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# Investigation of Water Masses in İzmir Bay, Western Turkey

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**Abstract:** The main purpose of this paper is to explore seasonal variability of the local hydrography and investigate the water masses, their seasonal and regional variations in the vicinity of İzmir Bay based on data sets collected between 1994 and 2003. The general water movement characteristics in the bay are provided by CTD data analysis together with Killworth's general circulation model. In the bay, three distinct water masses exist: ASW (Aegean Sea water), IBW (İzmir Bay water) and IBIW (İzmir Bay inner water). Generally, vertically homogenous ASW enters the bay from the north, near Karaburun in winter, and horizontally homogeneous ASW inflow occurs above a pcynocline through the Foça-Karaburun vertical section in summer. The outflow occurs in the sub-surface and bottom layer near the coast of Foça in winter while it flows out under the pycnocline in summer as a result of thermohaline behavior of stratified water. Wind-driven circulation causes cyclonic or anti-cyclonic movements in the middle section of İzmir Bay. Cyclonic movement takes place under the influence of southerly and westerly winds. On the other hand, northerly and easterly winds cause an anti-cyclonic movement.

**Key Words:** seawater properties, hydrology, water mass, water movements, circulation, İzmir Bay

## İzmir Körfezi'ndeki Su Kütlelerinin Araştırılması, Batı Türkiye

**Özet:** Bu çalışmanın temel amacı 1994–2003 yılları arasında K. Piri Reis araştırma gemisiyle toplanan veriler ışığında, İzmir Körfezi yöre hidrografisinin ve oluşan su kütlelerinin mevsimsel ve bölgesel değişimlerini araştırmaktır. Körfezdeki genel su hareketliliği, CTD analizleri ve Killworth genel sirkülasyon modeli yardımıyla ortaya konmuştur. Körfezde birbirinden farklı üç tip su kütlesi tesbit edilmiştir: ASW (Ege Denizi suyu), IBW (İzmir Körfez suyu) ve IBIW (İzmir İç Körfez suyu). Genel olarak, kış döneminde su kolonu boyunca homojen ASW Karaburun açıklarından, yaz döneminde ise yatayda homojen ASW piknoklin üzerinden Karaburun-Foça ara kesiti boyunca, Körfeze girer. Körfezden su çıkışı, yaz döneminde tabakalı akışın termohalin özelliği sonucu piknoklin tabakasının altından kış döneminde ise Foça yakınlarından yüzey altı ve dip tabaka suyu olarak Ege Denizine doğru oluşur. Rüzgar etkisi altındaki sirkülasyon Körfezde (Uzun Ada'nın güney doğusu) rüzgarın yönüne bağlı olarak saat yönü veya saat yönünün tersi istikametinde döngüler oluşturur. Saat yönü tersine doğru olan hareketlilik genellikle batı ve güneyli rüzgarların etkisinde meydana gelir. Diğer taraftan, doğu ve kuzey yönünden esen rüzgarlar saat yönündeki hareketliliğe neden olurlar.

**Anahtar Sözcükler:** deniz suyu özellikleri, hidroloji, su kütleleri, su hareketliliği, sirkülasyon, İzmir Körfezi

## Introduction

İzmir Bay (western Turkey) is one of the great natural bays of the Aegean Sea. The bay is roughly 'L' shaped with a total length 64 km and opens to the Aegean Sea in the north. There are series of islands parallel to the west coast of the bay. İzmir Bay has been studied in three areas distinguished according to their physical characteristics: outer, middle and inner bays. The outer bay is further divided into three sub-regions, outer I, outer II and outer III (Figure 1a). The water properties of the bay were analyzed generally using the data from these different regions. The previous studies are concentrated on the water properties of these regions and compare the water properties according to their physical, chemical and biological characteristics. The numbers of the studies directly concerned with the water masses are few and most of them examine the water movements and forces that influence the water

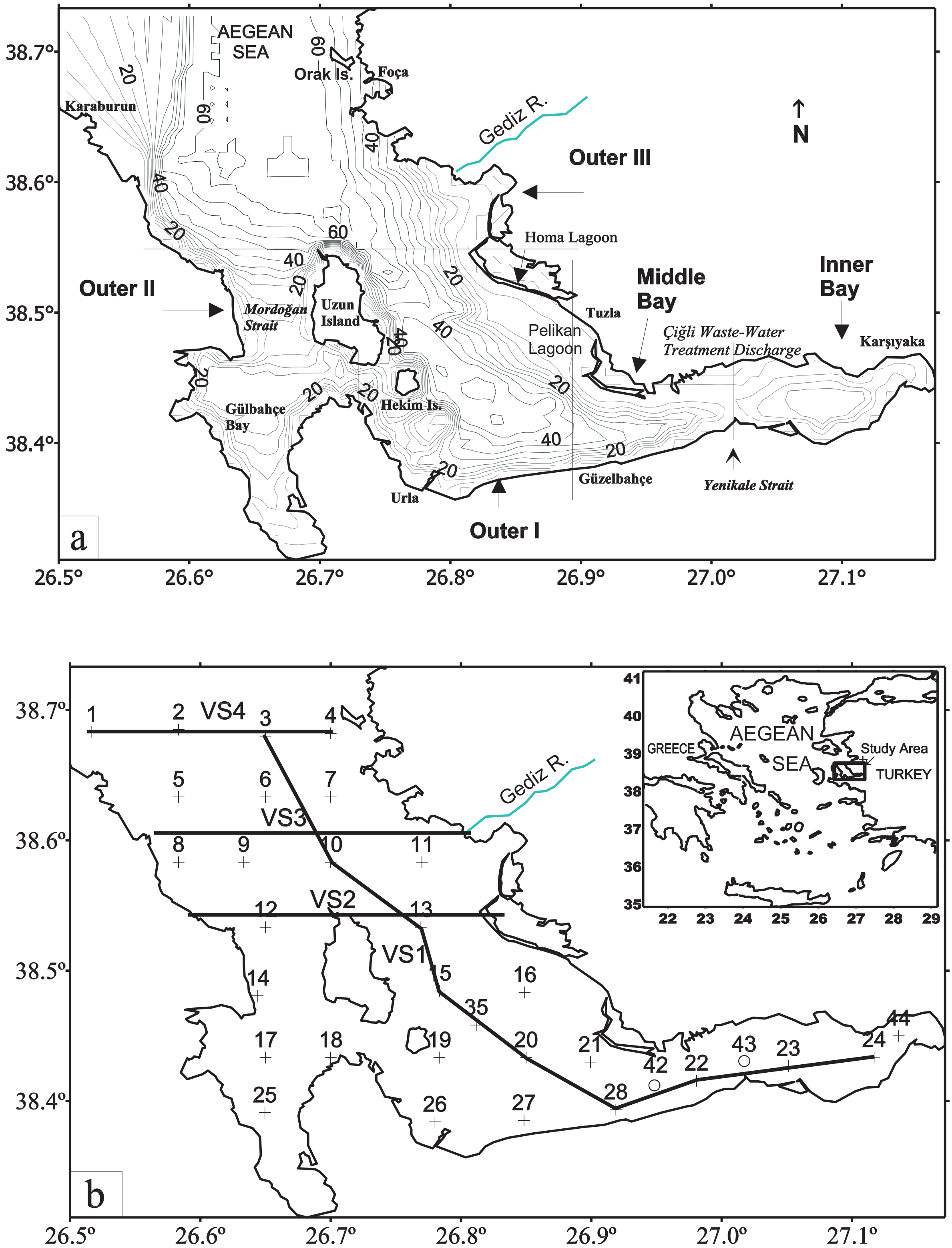



Figure 1. (a) The regions, which have different type of water properties and İzmir Bay topography (contour interval 5 m), (b) the locations of CTD stations (Generally, CTD measurements are made at these stations on every cruise).

movements. Akyarlı *et al.* (1988) have examined the current system and water movement in the bay. Saner (1994) has calculated the circulation pattern and the water exchange between the different regions of the İzmir Bay using a three dimensional wind-driven mathematical model. Vlasenko *et al.* (1998) have tried to find the baroclinic effect of the Black Sea water in the İzmir Bay. The earlier investigations emphasize the role of the wind in the İzmir Bay current system. However, beyond the wind effects, sea level differences related to large-scale motions affect the currents in the considerably. Alpar *et al.* (1997) have found that barometric pressure is an important factor affecting sea level in the bay. Sayın & Ücüncüoglu (1999) have analyzed the common oscillations of the wind and currents in the İzmir Bay and Pazı (2000) has studied the current system in the bay. Sayın (2003) has given the important physical features based on observations and modeling studies. Although the relevant physical properties of İzmir Bay have been studied before, water masses were not determined in detail.

This manuscript presents a wealth of new data on the hydrography of İzmir Bay. İzmir Bay is an interesting place, as its waters are on the one hand locally forced, but are also subject to exchange with the Aegean waters outside on the other hand. Current knowledge on the water masses and the circulation of the İzmir Bay is based on an eclectic collection of data and therefore no integrated approach to address the bay has been undertaken. The paper reports the hydrography of the İzmir Bay, which is characterized seasonally by thermohaline processes between different water masses. The current scientific interest in the İzmir Bay has provided more detailed research with which to determine: (a) the existence of permanent and semi-permanent flows and (b) the seasonal variability of the water masses in the bay. The authors also report evidence on the seasonal and spatial variation of the circulation in the bay. The discussion is based on the results from 37 oceanographic cruises performed in different seasons within an annual cycle. The current system, together with water properties, plays a very important role on the distributions of pollutants, plankton and fish larvae in İzmir Bay, a region with an important recreational potential. It is necessary to understand the water movements and properties in the bay in order to manage the ecosystems. On the other hand, the evaporation, mixing and convection processes in the coastal area influence the water properties of adjacent offshore seas. The densest water of the Aegean Sea is thought to occur in the coastal area especially as a result of strong evaporation in the shelf and in the bays during the summer season. This study can also be an example for the other bays along the coastal area of the eastern Aegean Sea which plays crucial roles in forming water masses in the Aegean Sea according to their water exchange potentials. A more solid foundation to our knowledge of the circulation and hydrography of İzmir Bay is therefore of considerably wider interest than merely regional. A considerable number of collected data in İzmir Bay makes it possible to analyze the water masses in detail. Consequently, the combination of observation and numerical modeling clarify the formation of water masses and their movements in the bay.

The main hydrographic structures of the bay and zonation of local water masses are discussed in the present study in terms of temperature and salinity. A description of the data set and the methods used are presented and some general hydrographic and physical properties of İzmir Bay are explained in the discussion. The seasonal variations of physical properties are considered in detail and related to the forming water masses.

## Methods

Monitoring studies in İzmir Bay, have been carried out by the Institute of Marine Sciences and Technology of Dokuz Eylül University, İzmir with R/V K. Piri Reis, since 1980. The CTD data were collected during 37 cruises from January 1994 to March 2003. Monthly CTD measurements were carried out at 34 stations using SBE 911 plus CTD system. The CTD probe records temperature, conductivity, light transmission, and dissolved oxygen. Besides the measured temperature values, calculated salinity and density values are important for analysing the water mass distribution in the bay. The location of the CTD stations is shown in Figure 1b. All CTD sensors have been calibrated annually by the Sea-Bird Electronics. The characteristics of the sensors employed are given on Table 1. The accuracy of salinity from the other sensor characteristics can be estimated by translating the values for conductivity and temperature and is found to be about ±0.0005 psu. with a resolution of about ±0.0001 psu.

Table 1. Properties of SBE 911plus CTD system sensors.

| Parametre | Measurement Range | Accuracy | Resolution |
|---|---|---|---|
| Pressure | 0 to 3000 psi | 0.015% of full scale | 0.001% of full scale |
| Temperature | -5 to +35 °C | ±0.001 °C | 0.0002 °C |
| Conductivity | 0 to 7 S/m | ±0.0003 S/m | 0.00004 S/m |
| Dissolved Oxygen | 0 to 15 ml/l | ±0.1 ml/l | ±0.01 ml/l |
| Light Transmission | 0–100 | ±0.025 | |

T-S diagrams and Killworth's Model are used to explore the seasonal variability of the local hydrography in order to determine the local water masses and compute the three-dimensional circulation, respectively. Vertical sections, horizontal contour maps and vertical profiles are drawn to analyze the data in three-dimensions.

### *Model*

The KILLWORTH numerical Ocean General Circulation Model (OGCM) is based on the primitive equations as described by Bryan (1969) and Cox (1984). The specific model configuration was developed by Killworth *et al.* (1989). The free surface version of the Princeton model, which is a modification of the Bryan-Cox-Semtner numerical ocean general circulation model, has been adapted to include a free surface explicitly. The chosen model parameters are shown in Table 2.

The model is forced using real wind data obtained from the Çiğli Meteorological Centre, and four selected sets of hydrological cruise data. To define a realistic stratification, temperature-salinity distributions from the CTD surveys are prescribed in the model as an initial condition. Generally, the surface velocities for thermohaline circulation are weaker compared to the surface velocities of a wind-driven one. On the other hand, thermohaline forcing is not negligible especially in calm weather condition. The simulations are used to examine the evolution of the circulation.

Table 2. The chosen model parameters for the wind-driven circulation experiments.

| Parameters | |
|---|---|
| Horizontal resolution | 500 m |
| Number of vertical layers | 6 |
| Layer thickness (m) (layer 1,2,3,4,5 and 6) | 5, 10 , 15 , 15 , 15 and 10 m |
| Horizontal eddy coefficient for momentum | 1.0E5 $cm^2$/sec |
| Vertical eddy coefficient for momentum | 1.0 $cm^2$/sec |
| Horizontal eddy coefficient for heat | 1.0E5 $cm^2$/sec |
| Vertical eddy coefficient for heat | 0.1 $cm^2$/sec |
| Baroclinic time step | 200 sec |
| Barotropic time step | 5 sec |

Prognostic equations for salinity and temperature are computed for a period of four days with very high horizontal viscosity and diffusivity ($\cong 10^5$ $cm^2$/sec) in order to allow further smoothing of the initial conditions. The model domain is connected to the Aegean Sea. At the northern boundary of the model, the Stevens (1990) active open boundary condition for the tracer field and the Orlanski (1976) radiation condition for the external mode are used. The Stevens active boundary is chosen to force the model with observed temperature and salinity values at the boundary. It is suitable for choosing the radiation condition for the barotropic part due to the lack of surface elevation information related to the Aegean Sea general circulation dynamics. The barotropic part of the model is designed to conserve mass. Therefore, zero net flux through northern boundary is met by the Orlanski boundary condition. The horizontal grid spacing (500 m) was chosen to capture all the scales that may be present in the topographic data and it is also suitable to resolve the internal Rossby radius, varying from 2 km to 12.5 km in the bay.

