAS density. Thus additional heat loss is required for adequate NADDW production in the following winter. Finally, the study also demonstrated that total heat budget of the NAS during the winter season was negative, as the amount of heat lost at the air-sea interface during that period was much larger than the amount of heat gained by horizontal advection. As a result, the NAS during the winter season experienced a strong heat content decrease.

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1. Introduction

[2] The Adriatic Sea is a semienclosed shelf sea opening to the eastern Mediterranean Sea through Otranto Strait which is 75 km wide and 800 m deep (Figure 1). The basin has almost rectangular shape approximately 800 km long and 200 km wide. It consists of a shallow northern shelf with depth less than 80 m, a depression of 270 m in the middle basin (Jabuka Pit) and a deep southern part with a maximum depth of 1320 m. On the western coast of the Adriatic Sea, the shelf has a gradual slope with isobaths running parallel to the coastline. The eastern coast is irregular, and composed of many islands with steep continental shelf. In this study we define the northern Adriatic Sea (NAS) as an area from the northern tip to the latitude marked by the cross section N; and the southern Adriatic Sea (SAS) as an area from 42°N to Otranto Strait (Figure 1).

[3] The Northern Adriatic Deep Water (NADDW) is cold and relatively fresh dense water mass produced by the surface heat loss driven by bora storms in the NAS during autumn and winter. Bora storms that can last for several

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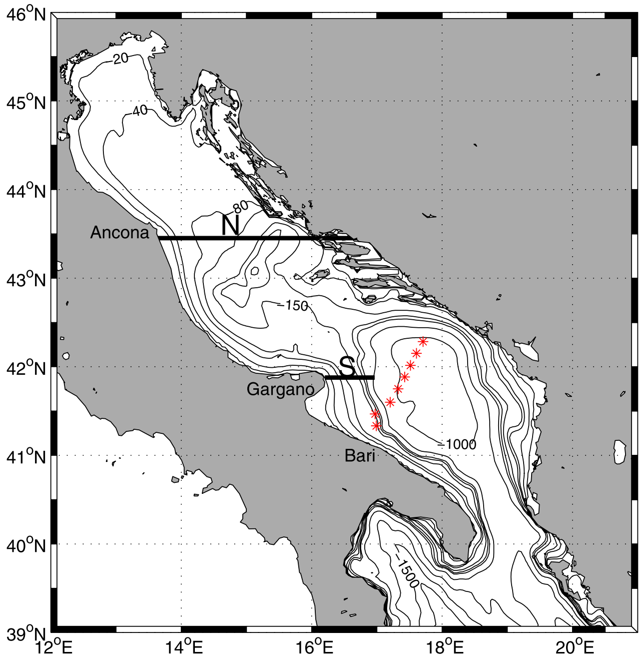


Figure 1. Adriatic Sea general circulation model domain and the Adriatic Sea bathymetry. N and S denote the cross section at the end of the northern Adriatic Sea and a transect section offshore of Gargano Peninsula, respectively. November 2002 XBT stations and transect is also shown.

days are connected with a depression over south Adriatic or a high-pressure system over eastern Europe. They bring cold, dry winds that have fine-scale variability in speed ultimately controlled by orography of the Dinaric Alps on the eastern Adriatic coast [*Grubišić*, 2004]. *Vilibić et al.* [2004] found that a strong bora wind event in November 1998 resulted in heat loss exceeding 800 W m^{-2}, cooling the whole water column by 2.4°C, while another similar bora episode in January/February with a cooling rate of 1.4°C ended with NADDW generation. Similarly, *Wang* [2005] has shown that a single winter bora storm in January 2001 reduced the average temperature and heat content of the NAS by up to 0.7°C and 200 W m^{-2}, respectively.

[4] Since *Pollak* [1951], NADDW has been considered as the most important sources for deep water formation for the eastern Mediterranean [*Zoccolotti and Salusti*, 1987; *Bignami et al.*, 1990a and *Manca et al.*, 2002]. In contrast, *Mantziafou and Lascaratos* [2004] suggested that the Adriatic Deep Water (ADW) exiting through the Otranto Strait is a combination of both NADDW and SADDW (Southern Adriatic Deep Water) and the latter was formed by open ocean deep convection over the Southern Adriatic Pit during the period of the strongest winter cooling [e.g., *Vilibić and Orlić*, 2002; *Manca et al.*, 2002]. A recent increase in the formation of Cretan Deep Waters of the Aegean Sea, generating the so-called eastern Mediterranean Transient (EMT), produced a new mass of denser water that has temporarily replaced the Adriatic water as an alternative source to influence the properties of the eastern Mediterranean Sea bottom water formed outside of the Adriatic [*Roether et al.*, 1996], although *Klein et al.* [2000] predicted that the Adriatic is probably returning its previous dominating role in producing the deep waters of the eastern Mediterranean.

[5] Numerous studies [e.g., *Artegiani and Salusti*, 1987; *Artegiani et al.*, 1989, 1997; *Bignami et al.*, 1990a, 1990b; *Paklar et al.*, 2001; *Manca et al.*, 2002; *Vilibić and Orlić*, 2001, 2002; *Vilibić*, 2003] have observed and characterized the NADDW with T < 11.35°C, S < 38.30 psu and sigma-t > 29.2 kg m^{-3}. Furthermore, the NADDW produced in the autumn and winter forms a cold bottom density current over the western Adriatic shelf at the depth between 100 and 200 m and arrives at Gargano Peninsula and offshore Bari in the following spring and summer [*Zoccolotti and Salusti*, 1987; *Bignami et al.*, 1990a; *Vilibić*, 2003]. Using an advection-diffusion equation for the density perturbation, *Shaw and Csanady* [1983] have shown that a bottom density current flows along the isobaths with a small downslope component due to the bottom friction. The model-predicted bottom density current speed is 0.05 m s^{-1}, and agrees with the observations of 0.06–0.08 m s^{-1} [*Hendershott and Rizzoli*, 1976; *Vilibić and Orlić*, 2001]. Thus we suppose that the vein of NADDW behaves like this and arrives up to the Gargano peninsula where the real Adriatic shelf escarpment is found. At this point the NADDW mixes with the higher-salinity local water masses (the Levantine Intermediate Water, LIW) probably contributing to the SADDW formation [*Bignami et al.*, 1990a, 1990b; *Manca et al.*, 2002].

[6] While there have been previous studies on observing and modeling the bottom density plume near the Gargano Peninsula, there has been no or very little work done in documenting the interannual variability of such plume and its connection with the NADDW formation process. Commenting on the fact that potential density found around the sill of the Otranto Strait in some years was higher than that of the deep eastern Mediterranean water, *Pollak* [1951] noted that the outflow of the ADW into the Ionian Sea is far from continuous, and dependant on the prevailing winter weather regime. On the basis of the long-term current meter measurements in the Otranto Strait, *Manca et al.* [2002] also found a fairly consistent interannual variability in the mass transport rate related to the intensity of winter convection. *Vilibić* [2003] argued that preconditioning of NAS salinity by the Po River runoff is important in NADDW formation, thus interannual variability in the Po River runoff affects the NADDW production. Indeed, recent quasi-synoptic CTD data by *Sellschopp and Alvarez* [2003] and the interannual model simulations by *Oddo et al.* [2005] confirmed that there was no NADDW formed during 2001 winter as it was an abnormally wet and mild winter.

[7] This paper uses an Adriatic Sea general circulation model (Adriatic Intermediate Model, AIM) in order to study the Gargano bottom density plume and its associated mass and heat transport by examining model interannual simulations from 1999 to 2002. A particular interest of this work is to investigate the interannual variability in the Gargano bottom density plume in the SAS, and its connection with the formation of NADDW in NAS. Section 2 describes the general circulation model (AIM) and its forcing functions including the surface heat flux and Po River runoff. Model simulations of the Gargano bottom density plume and its interannual vari-

ability are discussed in section 3, and section 4 offers discussion and conclusions of the paper.

2. Model Setup

[8] The AIM is based on the three dimensional Princeton Ocean Model (POM), [*Blumberg and Mellor*, 1987] which uses a seabed following sigma coordinate system, and proves to be advantageous in the study of the bottom boundary layer (BBL) dynamics [e.g., *Mellor and Wang*, 1996]. The model is implemented in the whole Adriatic Sea (Figure 1) with a regularly spaced grid of 5 km in horizontal and 21 sigma coordinate vertical levels that were distributed logarithmically in the bottom and surface boundary layers. See *Oddo et al.* [2005] for a detailed description of the model configuration and setup.

[9] The wind stress at the sea surface is computed by $\tau_s = C_D|\boldsymbol{W}|\boldsymbol{W}$ where $\boldsymbol{W}$ is the ECMWF wind, C_D is the surface drag coefficient according to *Hellerman and Rosenstein* [1983] and is a function of the difference of the air and sea surface temperature, and wind amplitude. The net surface heat flux Q_{surf} was given by $Q_{surf} = Q - Q_L - H_s - H_L$ using the bulk aerodynamic formulae. The solar radiation Q had been computed according to *Reed* [1975, 1977] with clear sky radiation according to *Rosati and Miyakoda* [1988] and the sea surface albedo due to *Payne* [1972]. The net longwave radiation flux Q_L [*May*, 1986] is a function of air temperature, sea surface temperature, cloud cover and relative humidity. Sensible heat flux H_s and latent heat flux H_L are computed by classical bulk formulae parameterized according to *Kondo* [1975]. The cloud cover from ECMWF analysis was used in the bulk parameterization. Details on the bulk formulae used are given by *Maggiore et al.* [1998].