## Results and Discussion

### *Physical Properties*

In this study, a comparison has been made in time and space to find out certain characteristics of the water that generally exists in the bay. Before analyzing the water properties, average monthly temperature and salinity values along the water column in the entire İzmir Bay between 1994 and 2003 are given in Figure 2. Basin wide horizontally averaged temperature (°C) and sigma-t (kg/m$^3$) time-series variations between January 1994 and March 2003 are demonstrated in Figure 3. From Figures 2 & 3, it is seen that the thermocline depth varies

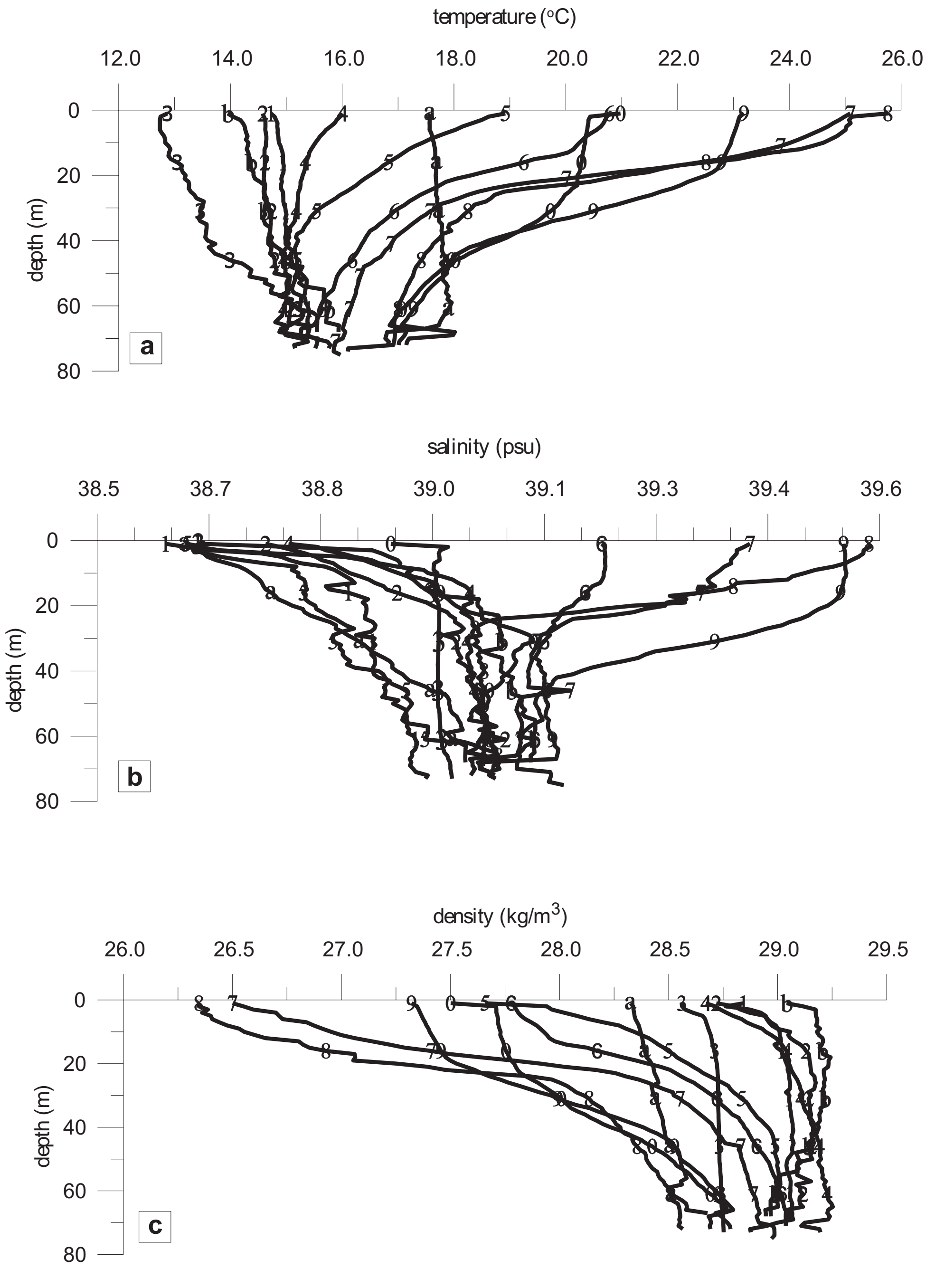



**Figure 2.** Seasonal variations of monthly averaged temperature values along the water column in İzmir Bay between 1994 and 2003. The number on the lines related to the number of months, for example 1 shows January, 2 February, 10 October, 11 November and 12 December.

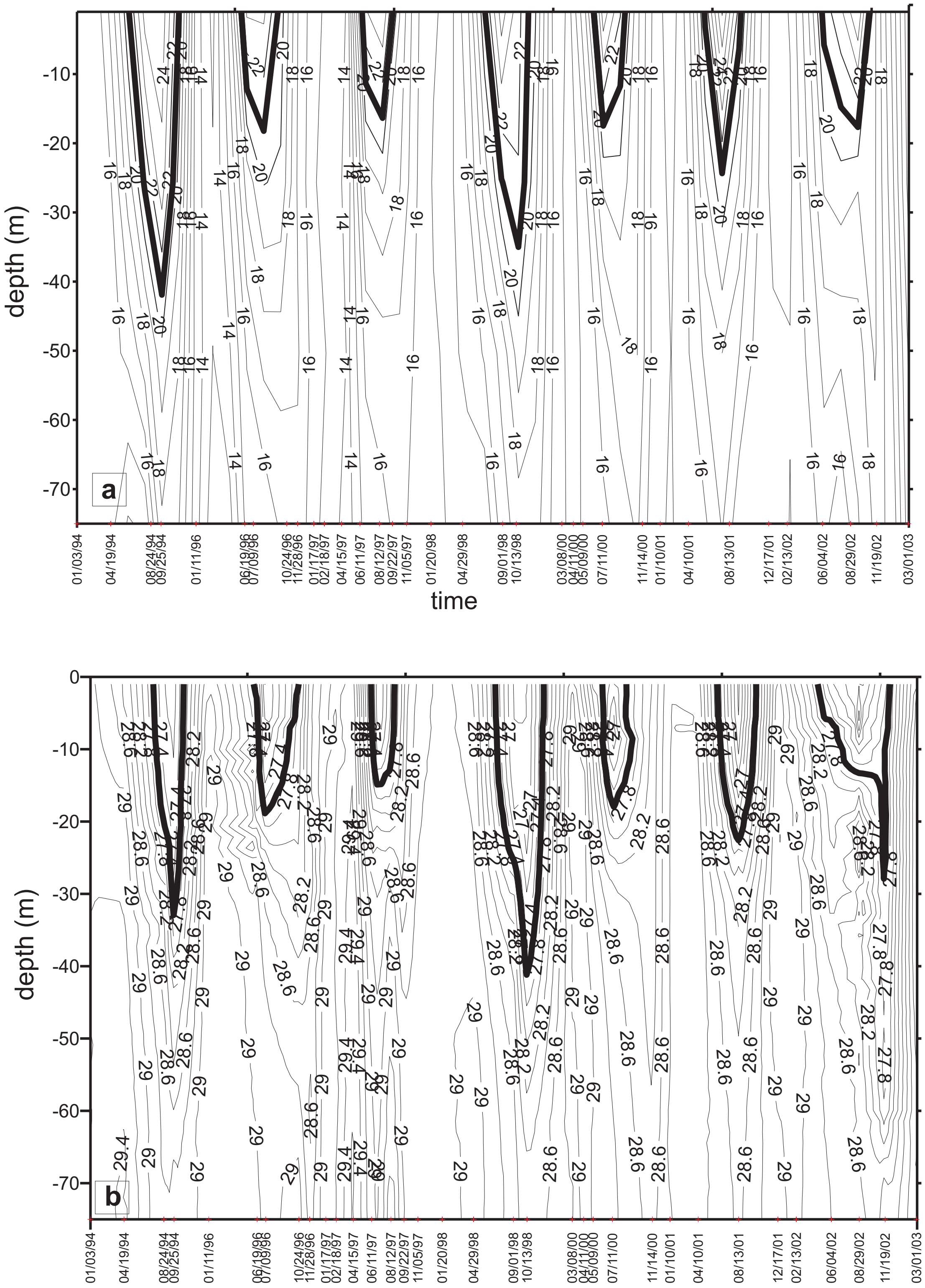



**Figure 3.** The interanual development of temperature (above, c.i.=2 °C) and density (below, c.i.=0.4 kg/m$^3$) in İzmir Bay between 1994 and 2003.

seasonally and annually. The bay is classified to be in the strongly stratified regime from May to September and in the weakly stratified regime during the winter period. April and October can be characterized as the transition months between winter and summer. This seasonal transition causes changes in surface heat content. During the late spring and summer seasons, water is intensely stratified by heating. The temperature difference in summer reaches 10 °C between the upper and lower layers. A sharp thermocline and halocline at 20–35 m depth separates the upper and lower layers from summer to early autumn, as can be observed from vertical profiles of temperature in the bay (Figures 2 & 3). By contrast, surface cooling causes the beginning of the formation of a vertically homogeneous water column in late autumn and winter.

In winter, the temperature decreases gradually from the Aegean Sea (15–16 °C) towards the inner Bay, which is always colder, denser, and fresher, because of differential cooling (Figures 4 & 5). The middle Bay water temperature is about 15.4 °C, salinity is about 38.8 psu and density (sigma-t) is 28.84 kg/m$^3$. Outer I has the same temperature and salinity as the middle bay. Outer II temperature is higher (about 16 °C) and its density is lower than the outer I and the middle bay. The salinity does not change significantly from outer I to outer II. Temperature increases towards outer III (16.3 °C) and surface densities are lower compared to other regions (i.e. lower than 28.7 kg/m$^3$). The surface and bottom layer of outer III has a constant salinity of 38.86 psu. In spring, the upper layer shows summer and the lower layer winter characteristics. Land-based warming causes the surface temperature of the bay to increases towards the inner Bay. On the other hand, near bottom water shows winter characteristics; therefore, the temperature decreases from the Aegean to the inner Bay. In the early spring, stratification is initiated especially from the surface and starts to be stronger through the late spring. In summer, temperatures decrease from the inner bay to outer III. This is the reverse of the winter situation. The seasonal pycnocline occurs to 25–30 m because of seasonal warming. Temperature is about 26 °C at the surface and decreases to 16 °C below the thermocline so that temperature dependent stratification takes place in the summer. Although the surface temperature of the middle bay is the highest, the temperature below the thermocline is 0.3 °C cooler than the outer bay. Under the thermocline, a weak temperature gradient exists between sub-regions of the bay. Density and salinity values change from 26.5 kg/m$^3$ to 28.5 kg/m$^3$ and from 39.0 to 39.45 psu respectively. In the fall the thermocline descends to 40 m, surface temperature starts to cool (~22 °C) and salinity decreases to 38.4 psu above the halocline (Figures 4 & 5).

### *Seasonal Variation*

The water properties of the bay are analyzed using the data retrieved from five different areas in a period of four different months: January 1998, April 2000, July 2000 and September 1998. Temperature and salinity distributions obtained from the four cruises were used as an initial condition to predict the wind-driven circulation at several stages of computation. It is important to choose the cruise data so that the space and time coverage is representative of the whole of the İzmir Bay area, and for seasonal analysis of water movements.

The seasonal variation of water properties in the Aegean Sea influences the İzmir Bay water properties and vice versa. Hence, the circulation and water mass formations in the Aegean Sea are important for analyzing the seasonal variation of water properties in the bay. The surface circulation in the North Aegean Sea is mostly cyclonic and the main surface water mass occupying the region is Black Sea Water (BSW) (Zodiatis 1994 and Theocharis *et al.* 1999). During winter the main volume of BSW flows towards the north of Limnos Island. In summer, BSW spreads out to the southwest and the core of this water mass appears south of Limnos. The relatively colder surface water seen in the eastern coastal area of Aegean Sea is formed as a result of a combination of both the southwards flowing BSW and the upwelling process observed frequently in the coastal area during the summer season (Ünlüata 1986). The cyclones move eastward over the Aegean Sea towards the Eastern Levantine Basin. The life of those cyclones in the area is about 3 to 5 days, although they may last much longer (Alpar *et al.* 1997). Tidal and 3 to 5 day periodicities are common and the most energetic in all seasons in the İzmir Bay (Sayın & Üçüncüoğlu 1999; Pazı 2000). These 3 to 5 days periodicities are due to the large-scale atmospheric motion seen in the Aegean region. The wind stress also indicated some variability and lies within the frequency band of 4–12 days in İzmir Bay (Alpar & Yüce 1996).