[10] Thirty-one freshwater sources including rivers along the Adriatic coastlines were represented in the model by point or line source functions. The most important of them, river Po, was set at daily flow rate values in the computation. The other freshwater runoffs were set equal to their monthly average runoff values for lack of higher-frequency data [*Raicich*, 1996]. Open boundary conditions in the Ionian Sea along a latitudinal boundary located at 39°N were nested within a large-scale model of the Mediterranean Sea [*Pinardi et al.*, 2003].

[11] In this paper, the AIM has been run with realistic wind stress, surface heat flux and river runoff forcings continuously from 1 January 1999 to 31 December 2002. Time series of NAS area averaged wind stress, surface heat flux and Po River runoff from January 1999 to December 2002 are shown in Figure 2. Most striking features of these forcing functions are that bora storm events caused surface heat loss as large as -800 W m^{-2}, and wind stress up to 0.5 N m^{-2} with large NE component. These events occurred mostly from November to January each year. Other wind episodes such as Sirocco events occurred more frequently in summer and autumn. These are hot or warm southeasterly winds originating in the Sahara desert as a dry dusty wind but becoming moist as it passes over the Mediterranean, therefore induced negligible surface heat loss in the NAS in winter. Furthermore, year 2001 was the wettest year with a maximum of winter integrated Po River runoff, being preceded by a November maximum reaching 9000 m^3 s^{-1}, and an average summer runoff of 1399 m^3 s^{-1}.

3. Results

3.1. Gargano Bottom Density Plume in 2000

[12] Autumn 1999 to winter 2000 is a year with strong and frequent bora events that produced an averaged surface heat loss of the order of -220 W m^{-2} and NE wind stress component of -0.04 N m^{-2} in the NAS (Table 1). The cold and dense NADDW was formed to its full strength with bottom temperature <10°C and sigma-t > 29.2 kg m^{-3} on 15 February 2000 (Figure 3a, temperature not shown). The initial southward spreading of the NADDW occurred across the entire middle basin centered over Jabuka Pit, and a more defined plume was formed along the western shelf near the Gargano Peninsula on 6 March, and can be identified by a tongue of dense water outlined by 29.2 isopycnal. The plume reached the Gargano Peninsula on 26 March and had become fully formed on 15 April. The results of the model presented indicate that the plume flows along the coast between Ancona and Gargano with speed of 0.09 m s^{-1}. It should be noted that multiple subplumes appearing along the eastern side of the plume (e.g., on 5 April) are the manifestation of the baroclinic instability discussed by *Smith* [1976] and *Jiang and Garwood* [1996].

[13] At the transect S (Figure 1), the core of the bottom density plume (sigma-t = 29.2 kg m^{-3}) was located at a depth between 100 and 150 m over the shelf on 25 April, with a width of 22 km and thickness of 20 m (Figure 4). The core of the bottom plume was colder (T = 10°C) and relatively fresh (S = 38 psu) than the surroundings. The corresponding current had a along-shelf component (v) of 0.1 m s^{-1} in southward direction, and a downslope or across shelf component (u) of 0.05 m s^{-1}. Larger along-shore currents at the shelf break were part of larger cyclonic circulation connected to the intrusion of the Leventine Intermediate Water (not shown).

[14] Depth profiles for T, S, sigma-t, u, v at a site in the transect S with a depth of 125 m are also shown in Figure 5. The plots are for the dates of 15 February, 26 March, and 25 April. The temperature and salinity in February and March were better mixed, and spring surface warming stratified sigma-t of the water column on 25 April. The temperature at the bottom gradually decreased from 13.8 C in February to less than 12.9 C in April as the bottom plume arrived. Since the temperature dominates the plume density structure, the bottom density increased from February to April mimicking the marked bottom temperature variation both in space and time. Because of coastal intrusion of the interior ocean water, the salinity was slightly higher in the surface layer (<80 m) than the bottom on 15 February, and a stronger increase in salinity value can also been seen on 26 March for the entire water column. The bottom plume on 25 April can be characterized by a uniform bottom layer of approximately 10 m from the bottom with low temperatures and salinities (S = 38.45) but high sigma-t (>29) properties, showing its NADDW characteristics. The arrival of the plume can be further evidenced by a bottom intensified southward current of 0.09 m s^{-1} with an offshore zonal component of 0.05 m s^{-1} indicating a downslope current

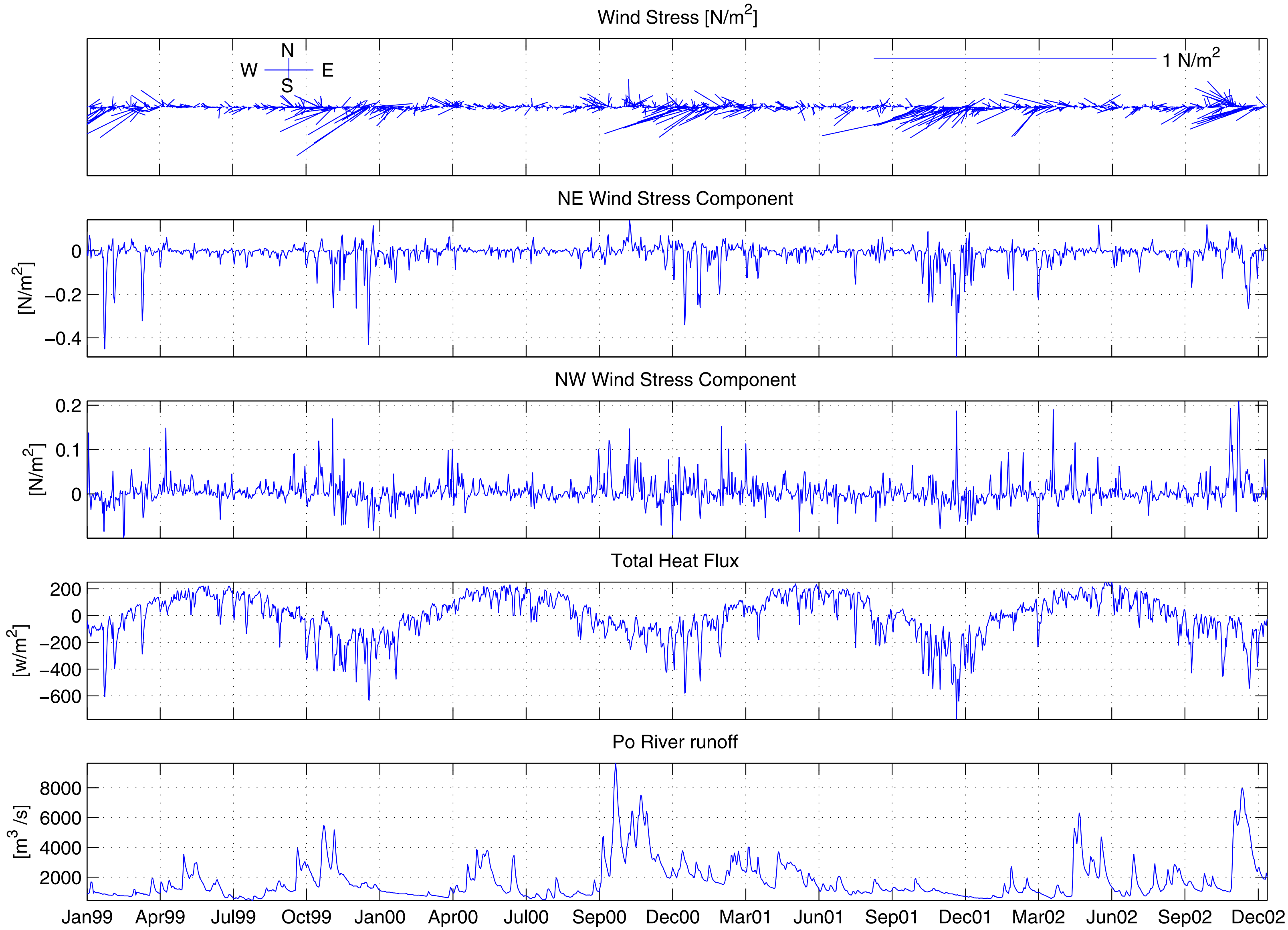


Figure 2. NAS area averaged time series of wind stress, total surface heat flux, and Po River runoff from January 1999 to December 2002. The time series are spatially averaged over the area north of cross section N. The European Centre for Medium-Range Weather Forecasts (ECMWF) 6-hour analysis wind fields were used for the wind stress computation. The ECMWF data were used to compute the surface heat flux by bulk parameterization.

Table 1. Spatial and Time Mean Total Surface Heat Flux ($\overline{Q}_{surf}$), NE Wind Stress Component (N m^{-2}), Time Mean NADDW Production Rate, and the Volume and Time Mean Salinity[a]

	$\overline{Q}_{surf}$, W m^{-2}	NE Wind Stress Component, N m^{-2}	NADDW Production Rate,[b] Sv	S, psu	Po River Runoff, m^3 s^{-1}
1999–2000	−220	−0.04	0.33	37.84	903
2000–2001	−156	−0.03	0.0	37.56	1037
2001–2002	−243	−0.06	0.22	37.53	1399

[a]All the rates are spatial/volume averaged for the entire NAS and time averaged over the period from November to January of the years 1999–2000, 2000–2001, and 2001–2002. Po River runoff is time averaged from June to August in 1999, 2000, and 2001, respectively.
[b]NADDW: T < 11.35°C, S < 38.30 psu, and sigma-t > 29.2 kg m^{-3}.

component. This downslope component of the current was not evident in the bottom layer water on 15 February.

3.2. Gargano Plume Interannual Variability

[15] As discussed in the previous section, the Gargano bottom density plume observed in spring 2000 was the southward advection of NADDW that had first spread over all the middle Adriatic basin and then became a vein along the western shelf close to the Gargano Peninsula. The NADDW amount was dependant on the successive bora driven cooling events. This dependence is demonstrated by Table 1 that shows the production rate of NADDW averaged for the period from November to January of each year. NADDW production rate (Sv) was the time averaged NADDW water volume (T < 11.35°C, S < 38.30 psu and sigma-t > 29.2 kg m^{-3}) produced in the entire NAS over the three month duration. The winter of 2000 had experienced frequent cooling events, the average heat loss was 220 W m^{-2} and the NADDW production reached 0.33 Sv. In contrast, 2001 was an abnormally mild winter with an average heat loss equaling 156 W m^{-2} only. The mild winter can also be measured by a smaller winter averaged NE wind stress component (Table 1). The NADDW was not formed in the NAS thus no Gargano bottom density plume was found in 2001 (Figures 3b and 6a). This model result agrees with the findings by *Sellschopp and Alvarez* [2003] who quasi-synoptically conducted the CTD survey for the entire Adriatic Sea in January to February 2001. Although an averaged NADDW production of 0.22 Sv was found in winter 2002, this cold and dense water mass was dispersed as it spread toward the south, and completely disappeared before it reached the Gargano Peninsula (Figure 3c). Nevertheless, a weak bottom density plume with T = 12°C, S = 38 psu and sigma-t = 29 kg m^{-3} in late April can still be seen offshore of the Gargano coast (Figure 6b).

[16] From the above discussion, we have seen a clear interannual variability in the formation and characteristics of the Gargano plume that is connected to the NAS autumn and winter heat flux. The density perturbation $\Delta\rho$ produced by prolonged surface cooling in the NAS between 1 November and 30 January is quantified by *Shaw and Csanady* [1983] in the following formula:

$$\Delta\rho = \frac{2tc^2}{L_0 s^2}, \tag{1}$$

where c is the propagation speed of plume, t and L_0 is the time and distance for the plume advection respectively, and s is the shelf slope. Assuming that the minimum c is 0.05 m s^{-1}, the maximum t for the plume to arrive at the Gargano Peninsula is 90 days, L_0 is 360 km and $s = 10^{-3}$, the density perturbation according to (1) is calculated to be 1.3 kg m^{-3}. Since the rate of change of the temperature in time of a column of water with a depth of h is subjected to an input of heat flux Q through the surface, a relation between Q and $\Delta\rho$ can be obtained from

$$Q = \frac{\Delta\rho h C_p}{\alpha t} \tag{2}$$

where c_p = 3980 J kg^{-1} K^{-1} is the heat capacity, and α (= 2 × 10^{-4} °C^{-1}) is coefficient of thermal expansion.

[17] If we assume that the density perturbation is the time-averaged density change between 1 November to 31 January due to the cooling of the water column in the NAS, a constant surface cooling of Q = 175 W m^{-2} is then required to achieve the density change $\Delta\rho$ = 1.3 kg m^{-3} for a well mixed NAS with an average water depth of 50 m. In other words, a constant heat loss of 175 W m^{-2} over three-month duration is needed in order to induce a density perturbation large enough to generate the Gargano bottom plume. Without a sufficient surface cooling, the bottom density current is too weak to arrive at the Gargano Peninsula before the water mass is dispersed. This explains why the Gargano plume was not formed during the winter 2001, as the autumn-winter surface heat loss was 156 W m^{-2}. In the winter 2000, the plume was fully formed since the heat loss was significantly larger than the minimum requirement.

[18] In addition to the strong surface cooling, *Vilibić* [2003] also found lower Po River runoff during summer and autumn months favors preconditioning for NADDW production in the following winter as the density generally increases in the area. *Vilibić and Orlić* [2001] found a phase lag of −1 and −4 months in the correlation between Po River runoff and the subsurface vein of dense water in the SAS, respectively. As shown in Table 1, although the winter 2002 total heat loss was 243 W m^{-2}, and the strongest among all three years, a weak and dispersed Gargano plume was observed. This is due to the fact that summer (June–August) 2001 was the wettest among all three years with an averaged Po River runoff of 1399 m^3 s^{-1} (Table 1). As a result, in winter 2002 the NAS had a lowest salinity with an averaged value of 37.52. In comparison, summer of 1999 had a Po River runoff of 903 m^3 s^{-1}, and an averaged salinity of 37.84 for winter 2000. The difference in the summer Po River runoff caused a winter NAS density difference of 0.25 kg m^{-3} between 2000 and 2002, thus according to (1) an additional 10 W m^{-2} surface heat loss would be needed for winter 2002 to produce same amount of NADDW as in 2000.

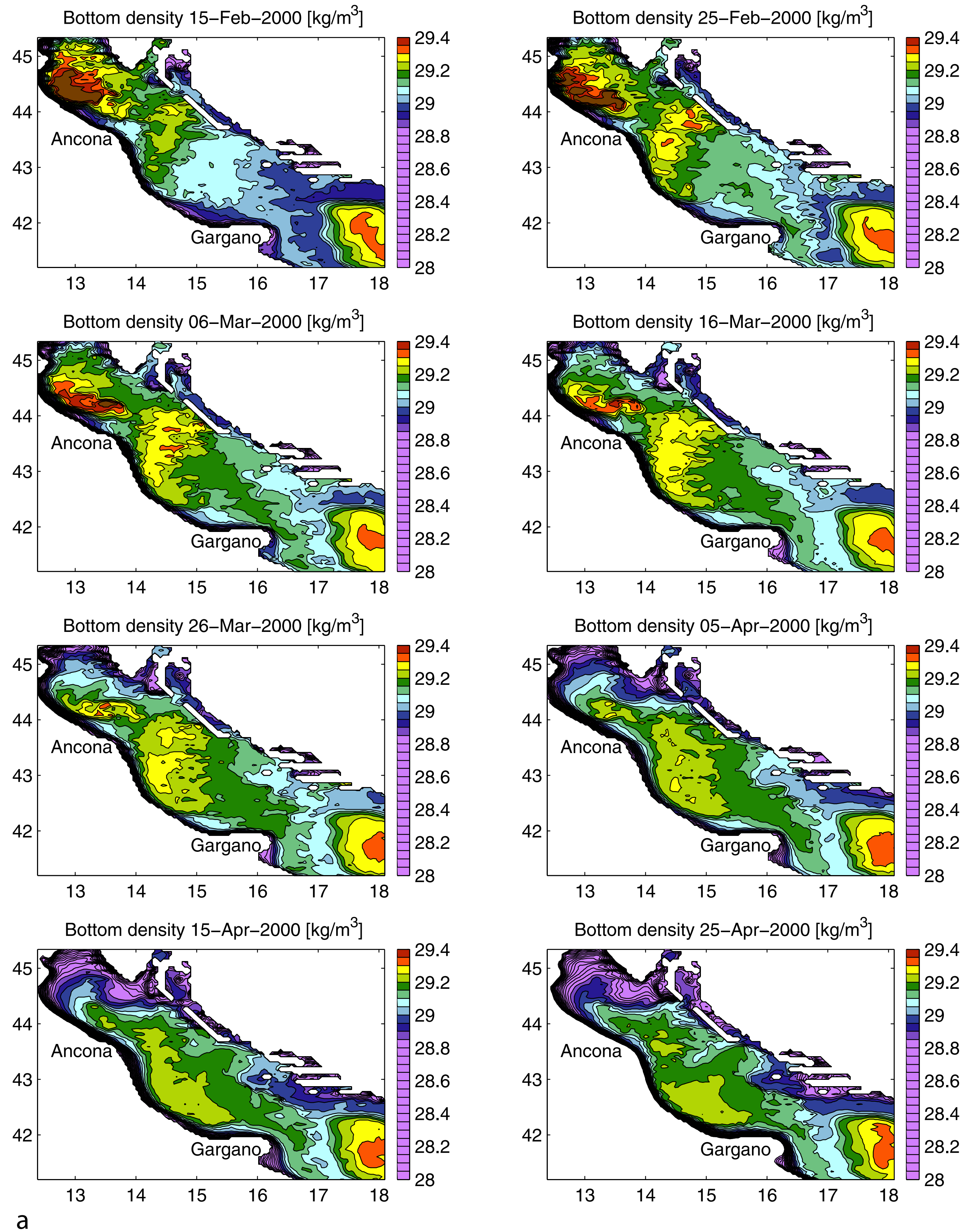
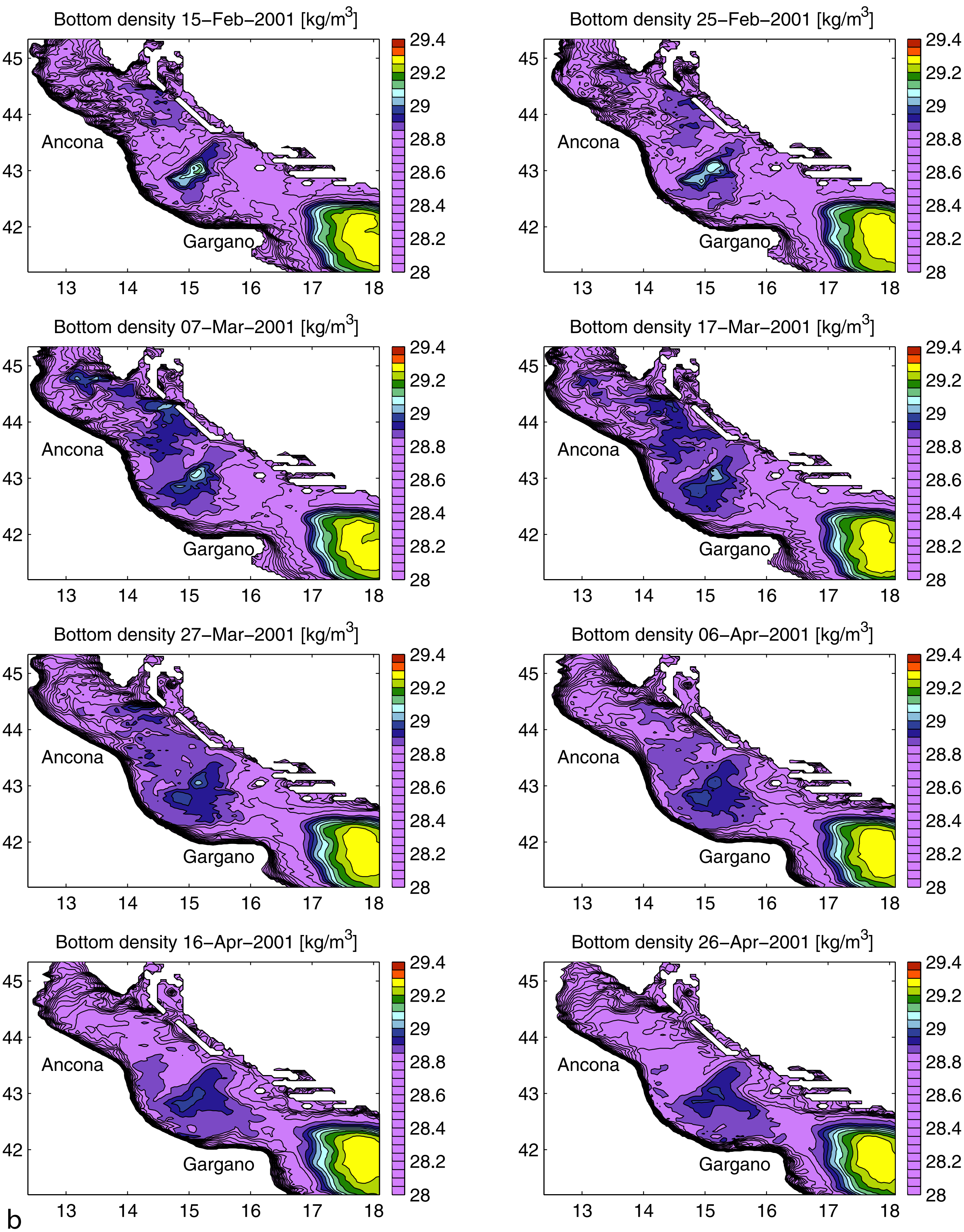