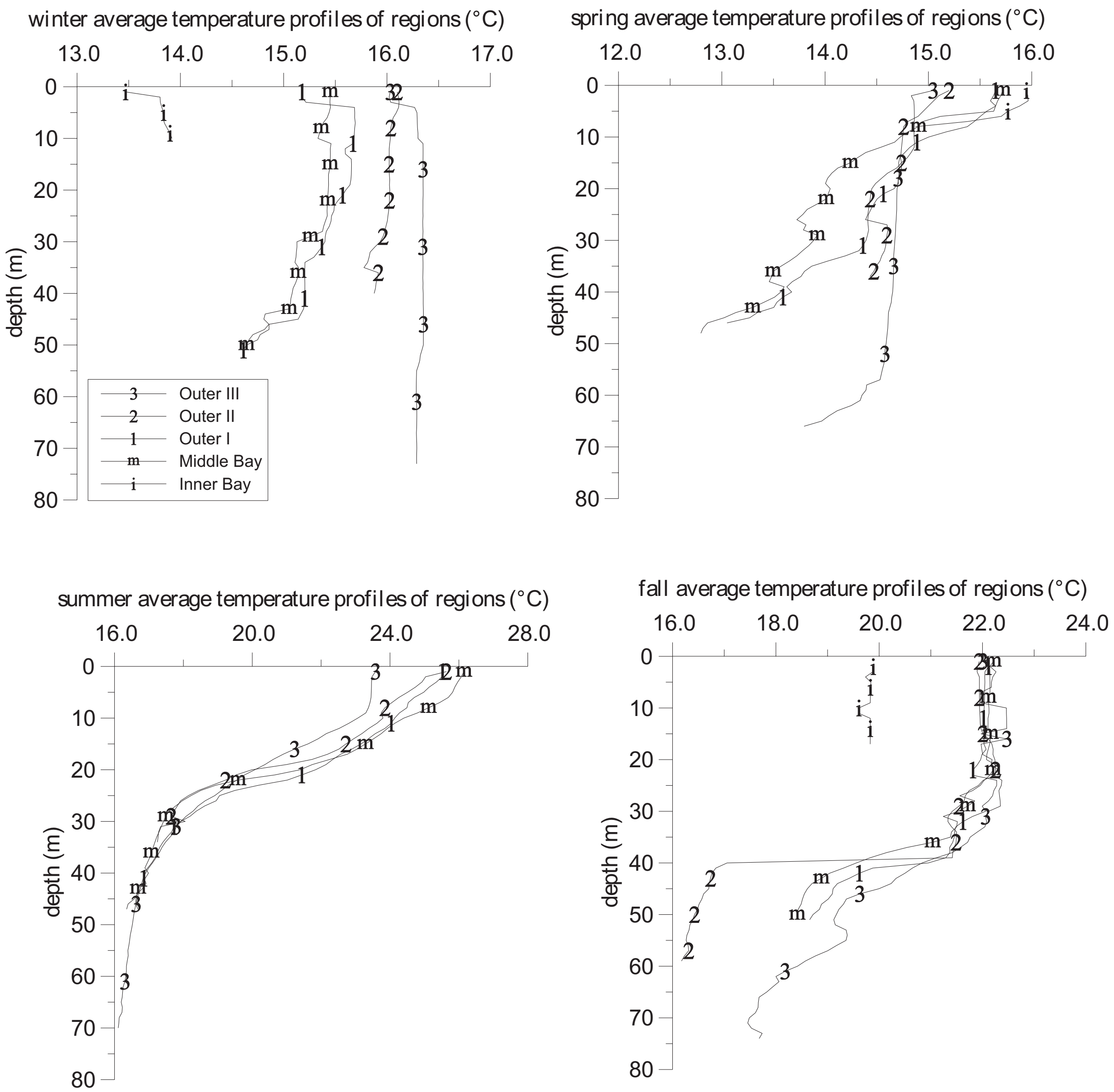



Figure 4. Regional average temperature profiles in İzmir Bay from 1994 to 2003.

*January 1998.* The representative winter survey was carried out in 20–22 January 1998. The temperature and salinity differences between the Aegean Sea and İzmir Bay form strong horizontal gradients in the outer III region (Figure 6). The temperature and salinity distribution for determining the inflow (ASW) and outflow (IBW) through the vertical sections VS4 that cross the basin from Karaburun to Foça (Figure 1b) are used in this study. In January 1998, the ASW entered İzmir Bay near the coast of Karaburun and brought relatively warmer, more saline and a less dense water mass into the bay (T=16.3 °C, S=39.04 psu and Sigma-t=28.75 kg/m$^3$, Figure 7).

The narrow Mordoğan Strait, which is situated between Uzun Island and the west coast of the bay, has a sill depth of 14 m and is 5 km wide. The baroclinic

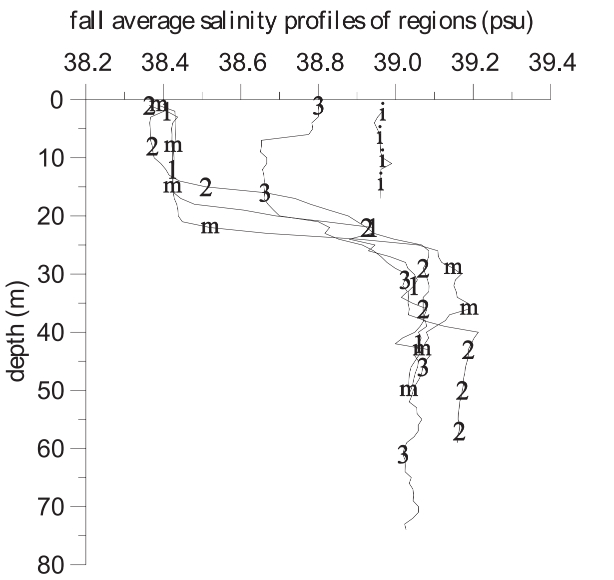



**Figure 5.** Regional average salinity profiles in İzmir Bay from 1994 to 2003.

Rossby radius of deformation varies from 2 km to 12.5 km in the bay. Generally, ASW enters to the middle Bay through the narrow Mordoğan passage. Sometimes, it turns to the east near the north coast of Uzun Island due to the formation of weak stratification in the water column. In this case, the baroclinic Rossby radius of deformation exceeds the width of the Mordoğan Passage. Outflow occurs mainly near the coast of Foça (Figure 7).

The bay was generally influenced by the northerly winds, but in January 1998 both northerly and southerly winds affected the bay. The model experiment was conducted for the case after 24 and 72 hours (Figure 9). From the Çiğli Meteorological Station wind data, the model is under the influence of a moderate southerly wind (~9.0 m/s) after 24 hours and under the influence of a weak northerly wind (~2.0 m/s) after 48 hours. Southerly winds cause a cyclonic gyre in the middle of the bay. This gyre is also quite evident in the temperature and salinity distributions and confirmed by the model current pattern using southerly wind data (Figure 9). As a result of this cyclonic movement, an upwelling occurs around station 15 (Figures 6 & 8). Relatively oxygen rich, cold, saline and dense water is carried to the surface. The cyclonic movement prevents ASW further entering into the bay. Although the authors expected to find an anti-cyclonic middle gyre in case of a northerly wind, no such anti-cyclonic gyre was encountered because of the weakness of the northerly wind. This can be explained by: (1) the weak wind force was not enough to overcome the background thermohaline force in January 1998 or (2) the weak northerly wind was unable to change the influence of a strong southerly wind that blows for a short time. The influence of southerly and northerly winds can be clearly seen from the v-component of the velocities (Figure 10) through the vertical sections VS2 and VS3 shown in Figure 9. For example, strong barotropic currents towards Aegean Sea (Figure 9) are the result of depth-integrated velocities intensified at the coast observed through the vertical section VS2.

*April 2000.* The representative spring cruise was carried out in 11–14 April 2000. The horizontal distribution of the surface hydrological characteristics (Figure 11) shows that the northern İzmir Bay is occupied by a slightly colder (14.9–15.0 °C) and more saline (38.85–39.0 psu) water layer. This relatively homogenous cold, saline and dense ASW, which flows near Karaburun coast (as seen in January), influences as far as Gülbahçe Bay and the middle Bay. Outflow occurs near Foça (T= 13.7 °C and S= 38.8 psu). Inflowing and outflowing water masses show winter characteristics, with their vertical quasi-homogeneous temperature and salinity distributions along the water column (Figure 12).

The entering ASW can be detected also from the model circulation pattern (Figure 13). The establishing current transfers the cold saline ASW into the bay. Because of weak wind (northerly, ~1.1 m/s), thermohaline forces are slightly more effective than the wind-driven forces; therefore the middle gyre does not form clearly in this transient month. The current that passes through Mordoğan Passage makes a small anticyclonic gyre in Gülbahçe Bay and turns to the southeast. It separates into two branches; one branch flows near the south coast of Hekim Island enhancing the anticyclonic middle gyre and the second branch combines with the coastal current near the east coast of Uzun Island. This latter current forms the coastal current extending from the middle of the bay to the Aegean Sea. Before entering to the Aegean Sea, it produces a small anticyclonic gyre in the outer III together with ASW inflow.

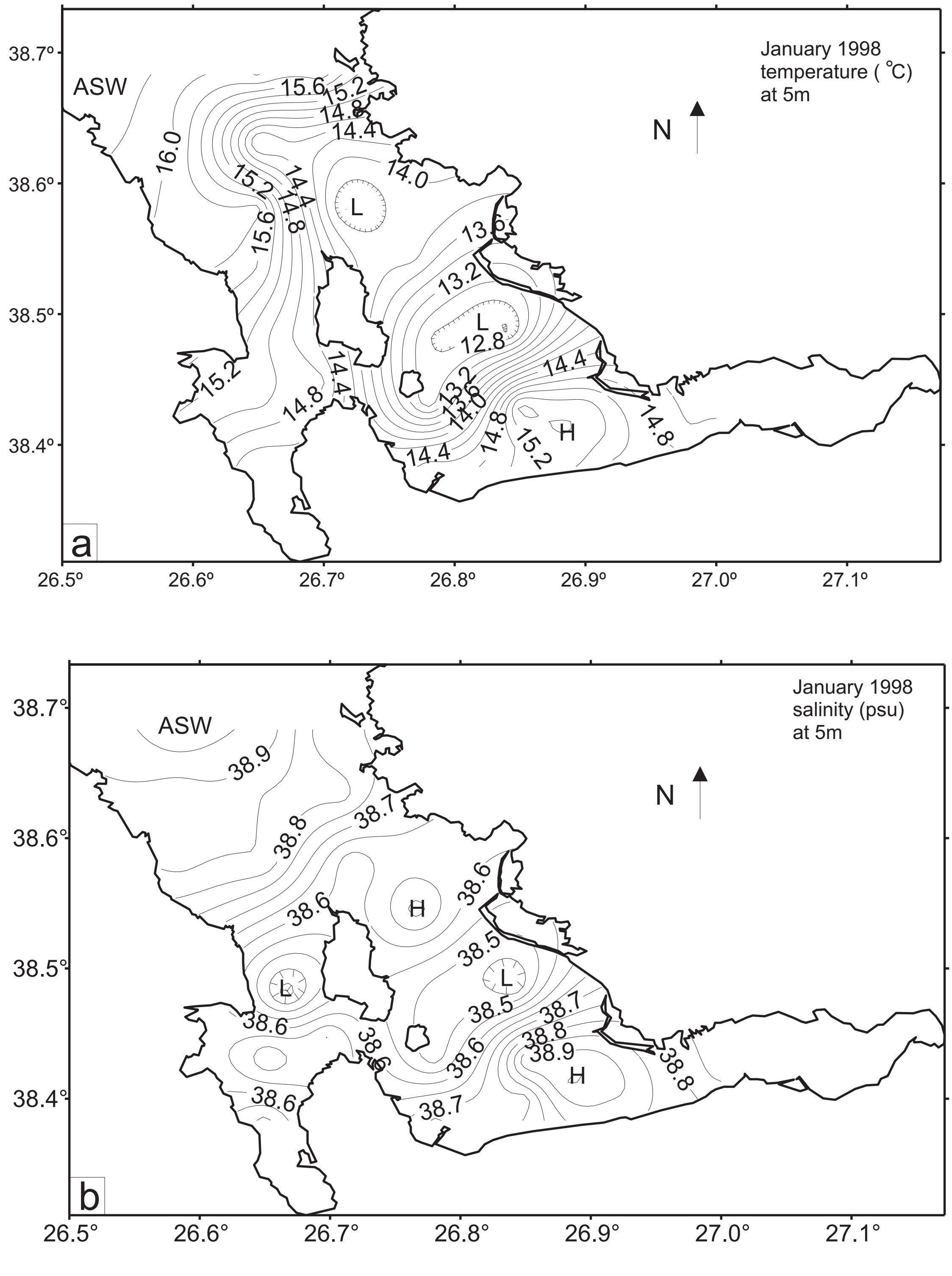



Figure 6. Temperature (a) and salinity (b) contours at 5 m depth in January 1998.

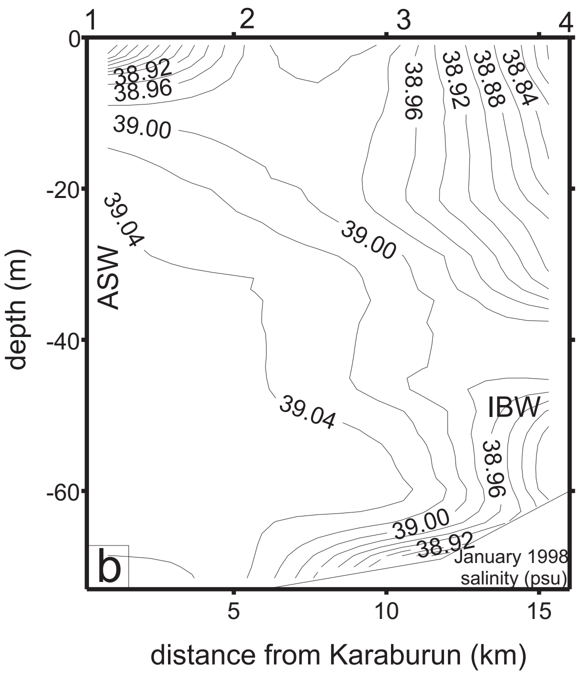



Figure 7. Winter (January) characteristics of inflowing (a) and outflowing (b) water through the vertical section VS4.

*July 2000*. The representative summer cruise was carried out in 11–14 July 2000. It was found that, contrary to findings of the winter, the currents from Aegean Sea transfer colder and less saline water into the bay (Figure 14). Outer III is occupied by a cold (23–23.5 °C) and less saline (39.2–39.26 psu) water layer from the surface to the depth of thermocline (20–25 m). ASW inflow occurs above pcynocline through the vertical section VS4 (Figure 15). IBW flows to the Aegean Sea through VS4 under the pycnocline. The density surfaces are horizontally parallel to each other in July 2000.

The bay was under the influence of northerly wind (~2.5 m/s) in July 2000. The middle Gyre showed a typical anticyclonic movement, which is seen always in case of northerly wind (Figure 16). Not only wind, but also the thermohaline forces play important roles on the current pattern. So the current left of the middle Gyre near the east coast of Uzun Island make a small gyre near the northeast corner of Island and flows to the west. It separates into two branches: one combines with compensation outflow from Mordoğan and flows into the Mordoğan Passage, and the other forms outflow near Karaburun. The currents flowing through Mordoğan Passage into the Gülbahçe Bay circulate cyclonically around the basin and turn back to the outer III. The v-components of velocities through the vertical sections VS2 and VS3 are shown in Figure 17.

*September 1998*. The representative fall cruise was carried out in between 22 and 24 September 1998. The horizontal distribution of the surface hydrological characteristics (Figure 18) shows that the outer III Basin was occupied by ASW, which is colder (≅ 23 °C) and less saline (39.1 psu) than IBW. Outflow and inflow occur through vertical section VS4 connecting Karaburun and Foça are similar to the summer (Figure 19). The inflow transfers cold and less saline surface ASW to İzmir Bay Basin. The narrow outflow is through the VS4 under the pycnocline to the Aegean Sea.

The relatively strong north wind (~2.3 m/s) affects the circulation in the bay. Wind forces are overwhelmed by the thermohaline forces in this month and the wind from north direction produces southerly coastal barotropic currents (Figure 20). In this study, the picture of the circulation shows the known predominant features, namely a middle gyre, and a newly developed current from the northwestern periphery of the middle gyre. This current to the north compensates the inflows near coasts. The middle gyre water, which is under the influence of wind and potential vorticity, is obvious and makes an anticyclonic movement.

### *Water Masses*

T-S diagram is used to define primary water masses that are homogeneous in temperature and salinity. Aegean Sea Water can be seen generally at Station 1 near Karaburun. Therefore Station 1 T-S values are used as a representative for ASW (Figure 1). Some stations in the bay are selected same way to see whether there is any distinct water mass. These are Station 7 (Foça), Station 11 (Gediz), Station 15 (Cyclonic middle gyre), Station 17 (outer II), Station 22 (middle bay), Station 23 (inner bay) and Station 3-4.

İzmir Bay as a part of the Aegean Sea is characterized by a typical Mediterranean type of climate. It is cool and rainy from November to March, hot and dry from May to September. April and October can be characterized as transient months between winter and summer. Therefore

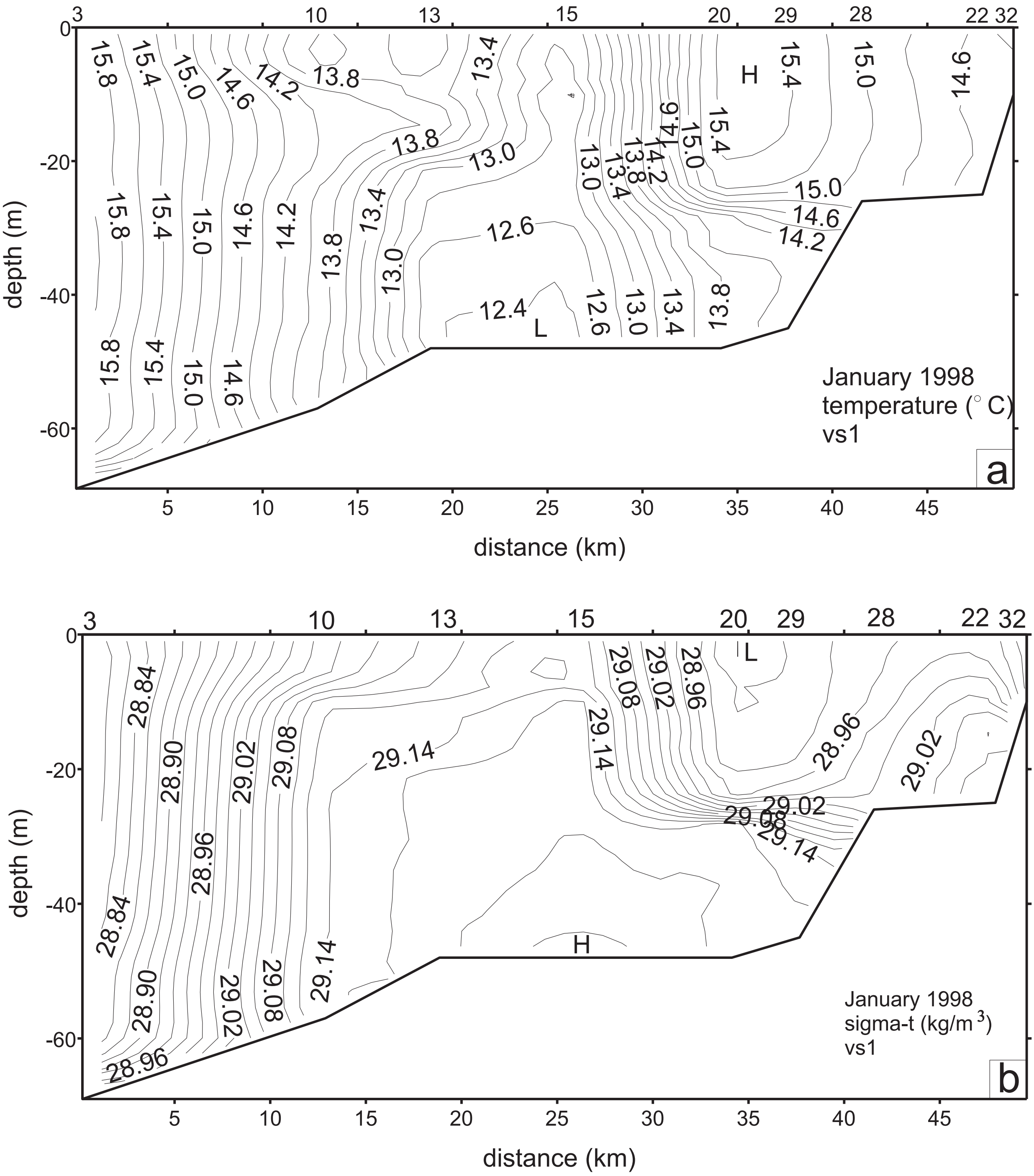



Figure 8. Temperature (a) and density (b) values in vertical section VS1 along İzmir Bay.

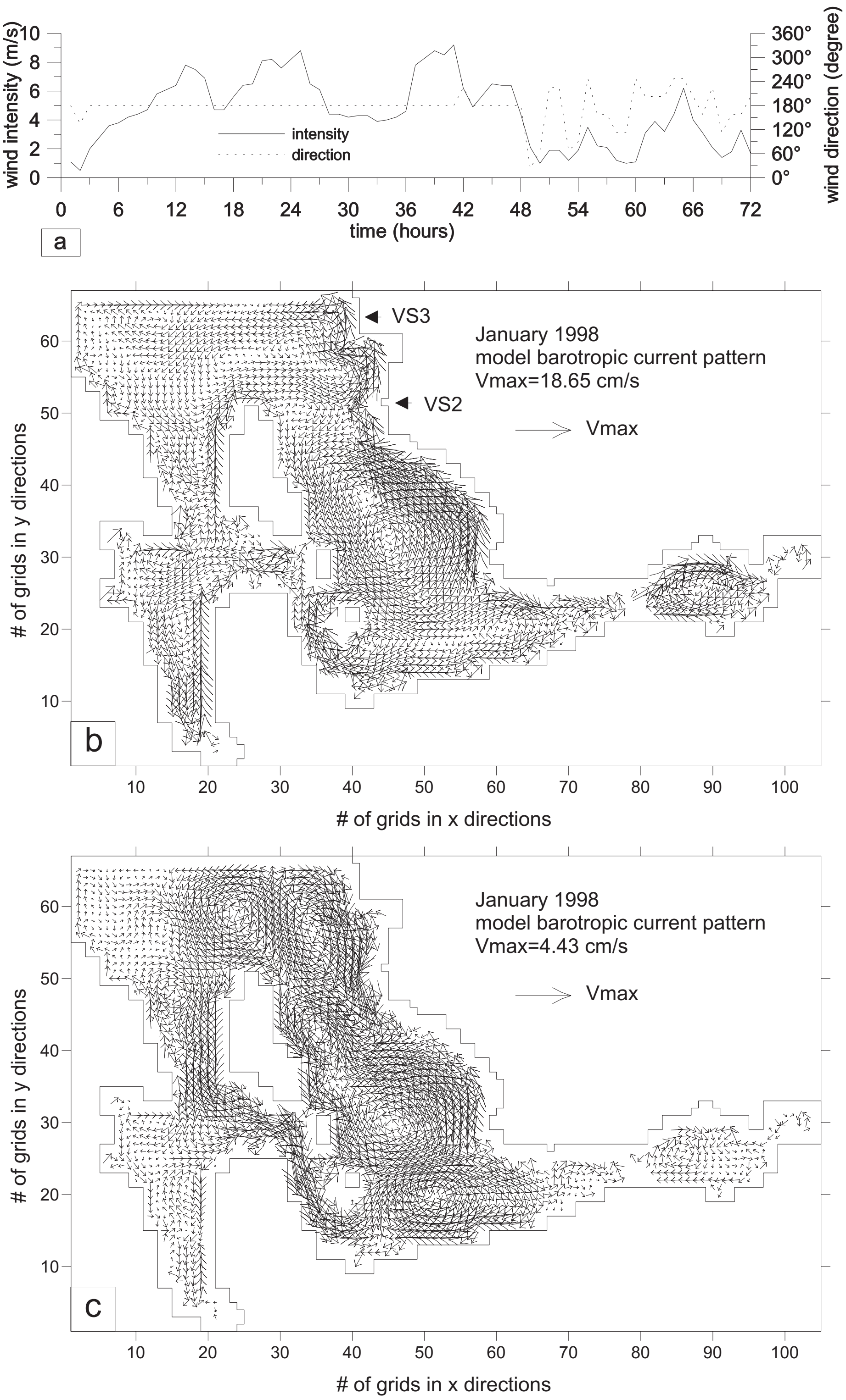



Figure 9. (a) The wind intensity and its direction. Model barotropic current patterns with a January 1998 density stratification (b) after 24 hours (in case of southerly wind) and (c) after 72 hours (in case of weak northerly wind).

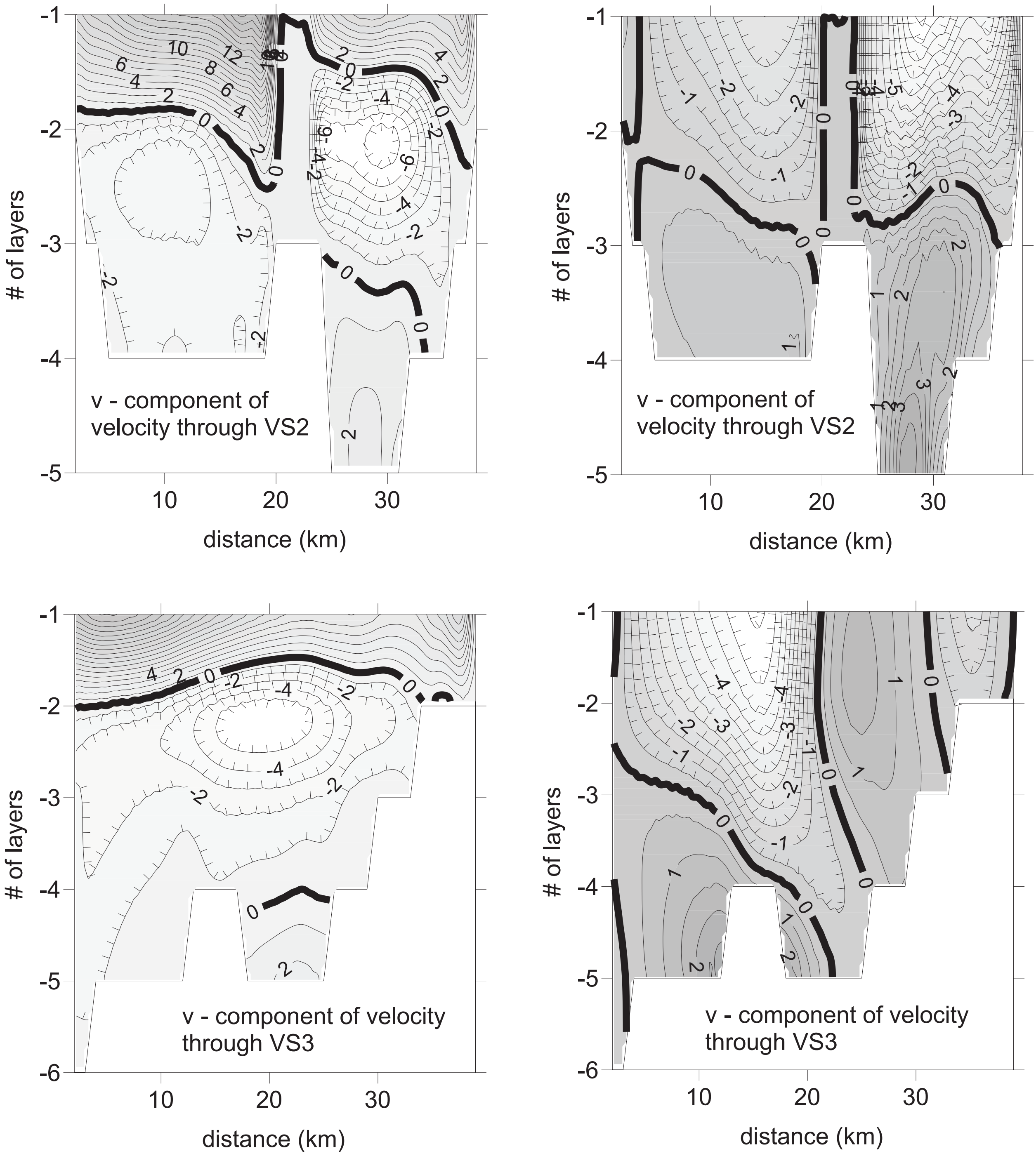



**Figure 10.** The V-component of velocities through the vertical sections VS2 (first row) and VS3 (second row) in case of southerly (first column) and of weak northerly wind (second column) in winter (positive values mean northward or outward of the bay and hatched lines represent the inflow).