Figure 3. Model-predicted bottom density fields (bottom layer) from 15 February to 25 April (a) 2000, (b) 2001, and (c) 2002.



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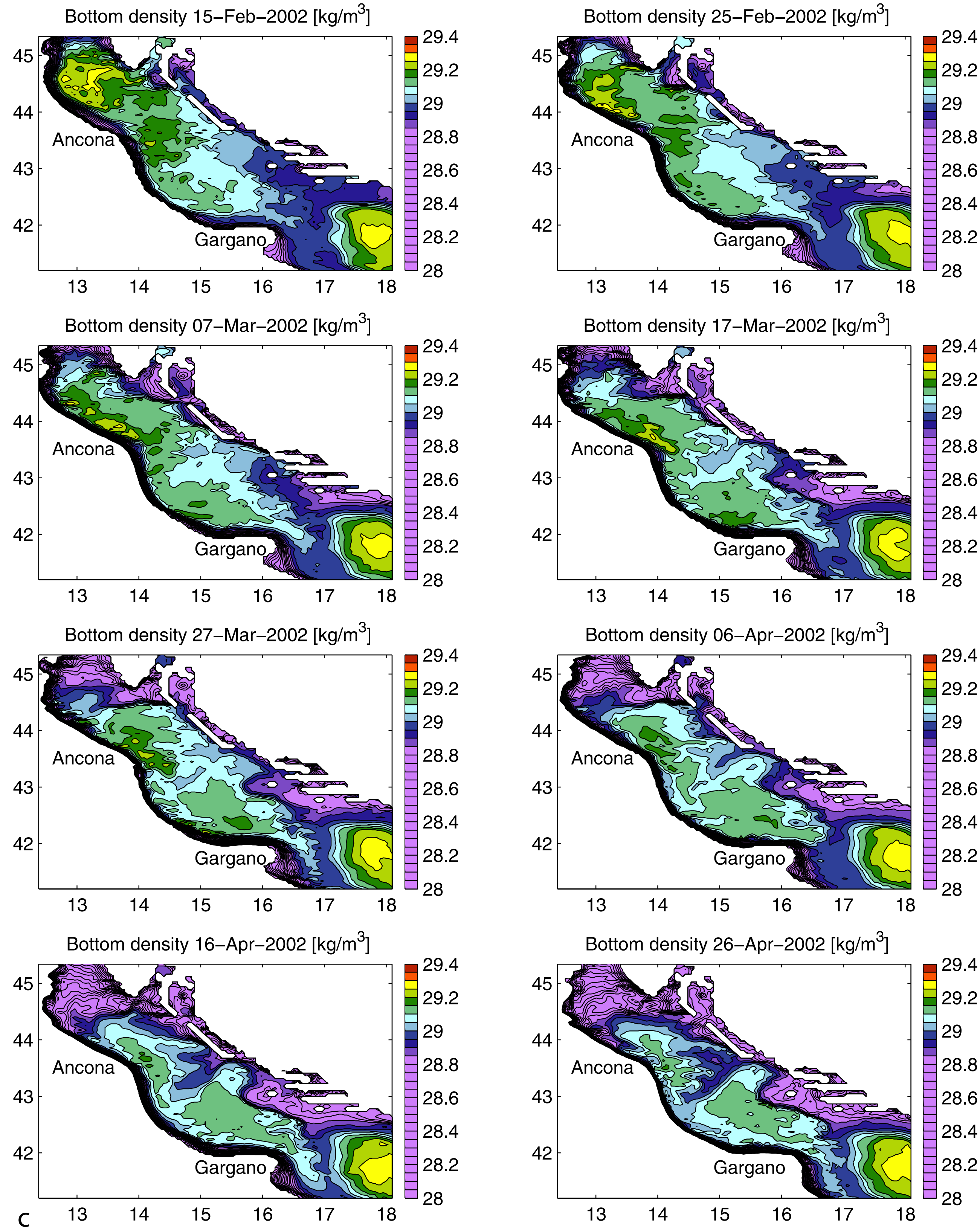

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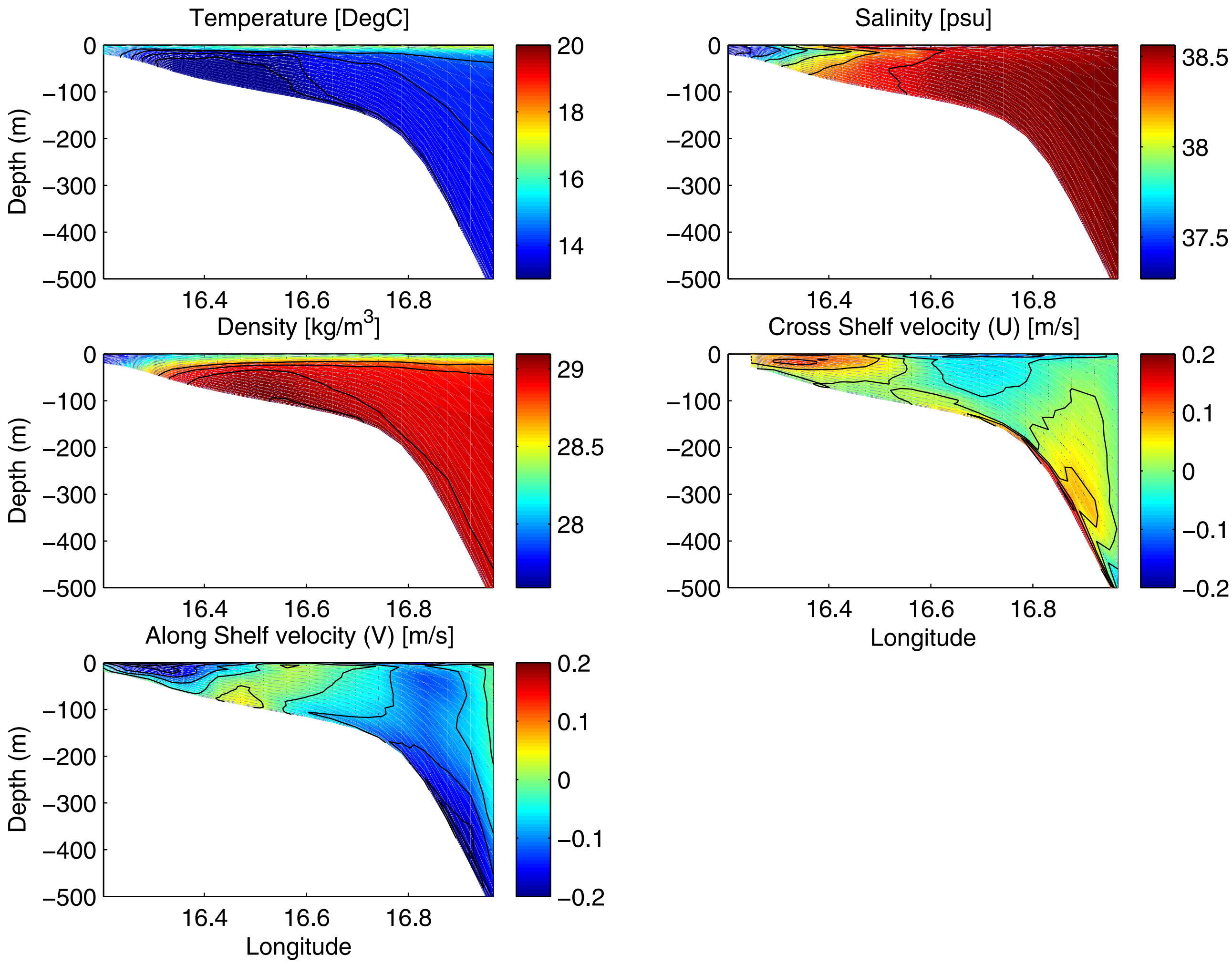