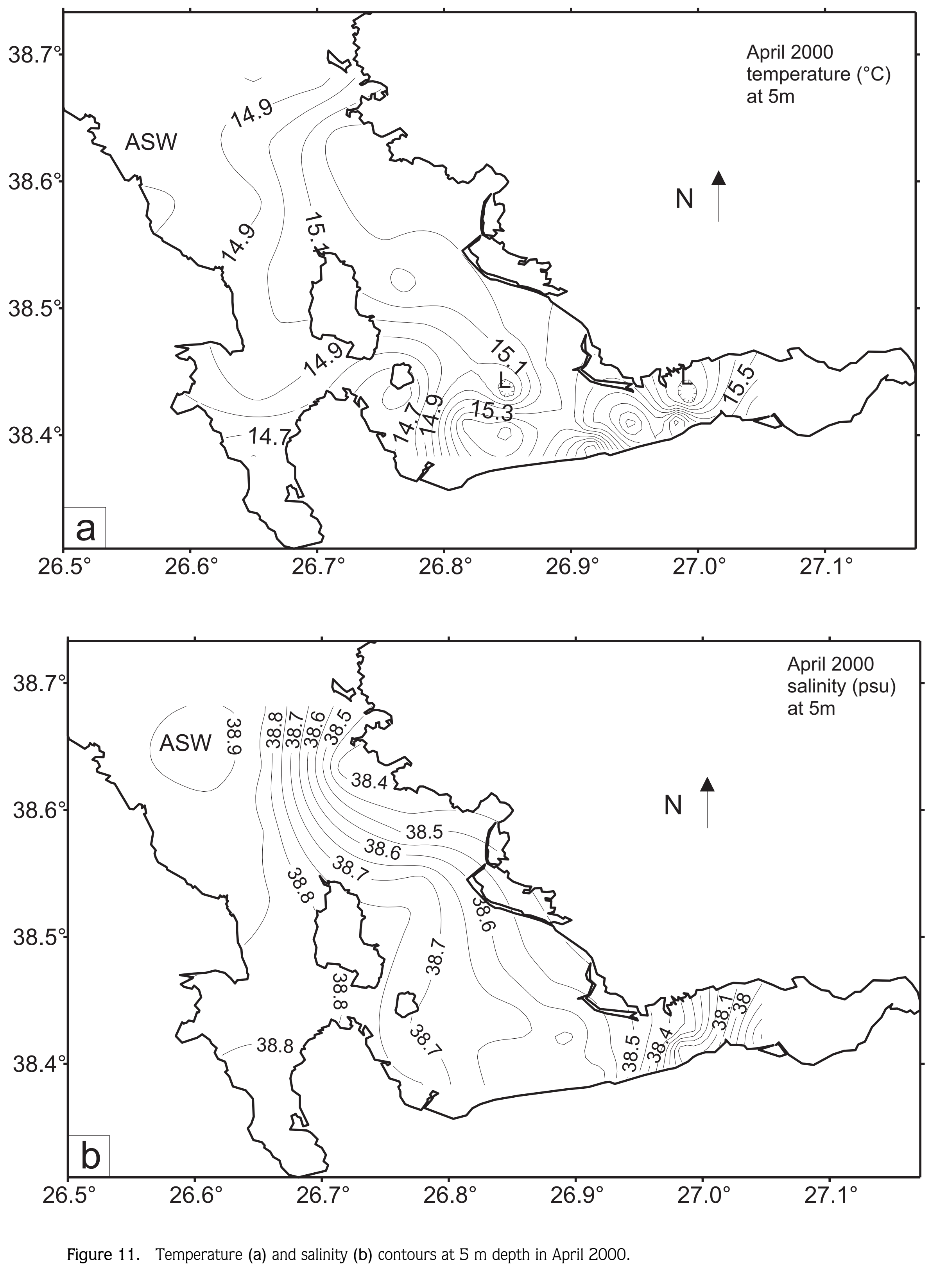



**Figure 11.** Temperature (**a**) and salinity (**b**) contours at 5 m depth in April 2000.

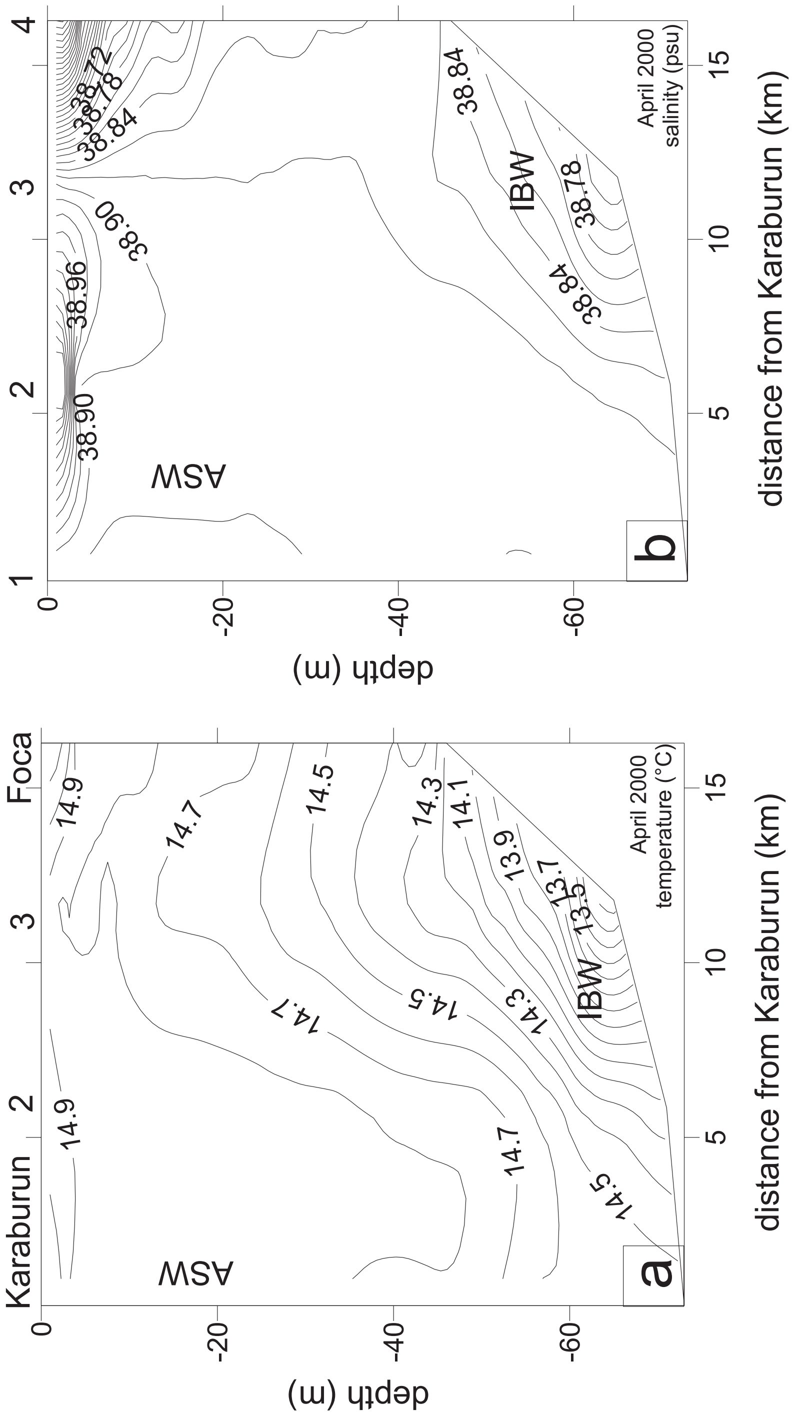



**Figure 12.** Spring (April) characteristics of inflowing (a) and outflowing (b) water through the vertical section VS4.

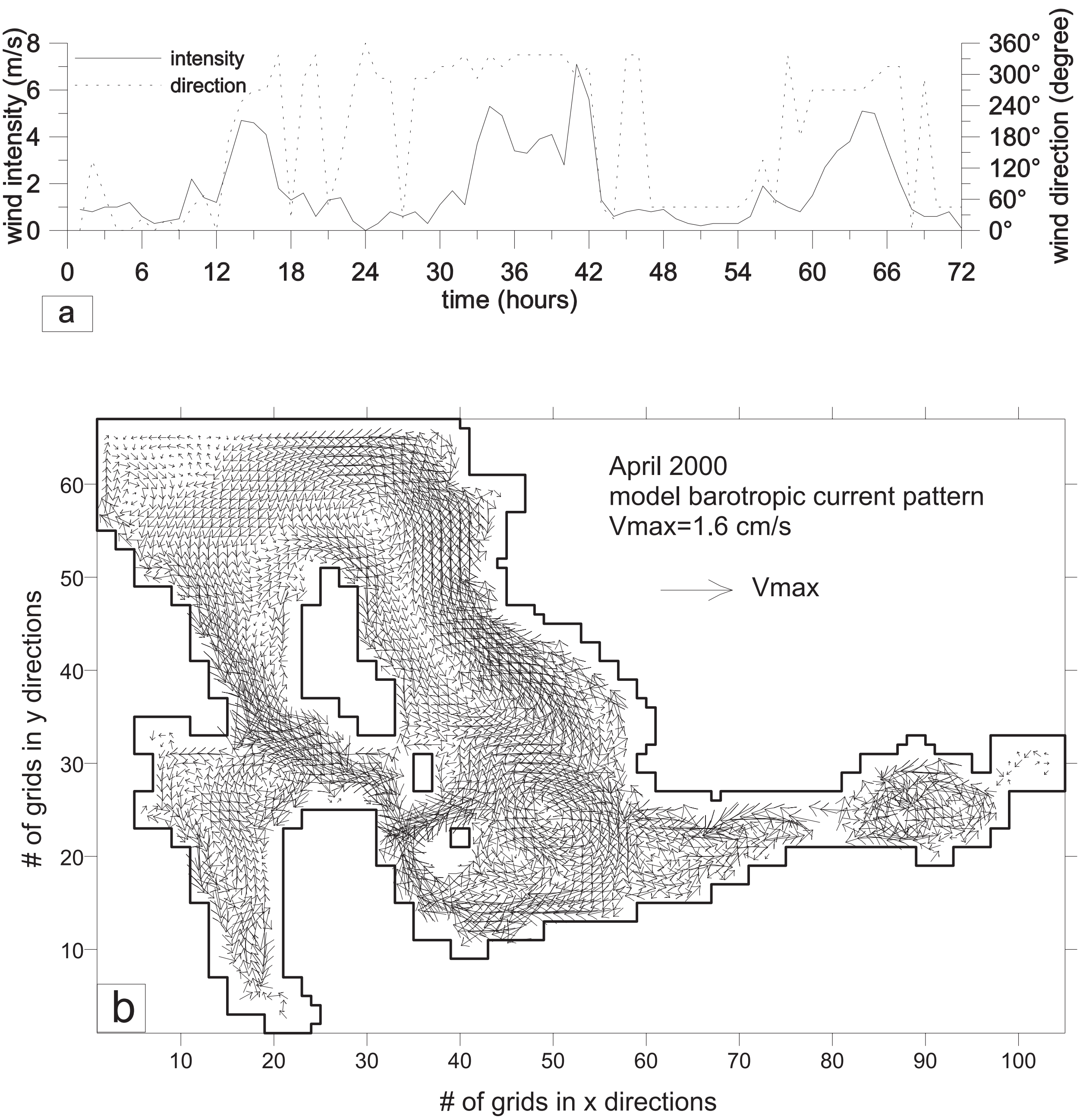



Figure 13. (a) The wind intensity and its direction. (b) Model barotropic current patterns with April 2000 density stratification (in case of weak northerly wind).

cold and warm season T-S characteristics of İzmir Bay subsurface water are shown in Figure 21. The T-S analysis shows three distinct water masses in the bay. The first and dominating one is the Aegean Sea water mass (ASW). The ASW has a greater volume than the other water masses in the bay. Relatively small temporal changes are observed in its temperature and salinity values due to its large volume. The second important one is the water mass of the inner bay (IBIW). It is stratified both horizontally and vertically during the year. IBIW is