Figure 4. Model-predicted daily averaged temperature (T), salinity (S), sigma-t, and along-shelf (v) and cross-shelf (u) velocity components on 25 April 2000 at the transect section S. Positive values of along-shelf and cross-shelf velocities indicate northward and eastward directions, respectively.

[19] We noted that from our numerical experiments, the Po influence on the NADDW formation was mainly found between their seasonally averaged values with a 5 month phase lag. We did not find correlation between Po River runoff and NADDW production rate at time period shorter than 3 months, like *Vilibić and Orlić* [2001] and *Vilibić* [2003].

3.3. Heat Transport by the Gargano Plume

[20] Shown in Figure 7 is the estimated averaged rate of the heat content change (heat flux) and total surface heat flux between 1 November 1999 and 31 January 2000. The change in heat content integrated over the depth (H) was estimated by $\int_{-H}^{0} \rho c_p \Delta T dz$ where ρ is water density, and ΔT is the temperature change with time. During this period the heat content in the northern Adriatic Sea (averaged over an area north of the cross section N) decreased at an average rate of -206 W m^{-2} (Table 2). The maximum heat loss occurred offshore of Split in Croatia (Figure 7a) that is in agreement with the location of the maximum surface heat loss (Figure 7b). A band of large surface heat loss along the eastern Adriatic coast is associated with the warm coastal current that determines a larger air and sea temperature difference thus a stronger sensible heat flux and longwave radiation there. The cloud distribution during the bora storms, when the cloud lines usually developed some distance away from the east coast of the Adriatic Sea due to the Foehn condition of the Dinaric Alps [*Wang*, 2005], may also contributes to the NAS surface heat flux. As the air picked up moisture from the ocean, the Stau effect of the Apennines further enhanced the cloud formation on the west coast and therefore reduced the surface heat loss there. Apart from the coastal zone of the western Adriatic, a minimum in heat content change can also be observed over the Jabuka Pit. This is a region with the large water depth in a region influenced by the bora events, thus minimum temperature changes occurred in the water column as a result of winter surface cooling.

[21] Table 2 shows the model-predicted heat balance (Q_{diff}) and horizontal heat flux ($\overline{Q}_{adv}$) at the cross section N for the winter of 1999–2000, 2000–2001, and 2001–2002. Q_{diff} is the difference between the averaged surface

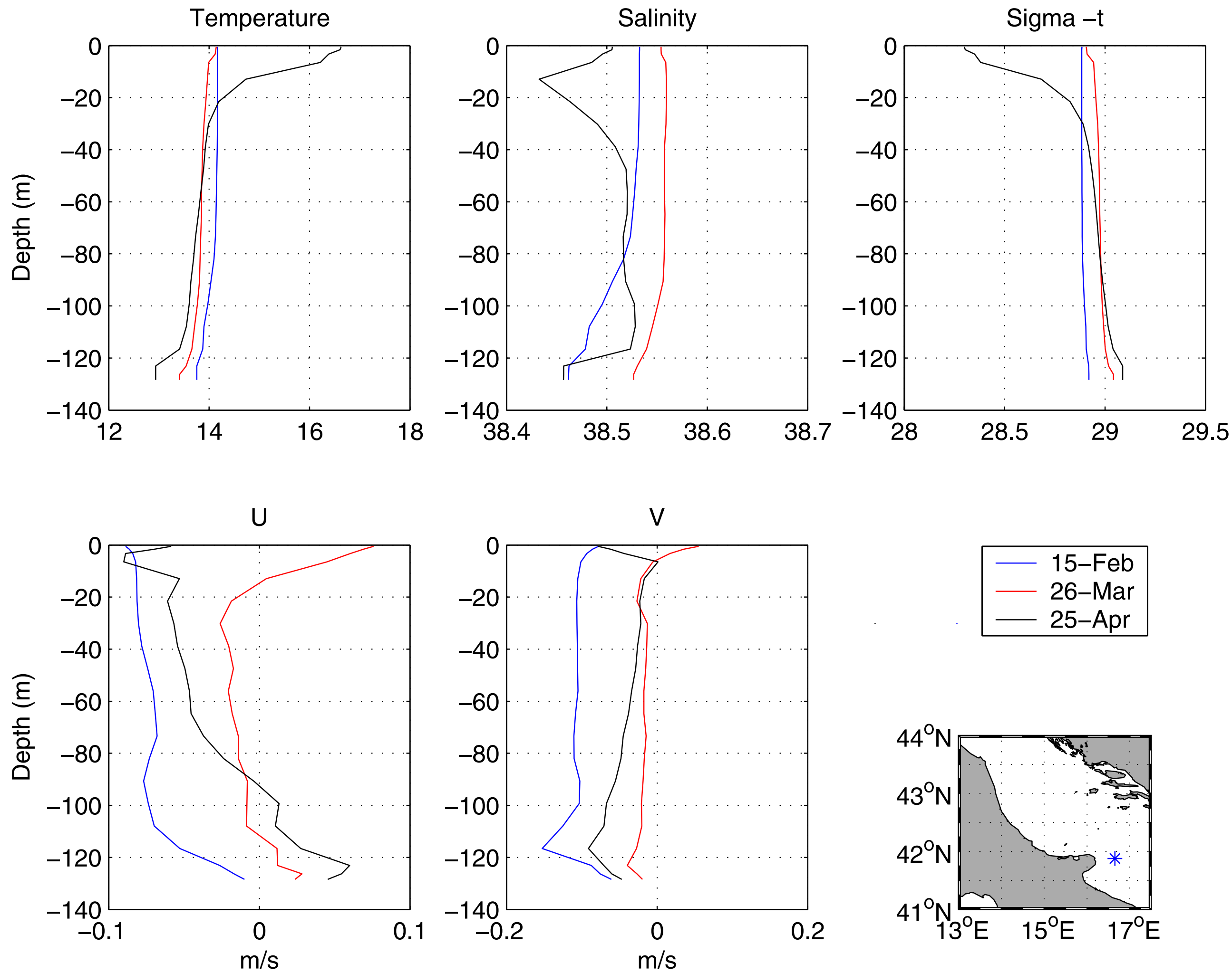

Figure 5. Model-predicted daily averaged depth profiles for temperature (*T*), salinity (*S*), sigma-t, and cross-shelf (*u*) and along-shelf (*v*) velocity components on 15 February, 26 March, and 25 April 2000. The location of the site is shown in the inset. Positive values of along-shelf and cross-shelf velocities indicate northward and eastward directions, respectively.

heat flux over the period of November–January ($\overline{Q}_{surf}$ in Table 1) and the heat content change for the area north of the cross section N ($Q_{hc} = \int_{-H}^{0} \rho c_p \Delta T dz$ in Table 2). $\overline{Q}_{adv}$ was time averaged over the same period of the model run, using $Q_{adv} = \frac{1}{S_0}\int\int_S \rho c_p v T ds$ where v and T are the model-predicted velocity and temperature at the cross sections, S is the cross section area and S_0 is the surface area. As shown in Table 2, Q_{diff} and $\overline{Q}_{adv}$ were all positive, indicating a net heat inflow from the south at the cross section. Close agreement between these two values confirms that the heat budget closure of the NAS during the bora event was a balance between the surface heat loss, horizontal net heat inflow from the south and resulting negative heat content change in the water column. In particular, the net heat inflow at the cross section N was only about 6% of the surface heat loss ($\overline{Q}_{surf}$) of the corresponding area, suggesting that horizontal advection played a minor role in controlling the heat content change over the shallower northern shelf during the winter periods. The net heat inflow at the cross section is a result of basin-scale cyclonic circulation that advected the warmer LIW northward into the NAS.

[22] Figure 8 shows southward water mass and heat transported by the Gargano plume (sigma-t > 29.2 kg m^{-3}) at the transect section S in year 2000. The horizontal flux of water mass and heat transported by the plume observed on 15 April 2000 were calculated to be 0.05 Sv and −30 W m^{-2}. In contrast, negligible mass and heat transport were observed for year 2001, and 2002. The model-predicted mass flux transported by the density plume in 2000 appears to be consistent, in its order of magnitude, with historical in situ observations, in which the bottom density plumes were identified in the region. For example, *Artegiani and Salusti* [1987] found a dense water vein at a transect section north of Vieste in April 1981. The vein had a mass flux of 0.04 Sv. Using June 1983 oceanographic cruise data, *Zoccolotti and Salusti* [1987] found the mass flux associated with the bottom plume to be 0.06 Sv at the northernmost transect section off the Gargano coast; and *Bignami et al.* [1990b] also

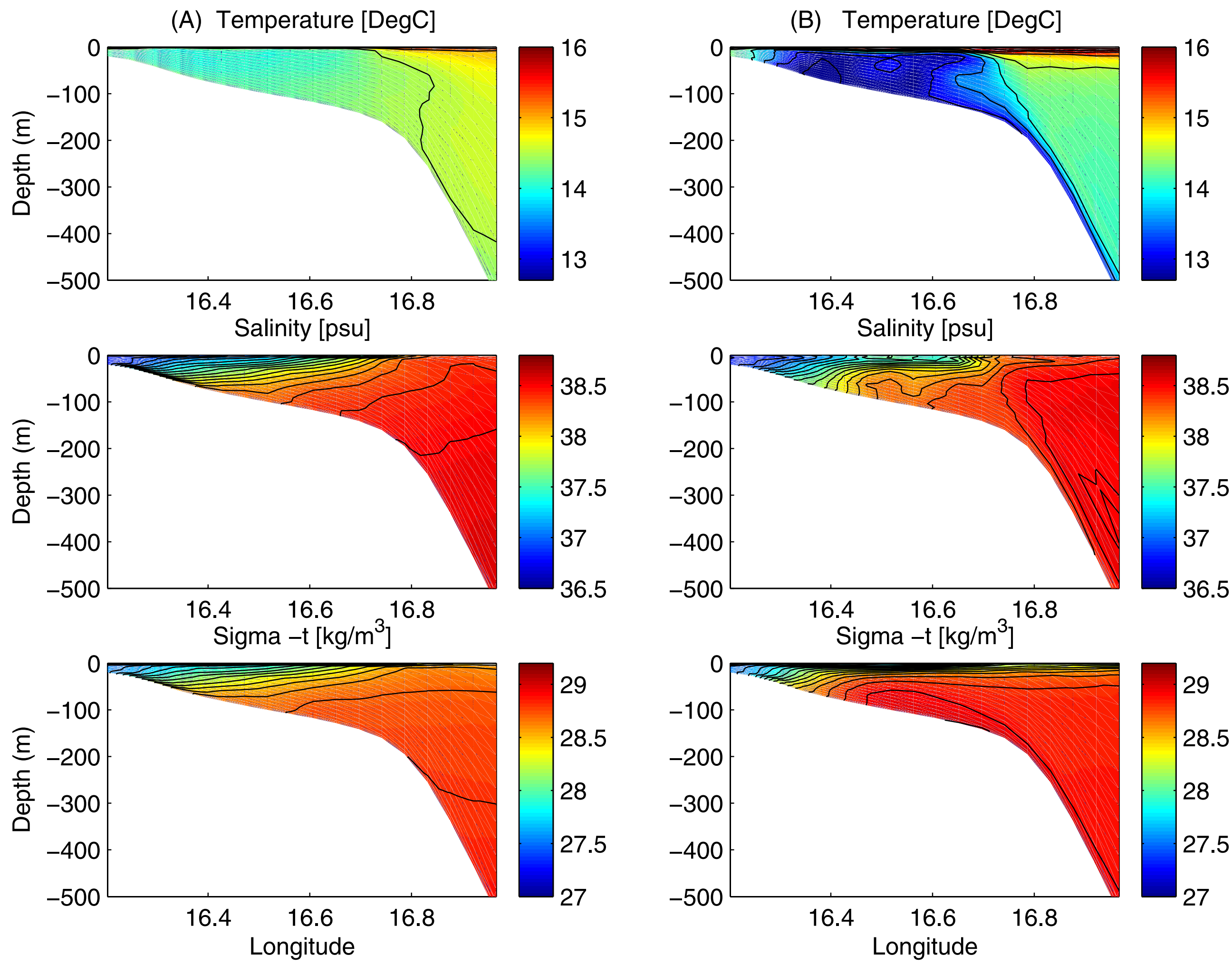

Figure 6. Model-predicted daily averaged temperature (*T*), salinity (*S*), and sigma-t at the transect section S on (a) 26 April 2001 and (b) 26 April 2002. Positive values of along-shelf and cross-shelf velocities indicate northward and eastward directions, respectively.

estimated a mass flux of 0.04 Sv for the bottom plume observed in a cross section upstream of the Bari Canyon in October 1987.

[23] It is interesting to note in Figure 8 that the bottom density plume arrived at the Gargano Peninsula in pulses. In our simulation, each pulse corresponded to a major bora wind storm occurred three months earlier in the previous autumn or winter months. For instance, two major bora episodes with surface heat flux less than -500 W m^{-2} in December 1999 produced corresponding pulses in March 2000.

3.4. Model Comparison With Observations

[24] In order to evaluate the general circulation model performance, we compared the temperature observation in a transect section south of Gargano Peninsula with the model results in November 2002 (Figure 9). The temperature measurements were done by the ship of opportunity XBT survey conducted on 6 November 2002 in the framework of the ADRICOSM project (http://www.bo.ingv.it/adricosm). The model prediction is the daily averaged temperature fields from the model.

[25] The model had successfully captured the general features of the temperature distributions including the observed thermocline at a depth of 50 m. Some disagreement between the model and data exists and can be discussed in the following. The model-predicted thermocline has a more smoothed temperature gradient than the observations that presented more rapid temperature changes from the warmer surface water to the colder bottom water. This disagreement is probably caused by the excessive vertical mixing of the model as already discussed by *Wang and Symonds* [1999] and *Wang* [2005]. As a result of the stronger mixing in the water column, the modeled surface temperature was lower than the observations. Since the open ocean deep convection is one of major mechanisms for SADDW formation, weaker stratification predicted by the model is likely to overestimate the depth of convection (typically 700–800 m) and the production rate of SADDW.

[26] The data model comparison for the winter period was performed in Figure 10. The CTD data from 28 January to 13 February 2001 was divided into three regions and compared with model results sampled at same stations on the T-S diagram. The model has clearly reproduced major

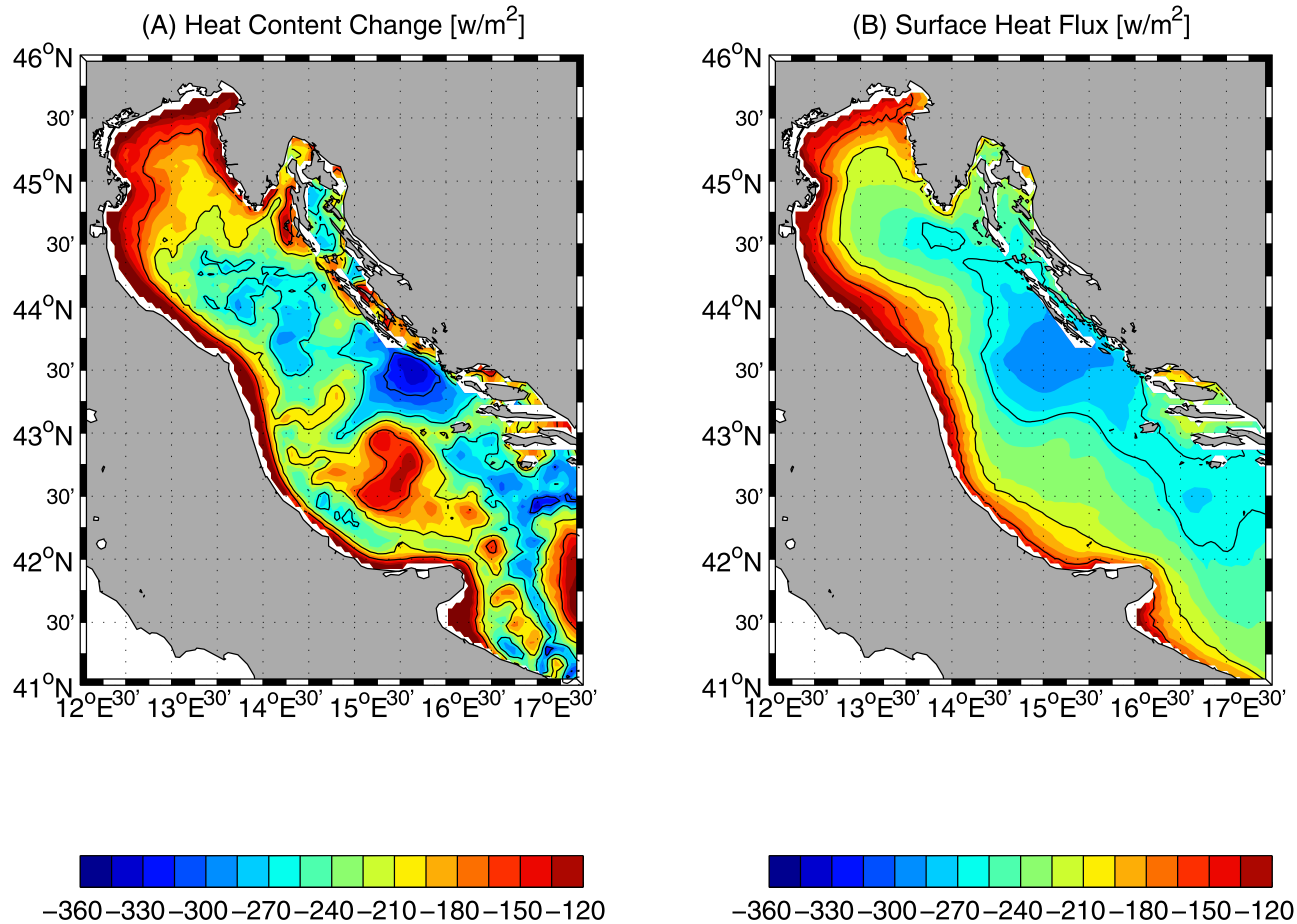

Figure 7. Model-predicted (a) time-averaged rate of the depth integrated heat content change (heat flux) and (b) total surface heat flux from 1 November 1999 to 31 January 2000.