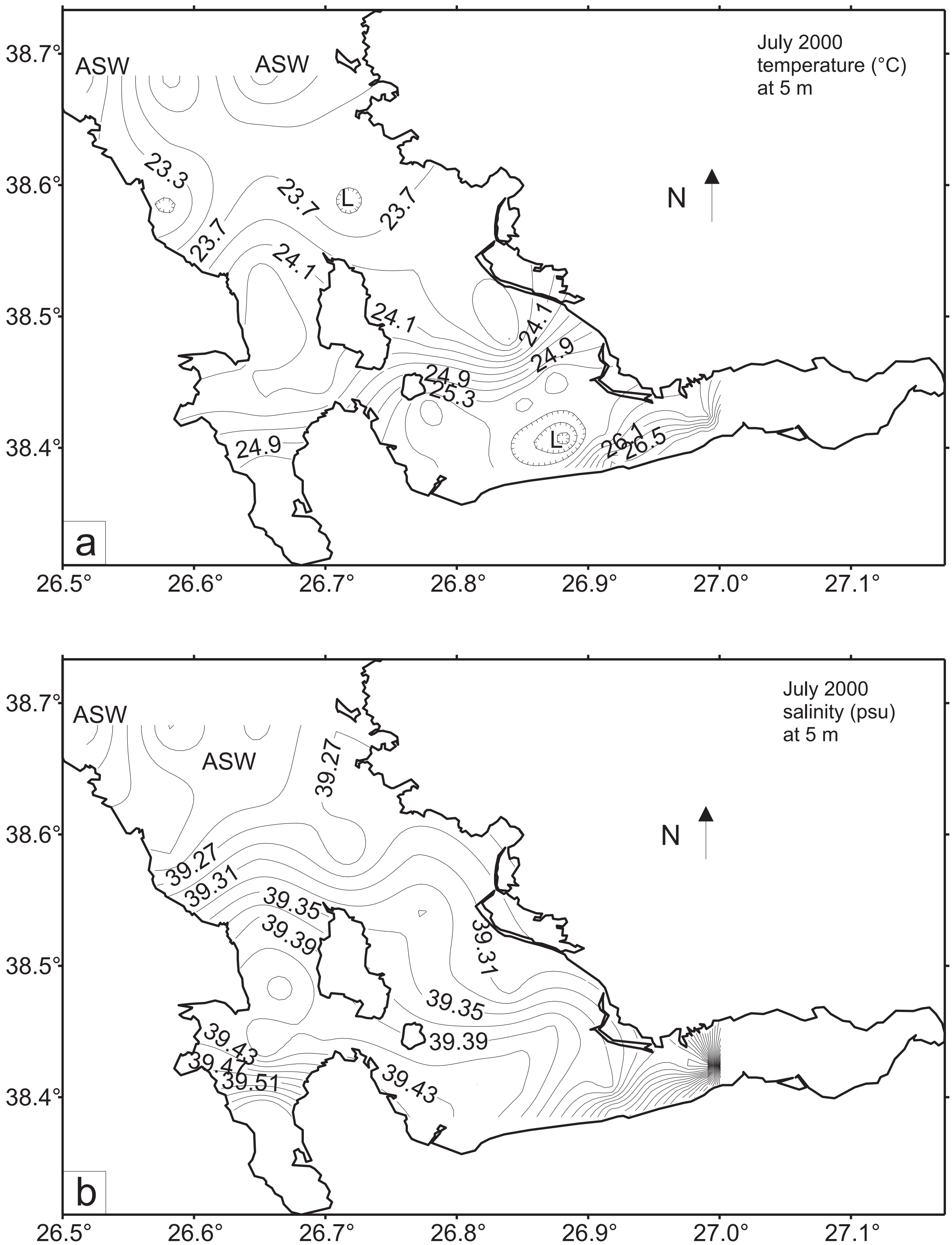



Figure 14. Temperature (a) and salinity (b) contours at 5 m depth in July 2000.

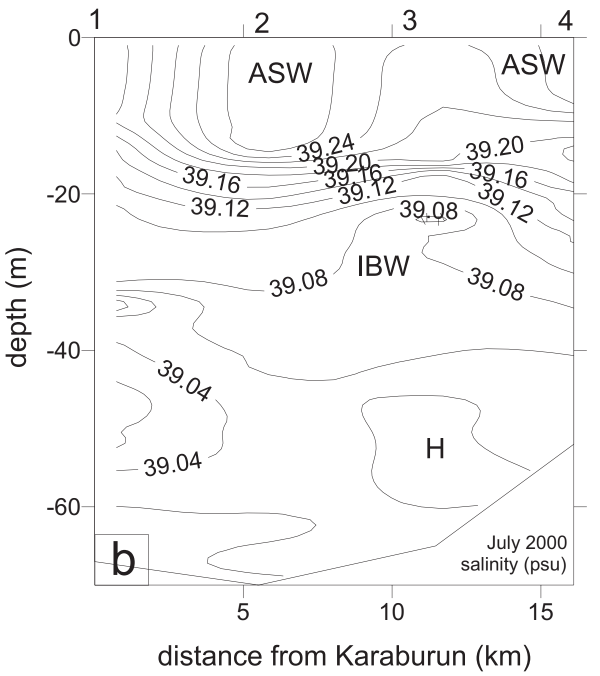



**Figure 15.** Summer (July) characteristics of inflowing **(a)** and outflowing **(b)** water through the vertical section VS4.

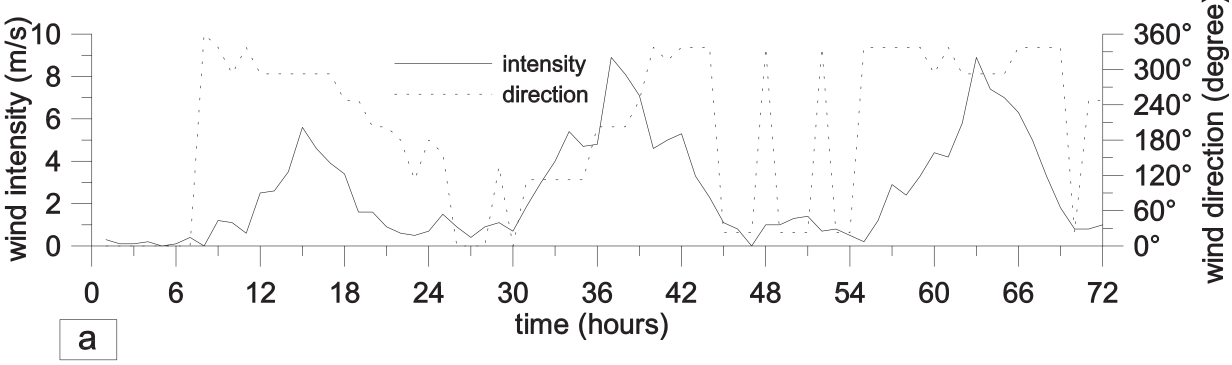
the coldest in winter and its temperature varies from 9.16 °C to 13.84 °C. It has a maximum temperature in summer and changes from 24.64 °C to 27.34 °C. The third one is the İzmir Bay Water (IBW). It is formed in the middle gyre, influenced by the Gediz River inflow and by the upwelling and downwelling processes that are mainly driven by southerly and northerly winds, respectively. IBW seems to be a mixture of IBIW and ASW in winter. But it is a very distinct water mass in summer with higher salinity values varying between 39.56 psu and 39.89 psu. These value comparisons to the salinity values of the ASW are very high and are thought to be the product of evaporation. Similar high salinity values are also observed in the other bays of the eastern Aegean Sea. They bring a question to mind related to how these saline-rich water masses affect the dense water formation in the Aegean Sea.

Because of the run-off the salinity values of the IBIW are not so high as the values observed in the IBW. The IBW characteristics change drastically in the direction to the inner Bay because of the existing narrow Yenikale Strait with a 13 m deep sill between middle and inner Bay.

The following T-S analyses are related to the period in which the current pattern has already been calculated in the seasonal variation section in this paper with an exception of the winter period.

*Winter.* Aegean Sea Water (ASW), İzmir Bay Water (IBW) and İzmir Inner Bay Water (IBIW) are all clearly distinguished in the T-S diagram. The T-S diagram of January 1997 is analyzed instead of the T-S diagram of January 1998 because of no existing representative data for the inner Bay in January 1998 (Figure 22). T and S values illustrate vertically homogeneous water masses. Inflowing ASW near Karaburun coast into İzmir Bay has characteristics varying between 16.02–16.64 °C in temperature and 38.87–39.06 psu in salinity. IBW, the mixture of adjacent region waters, is formed mainly in the middle gyre characterized by the core in the temperature ranging from 14.31 °C to 14.5 °C and salinity from 38.66 psu to 38.7 psu. Middle gyre water is transferred to the Gediz and Foça area by the coastal current and reaches to the Aegean Sea diluting on the way. The other water mass IBIW has the minimum temperature (13.17–13.47 °C) and salinity (38.12–38.25 psu) values measured in January 1997.

*Spring.* Figure 23 presents the T-S diagram in the İzmir Bay existing in April 2000. The three water masses ASW, IBW and IBIW, which are observed in winter, are detected also in April 2000. The IBIW found in the inner Bay is very distinct water with its minimum salinity. Decrease in salinity values (37.73–38.07 psu) of IBIW is due to increasing fresh water discharge to the inner bay in spring. The surface temperatures of the IBIW (14.88–15.97 °C) increase in a short time especially during late spring. The composite T-S diagram of all stations clearly demonstrates that IBW is formed in the region of middle gyre. The sub-surface and sub-bottom water of Foça have similar T-S characteristics with the middle gyre surface and bottom waters. The bottom water of the Station 3 has the same T and S values as the middle gyre bottom water. It indicates that the outflowing water, which is observed through the vertical section VS4, originates from the middle gyre area. It is also seen from April 2000 model circulation pattern (Figure 13). Vertically homogeneous ASW preserves its



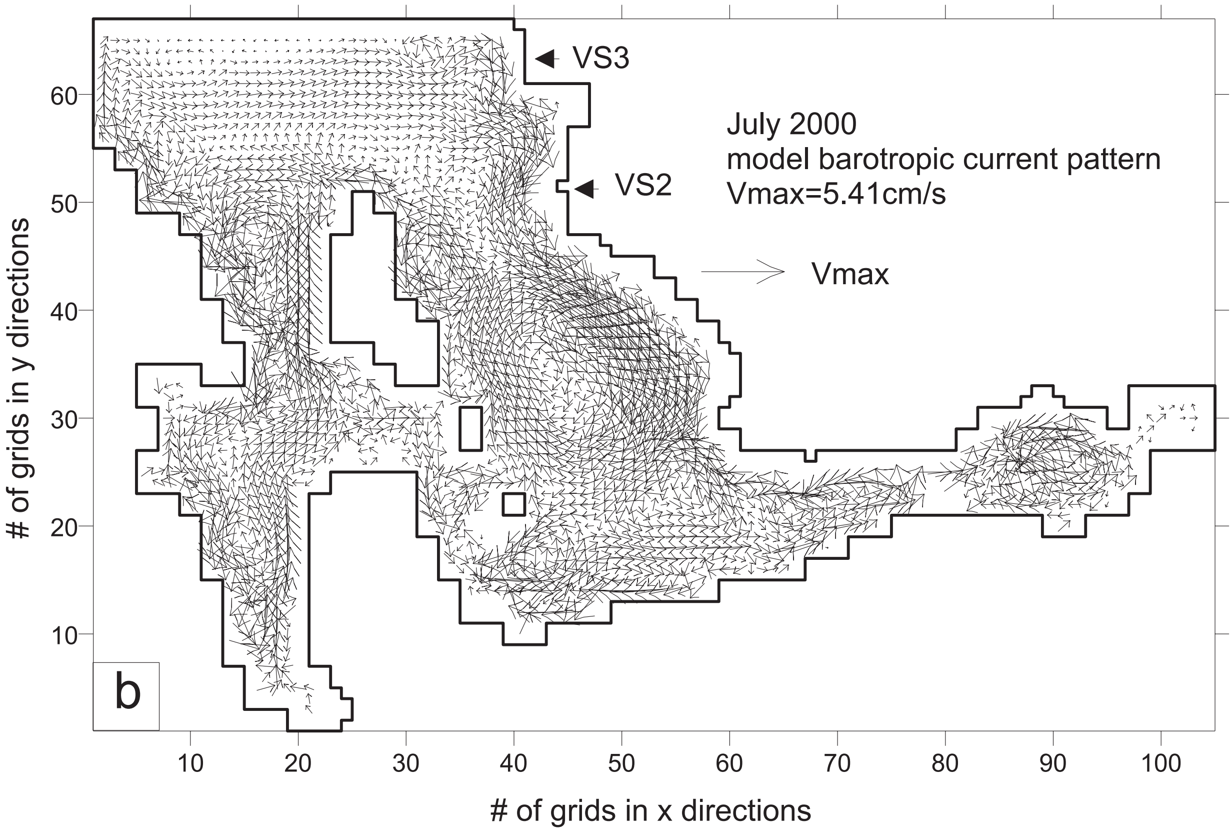




Figure 16. (a) The wind intensity and its direction. (b) Model barotropic current patterns with July 2000 density stratification (in case of northerly wind).

winter character in this transient month. The inflowing ASW characterized by relatively high salinity values (38.87–38.9 psu) influences the surface water of Gülbahçe Bay and the intermediate water of Foça area. Surface water of middle gyre and the bottom water of Gediz area have similar water characteristics. This link between the two water masses may be as a result of subduction processes. The buoyant fluid under the Gediz Plume and the upwelling water in the middle gyre might play some role on this process.