T-S characteristics for all three regions. These include the western Adriatic coastal current (WACC) water with low T and S in the NAS, the LIW of high T and S in both middle and southern Adriatic and the SADDW of highest density in the SAS. The major difference is the wider spreading of T-S values predicted by the model in the NAS, and thus underestimated minimum T-S values in the middle and southern Adriatic Sea, in comparison with the observations. This is again due to the diffusive nature of the model that predicted a more diffused T/S therefore less dense water mass in the NAS. As a result, the model cannot fully reproduce the cold and less saline water mass observed in the middle and southern Adriatic coast. For the same reason, the model underpredicted the water density in all three regions. We note that the 2001 is a wet and mild winter that did not produce the NADDW. The densest water observed in the Jabuka Pit in the middle Adriatic Sea is reminiscent of cold winters of previous years [*Sellschopp and Alvarez*, 2003]. The model again failed to simulate the water mass.

[27] Since our focus of the study is on the NADDW formation in the NAS and its relation with the bottom density plume dynamics off the coastal zone of Gargano Peninsular, our conclusion of the paper should not be affected by the smoothed model thermocline in the SAS, although the model-predicted NADDW production rate, and the intensity and speed of the Gargano bottom density plume may have been underestimated.

4. Summary and Conclusions

[28] The Adriatic Sea general circulation model (AIM) was implemented to study the Gargano bottom density plume in the SAS and its interannual variability for a period from 1 January 1999 to 31 December 2002. The study found that the Gargano bottom density plume is a bottom density current driven by a perturbation in density as a result of successive bora cooling events in the NAS from previous autumn and winter. The density current advects cold (T <

Table 2. Averaged Depth Integrated Heat Content Change (Q_{hc}) for the Area North of the Cross Section N, the Horizontal Heat Flux ($\overline{Q}_{adv}$), and the Heat Balance (Q_{diff}) at the Cross Section Over the Period of 1 November to 31 January of the Years 1999–2000, 2000–2001, and 2001–2002[a]

	Q_{hc}, W m^{-2}	Q_{diff}, W m^{-2}	$\overline{Q}_{adv}$, W m^{-2}
1999–2000	−206	14	11
2000–2001	−144	12	12
2001–2002	−225	18	10

[a]Note: $Q_{hc} = \int_{-h}^{0} \rho c_p \Delta T dz$ and $Q_{diff} = Q_{hc} - \overline{Q}_{surf}$.

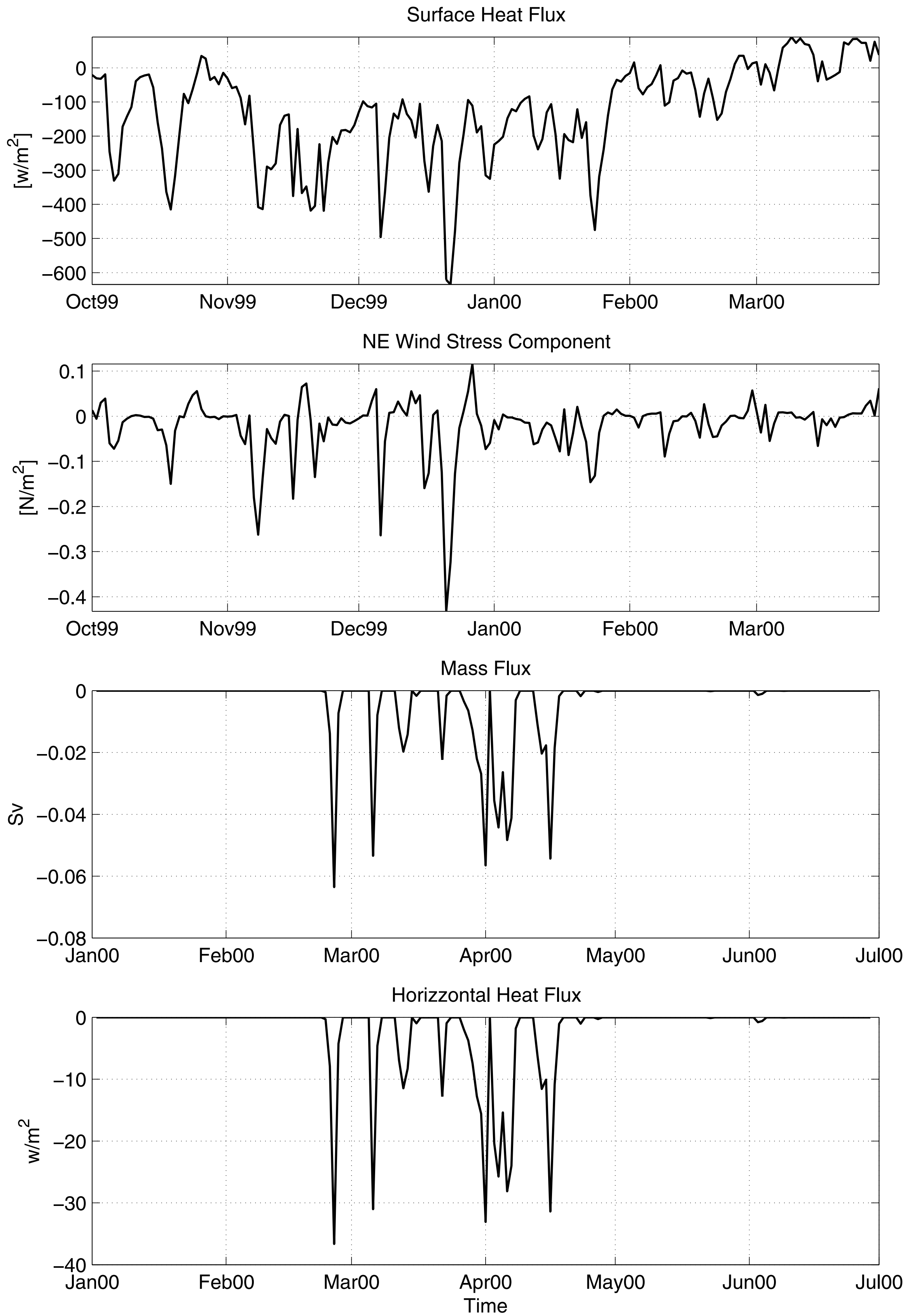

Figure 8. NAS area averaged time series of surface heat flux, NE wind stress component from October 1999 to April 2000, and the model-predicted southward horizontal mass and heat fluxes driven by the Gargano bottom density plume (sigma-t > 29.2 kg m^{-3}) at the transect section S from January to July 2000. Negligible mass and heat fluxes were predicted in years 2001 and 2002 at the same transect section.