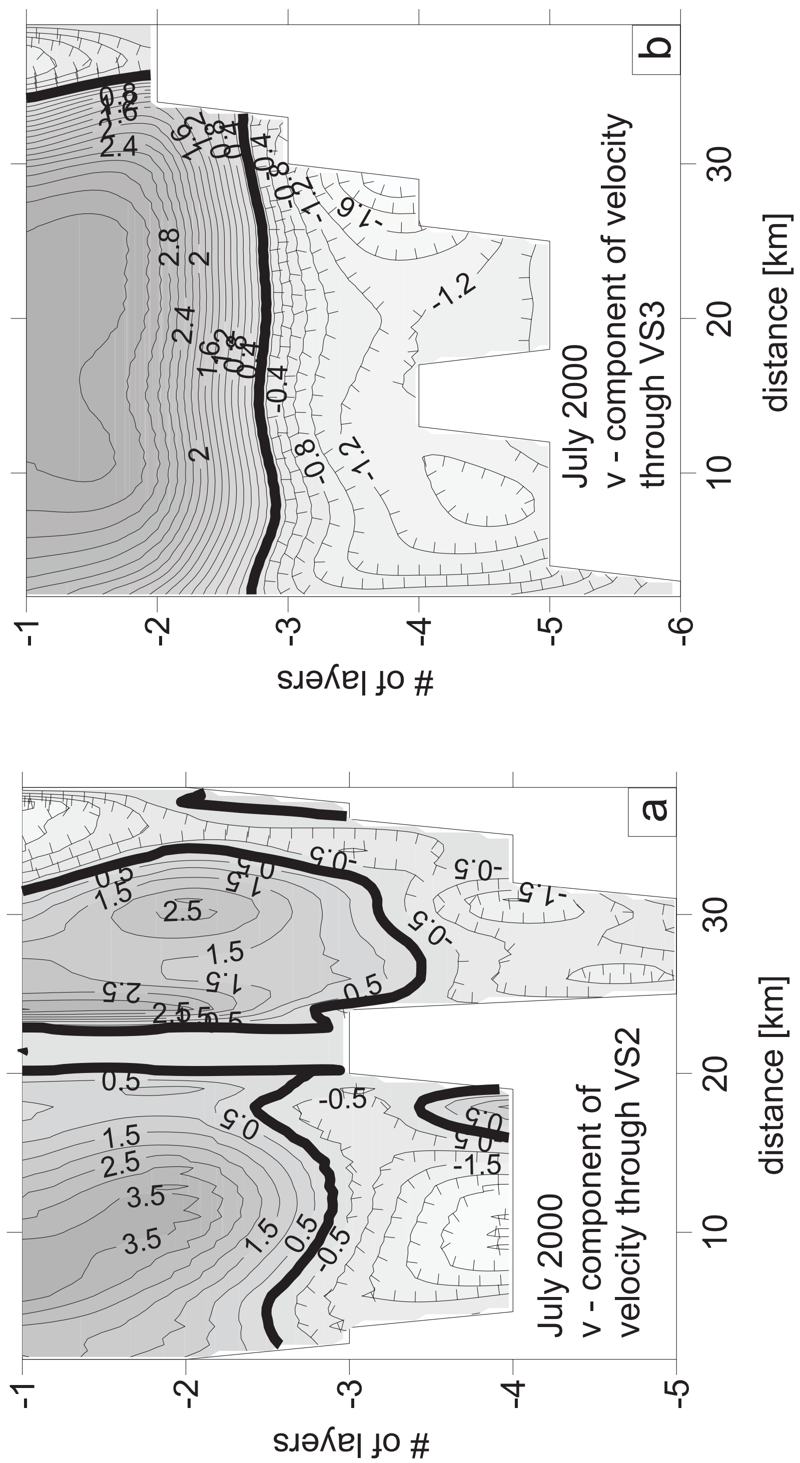



Figure 17. The V-component of model velocities through the vertical sections VS2 (a) and VS3 (b) (Hached lines represent the inflow).

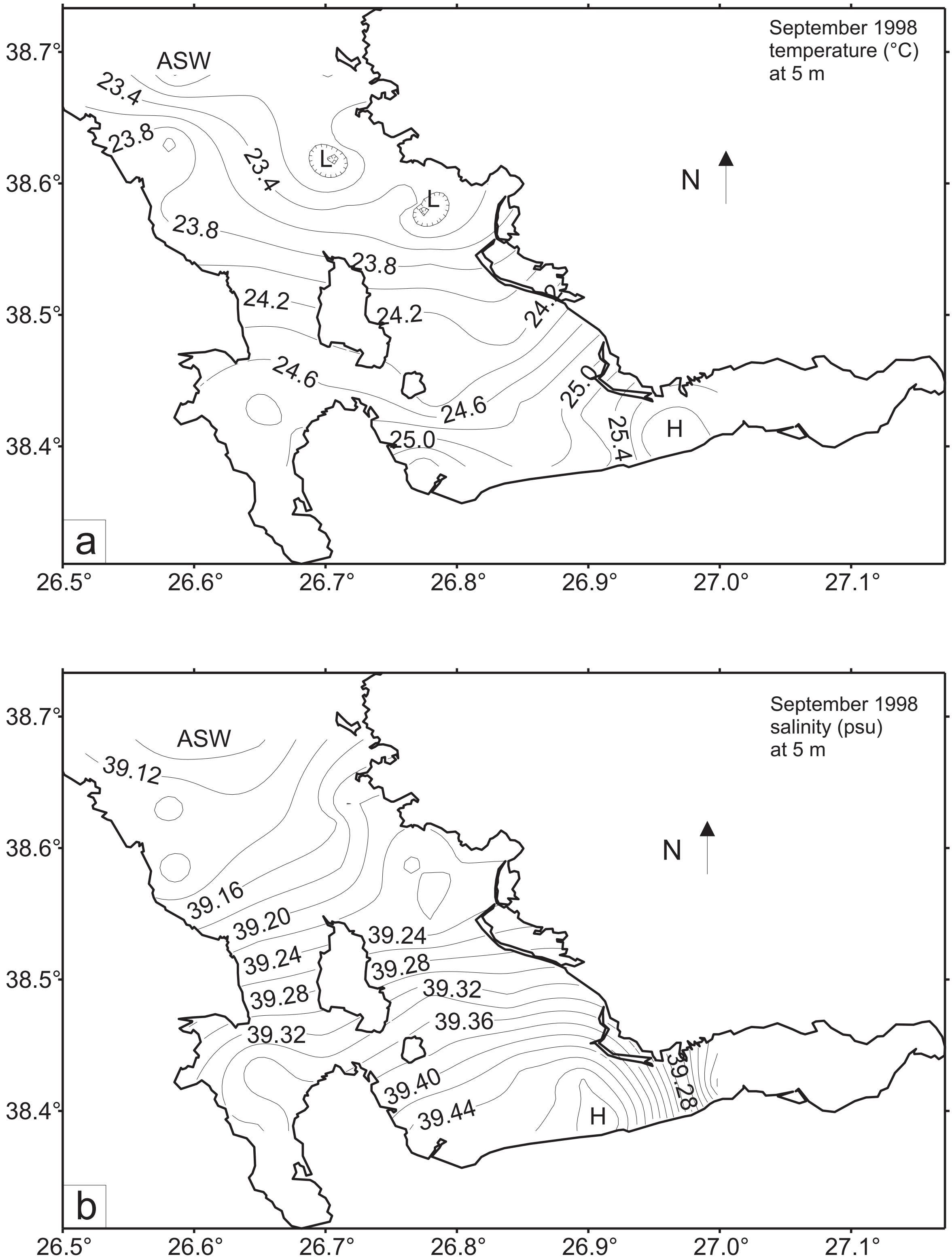



Figure 18. Temperature (a) and salinity (b) contours at 5 m depth in September 1998.

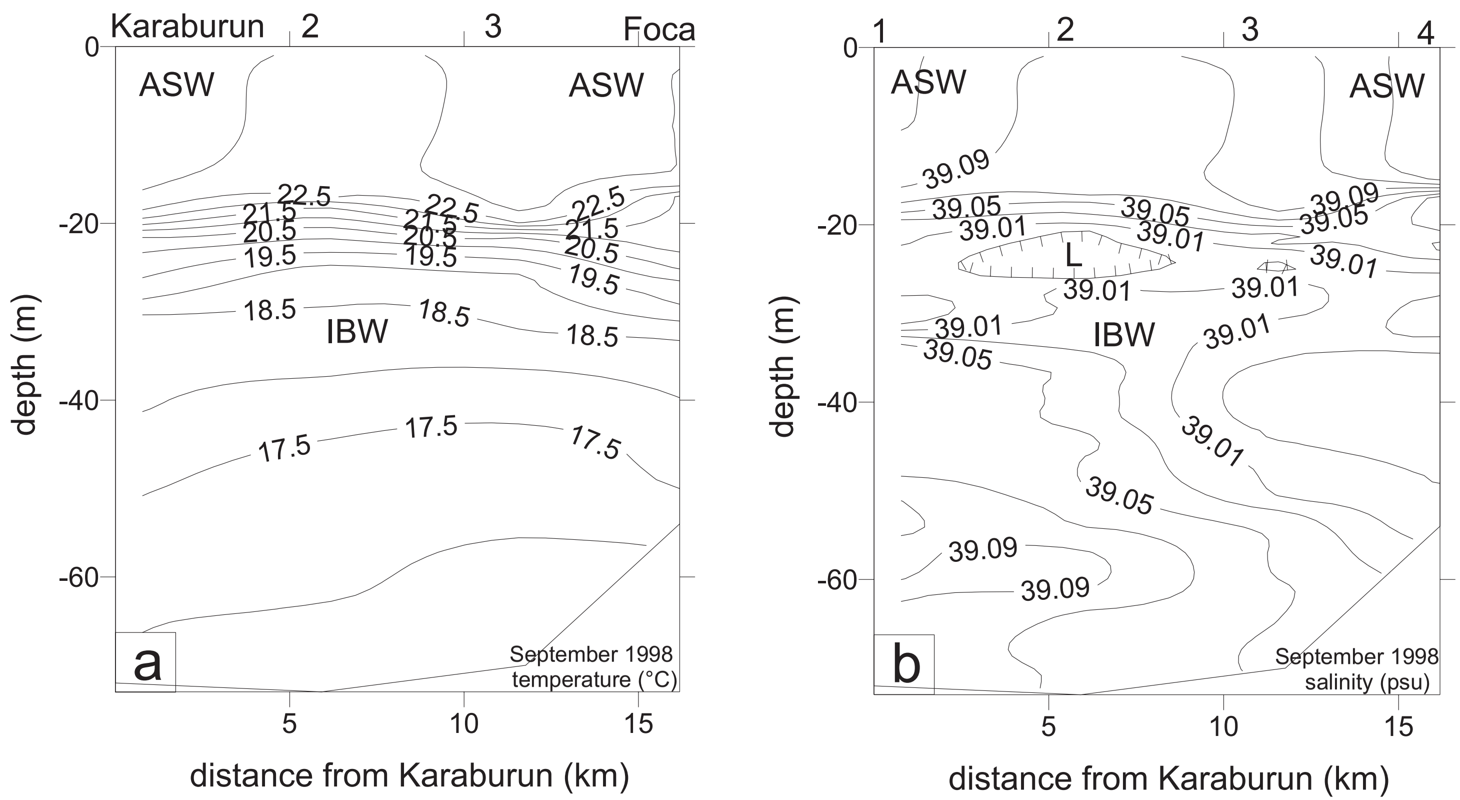
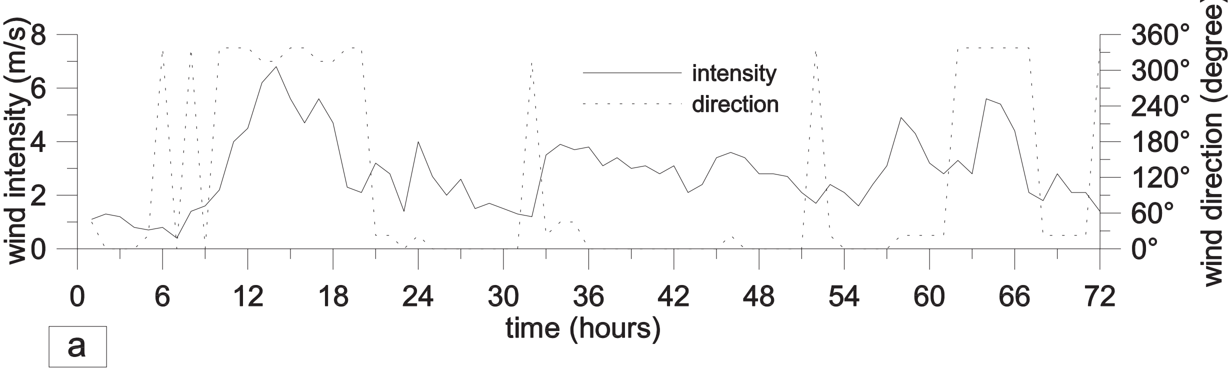



Figure 19. Fall (September) characteristics of inflowing (a) and outflowing (b) water through the vertical section VS4.



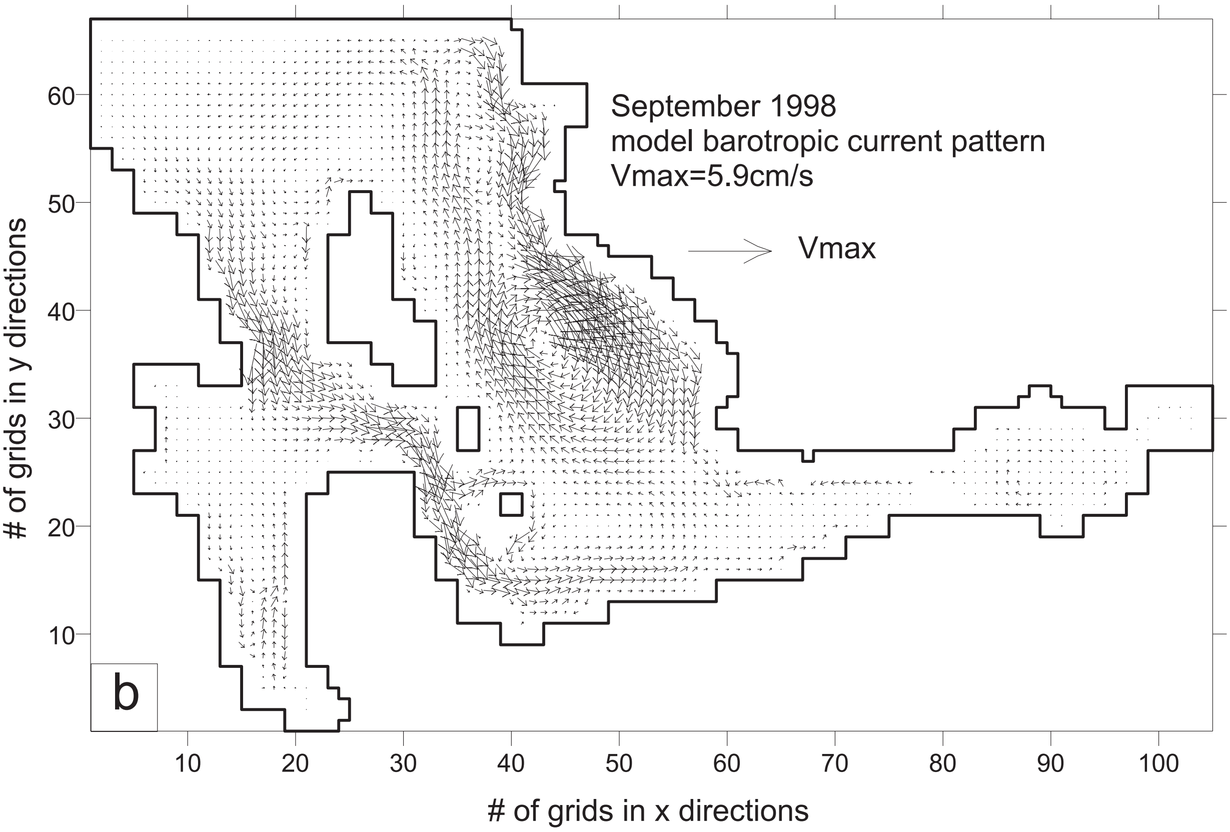




Figure 20. (a) The wind intensity and its direction. (b) Model barotropic current patterns with September 1998 density stratification (in case of northerly wind).