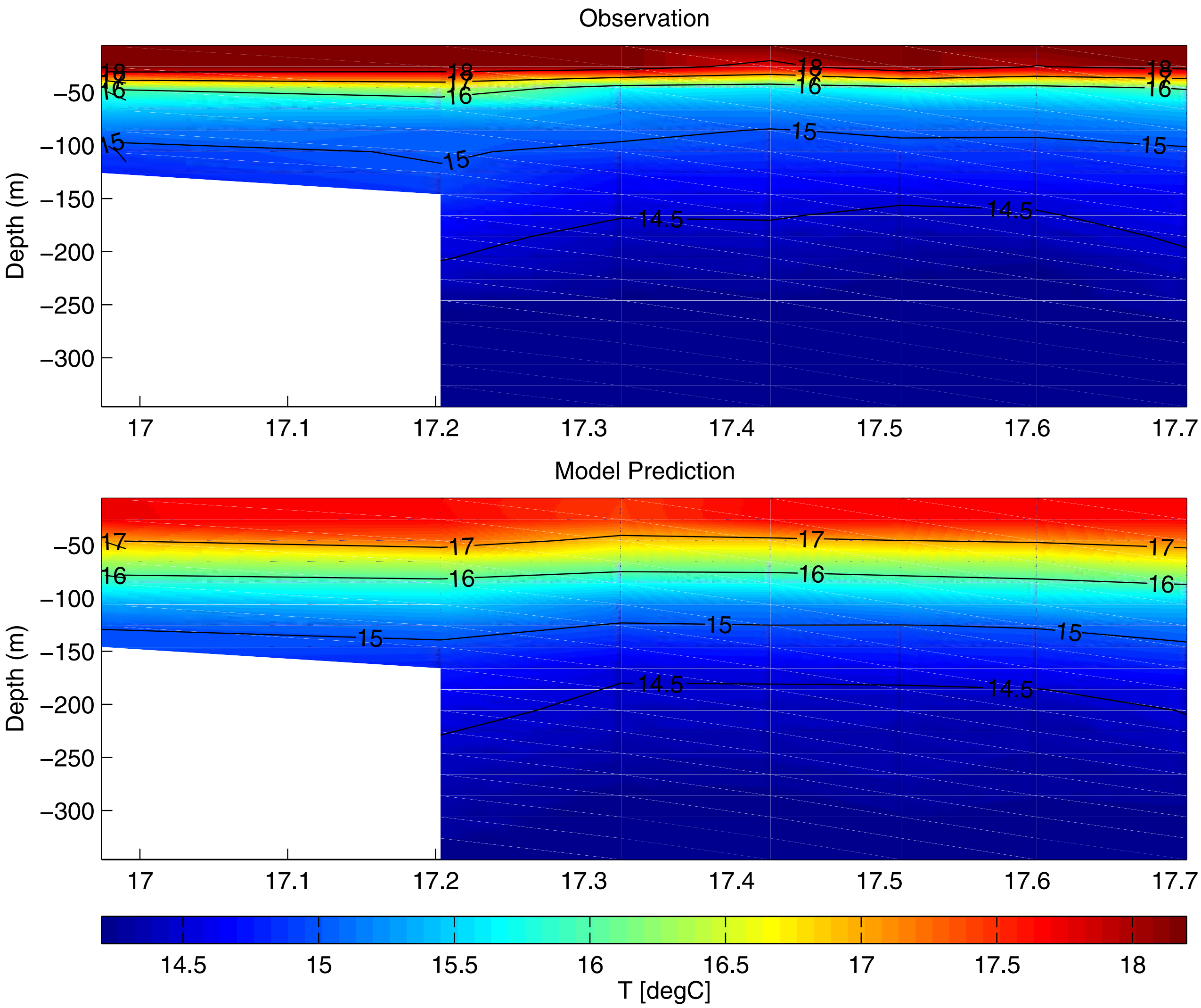

Figure 9. (top) Observed and (bottom) model-predicted temperature on 6 November 2002. The XBT transect was shown in Figure 1. The model prediction is the daily averaged field.

10°C) and less saline (S < 38) NADDW from the NAS to the SAS, and the propagation speed of the plume can reach 0.1 m s^{-1} with a downslope component in order of 0.05 m s^{-1} at the Gargano peninsula. The southward mass and heat transport associated with the Gargano plume can be calculated to be 0.05 Sv and −30 W m^{-2} at a transect section near Gargano Peninsula, where the core of the density plume (sigma-t = 29.2 kg m^{-3}) was located at a depth between 100 and 150 m over the shelf with a width of 22 km and thickness of 20 m. These results suggest that about 15% of the NADDW and NAS heat content change produced over previous winter was transported to the SAS by the Gargano plume. We note that these mass and heat transport rates are in agreement with previous theoretical and observational works conducted by *Shaw and Csanady* [1983] and *Zoccolotti and Salusti* [1987].

[29] One of most important findings of this work is connection between the interannual variability in the Gargano bottom density plume in the SAS and the production of NADDW in the NAS. The numerical study demonstrated that a continuous heat loss of 175 W m^{-2} from November to January is required to produce adequate volume of NADDW so that a density perturbation is formed which is large enough to drive a density current that reaches the Gargano Peninsula in the spring. This minimum requirement of heat loss for the Gargano plume formation approximately equates to 8 consecutive bora events assuming that each event lasts for 5 days, and has a typical surface heat flux of −371 W m^{-2} in the NAS [*Wang*, 2005]. In 2001, the total winter surface heat loss for the NAS was −156 W m^{-2}, therefore no Gargano plume was formed.

[30] In addition to the autumn and winter surface cooling, summer fresh water preconditioning of the NAS density is another important factor in the Gargano plume generation and may cause its interannual variability. A large runoff summer, resulting from a large Po river runoff, produces a low NAS density field. Thus additional heat loss is required for NADDW production to produce the Gargano density plume. This process was at work in year 2002. Summer 2001 was the wettest with the largest Po River runoff among

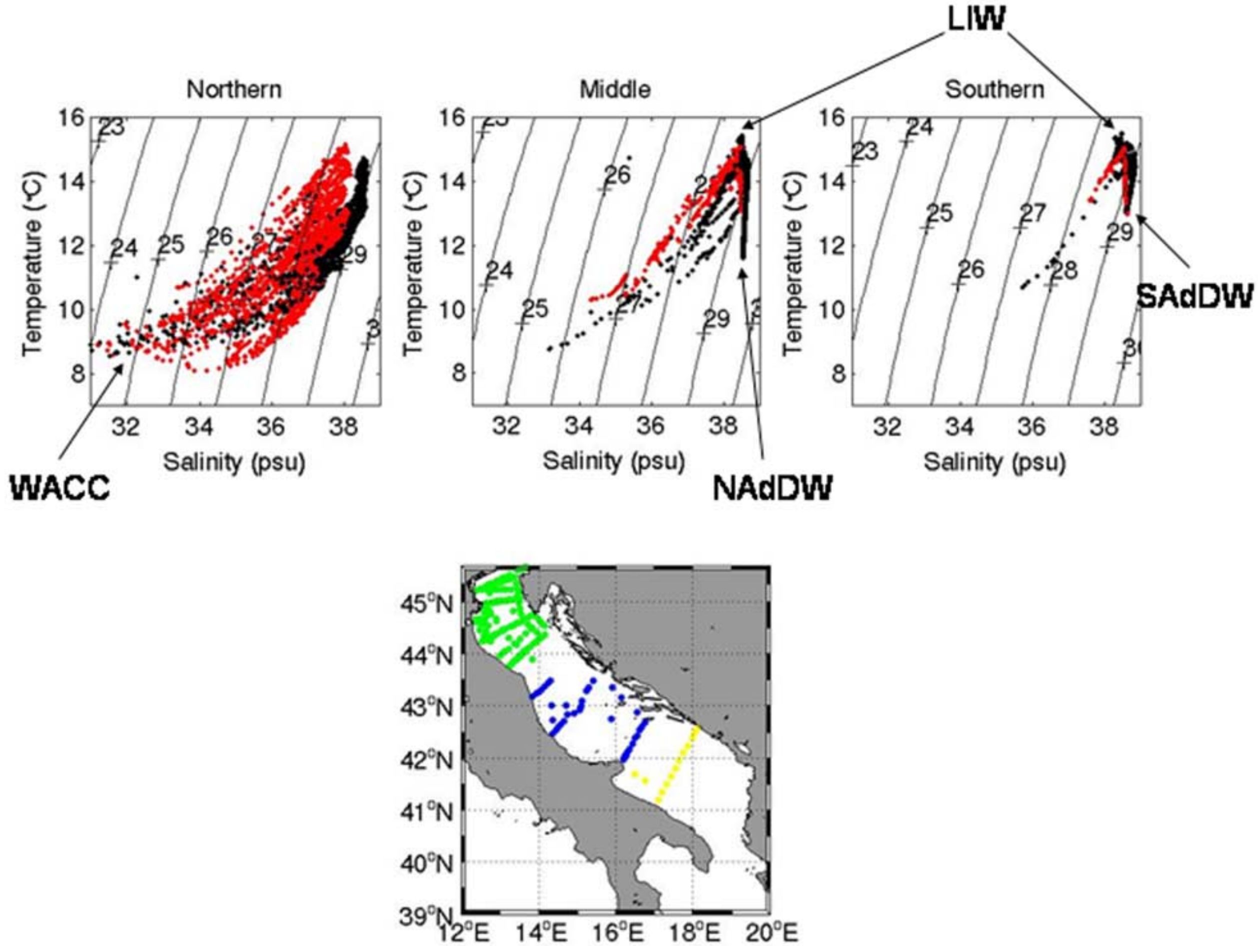

Figure 10. T-S diagrams of CTD data (black) and model prediction (red) for the period from 28 January to 13 February 2001. The CTD data and model predictions are divided into three regions of the NAS (northern), the middle basin (middle), and SAS (southern), where the CTD stations are indicated in green, blue, and yellow, respectively, in the inset map. WACC is the Western Adriatic Coastal Current as defined in the text. The CTD data are from Alliance cruise ADRIA01.

all three years. Therefore the NAS salinity field was the lowest in the winter 2002. Although winter 2002 had the strongest surface heat loss ($\overline{Q}_{surf} = -243$ W m^{-2}), lack of the summer preconditioning had weakened the NADDW production in the NAS, and a weaker and more dispersed Gargano plume was thus observed in the following spring.

[31] Finally, the study also demonstrated that total heat budget of the NAS during the winter season was negative, as the amount of heat lost at the air-sea interface during that period was much larger than the amount of heat gained by horizontal advection. As a result, the NAS during the winter season experienced a strong heat content decrease. Our simulation show that in winter of 2001, successive bora events decreased the heat content of the water column with an area averaged value of 206 W m^{-2} over the northern Adriatic Sea, and the net heat inflow occurred at the cross section N was only 5% of the total surface heat flux.

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