*Summer.* The seasonal evolution is clearly shown in the T-S diagram (Figure 23) where all characteristics water masses are identified. Low salinity (38.76–38.84 psu) and relatively high temperature (25.38–27.2 °C) are characteristics of the IBIW that occupies the inner bay in July 2000. IBIW communicates only with the surface water of the middle Bay. Besides IBIW, the ASW is relatively colder (16.28–22.81 °C) and less saline

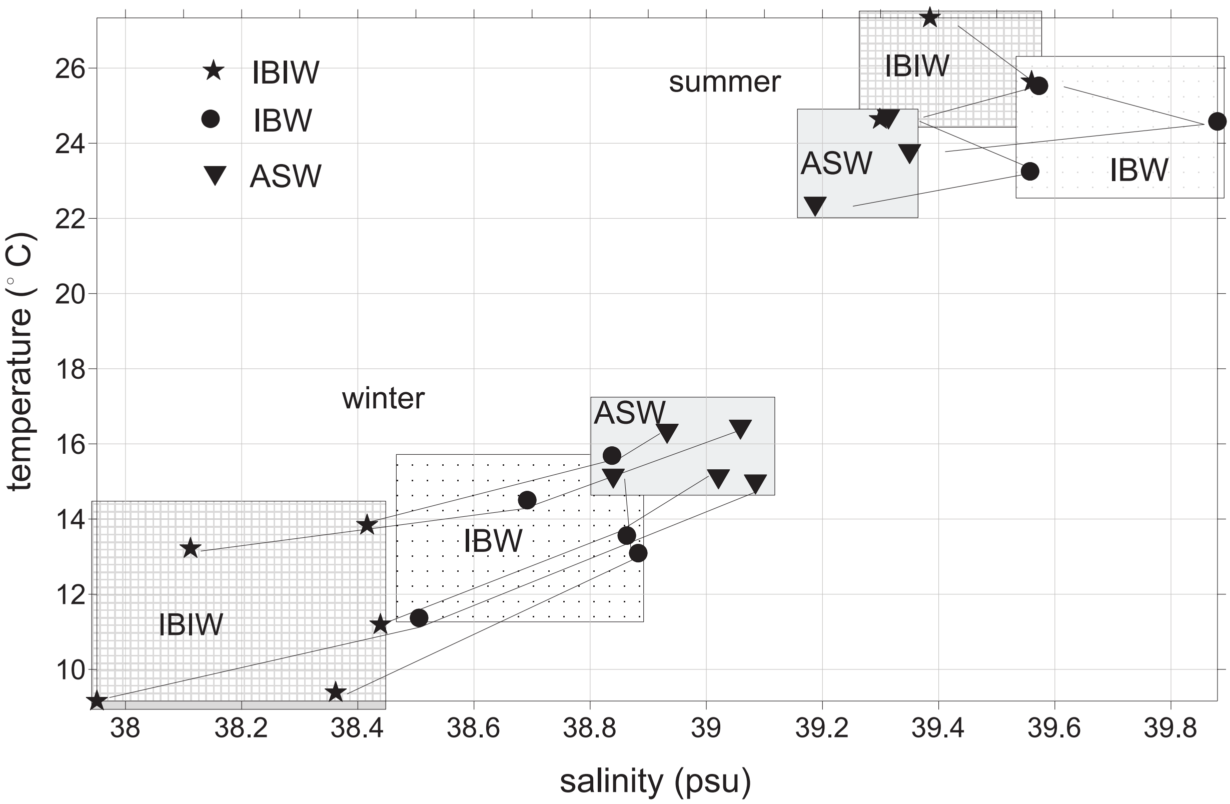



**Figure 21.** T-S diagram for the water masses IBIW, IBW and ASW in summer and winter.

(38.98–38.84 psu) compared to the other water masses in the bay in July 2000. The İzmir Bay bottom water, originating from the middle gyre area, influences the Gediz and Foça regions and reaches to the Aegean Sea as a result of thermohaline circulation in summer. Therefore the bottom waters of Gediz and Foça have the same T-S characteristics with ASW.

*Fall.* The T-S characteristics of September 1998 (Figure 24) are similar to the T-S characteristics observed in summer. The low salinities, observed near the bottom of Gediz and Foça area are due to water movement from south to north along the east coast. The inflowing surface current along the east coast is stronger compared to the bottom reverse current spreading to the Aegean Sea as a result of thermohaline circulation. On the other hand, the current from the Aegean Sea follows two paths, one is through the Mordoğan Strait and the second one is along the east coast. The incoming water properties change slightly on the way.

Previous work (Sayın 2003) deals with relevant physical properties of the İzmir Bay water and also covers information on water masses forming inside the bay. Water masses were not determined by the previous work, but were analyzed regionally even if they showed slight differences in heat and salt content. The present study concentrates mainly on the water masses formed in the bay. It determines the distinguished water masses and analyzes them by a combination of observation and numerical model to clarify their formation and movements in the bay.

## Conclusions

This paper provides a better understanding of water mass characteristics in İzmir Bay with well-presented data obtained as a result of decadal monitoring study. The

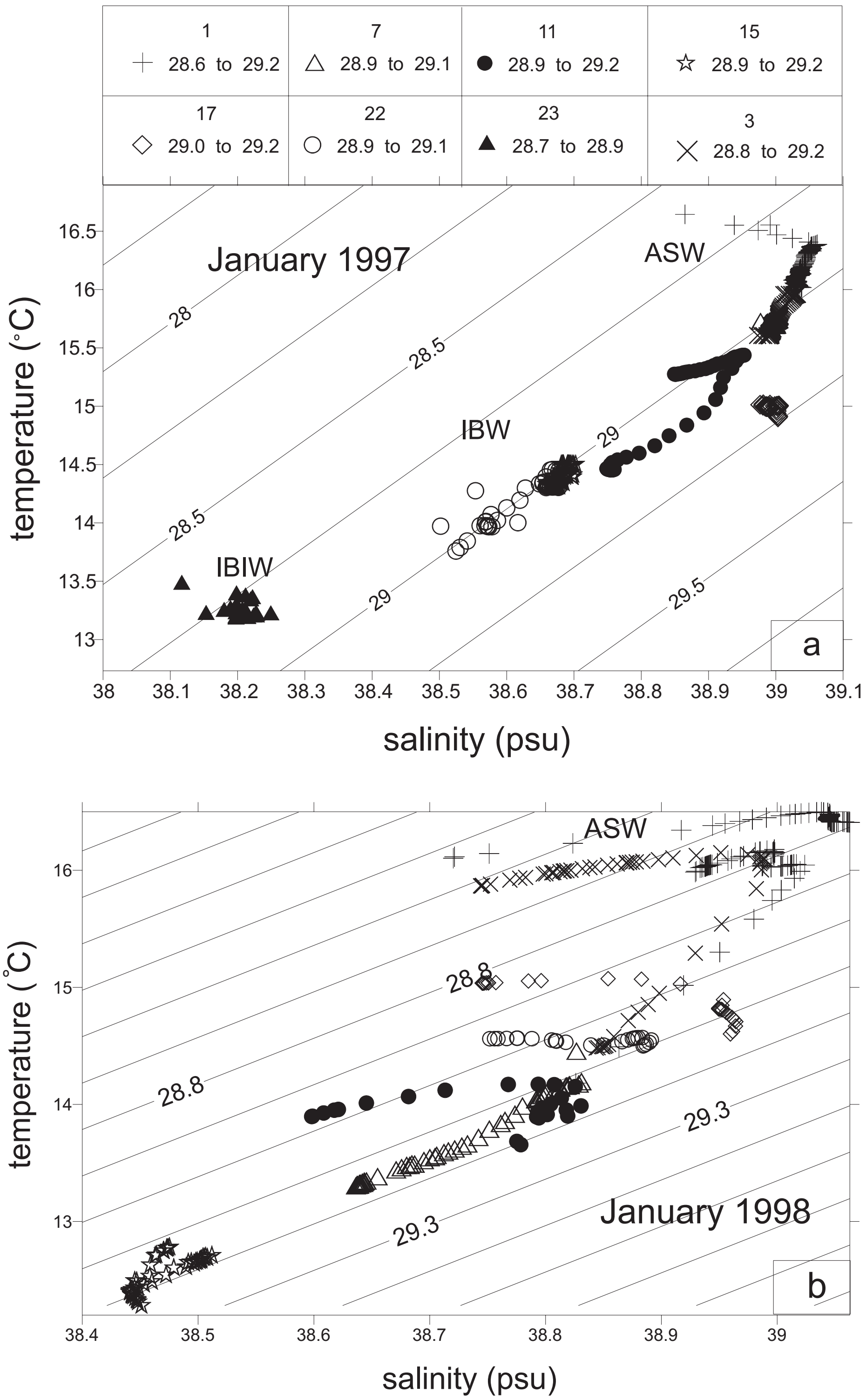



**Figure 22.** T-S diagrams of January 1997 (a) and 1998 (b), representative stations for distinct water masses, + – St.1 (ASW), x – St.3 & St.4, Δ – St.7 (Foça), ● – St.11 (Gediz), ✻ – St.15 (middle gyre), ◇ – St.17 (outer II), ❍ – St.22 (middle bay), ▲ - St.23 (inner bay).

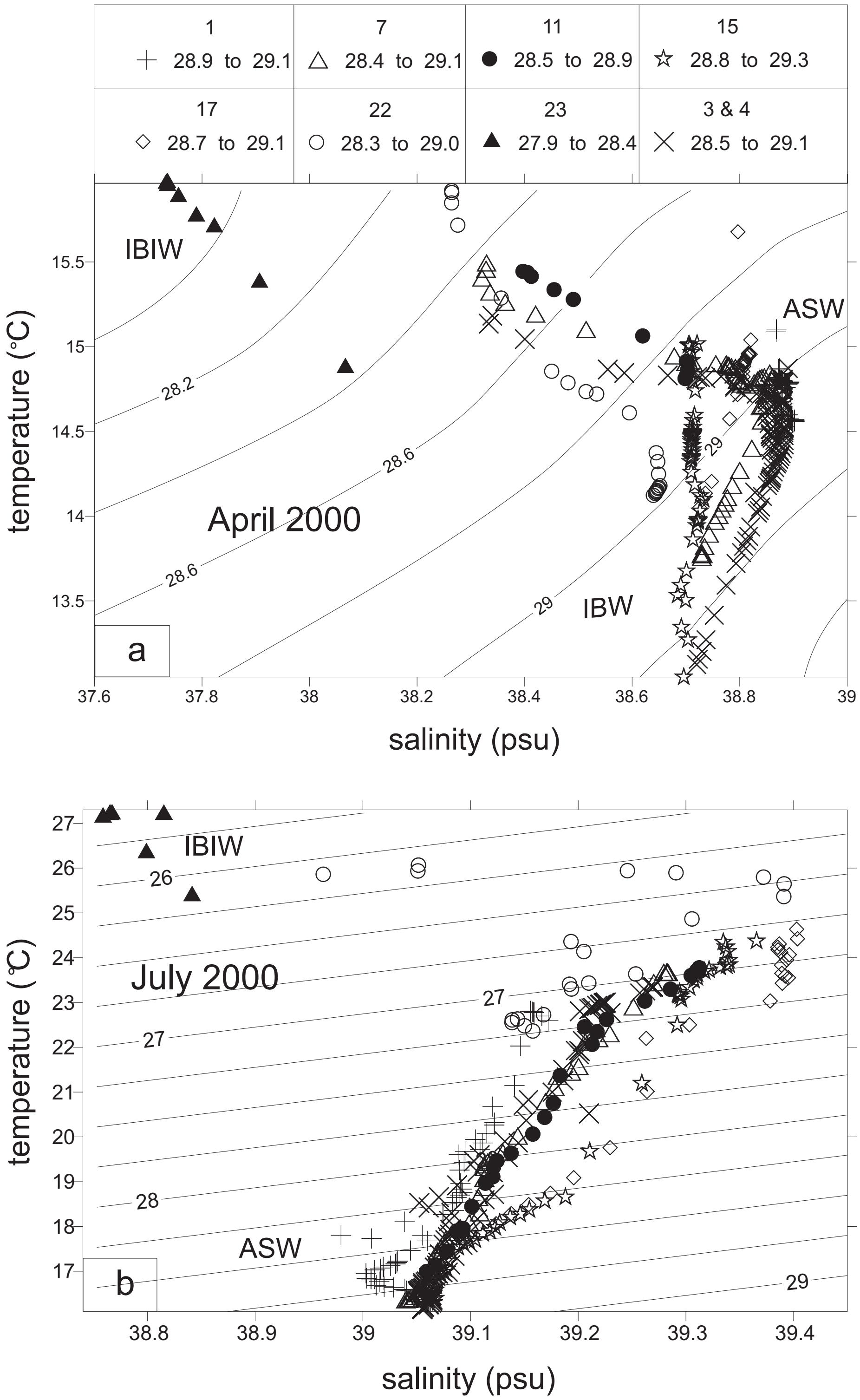



**Figure 23.** T-S diagrams of representative stations for distinct water masses in April 2000 **(a)** and July 2000 **(b)**, + – St.1 (ASW), x – St.3 & St.4, Δ – St.7 (Foça), ● – St.11 (Gediz), ✻ – St.15 (middle gyre water), ◇ – St.17 (outer II), ❍ – St.22 (middle bay), ▲ – St.24 (inner bay).

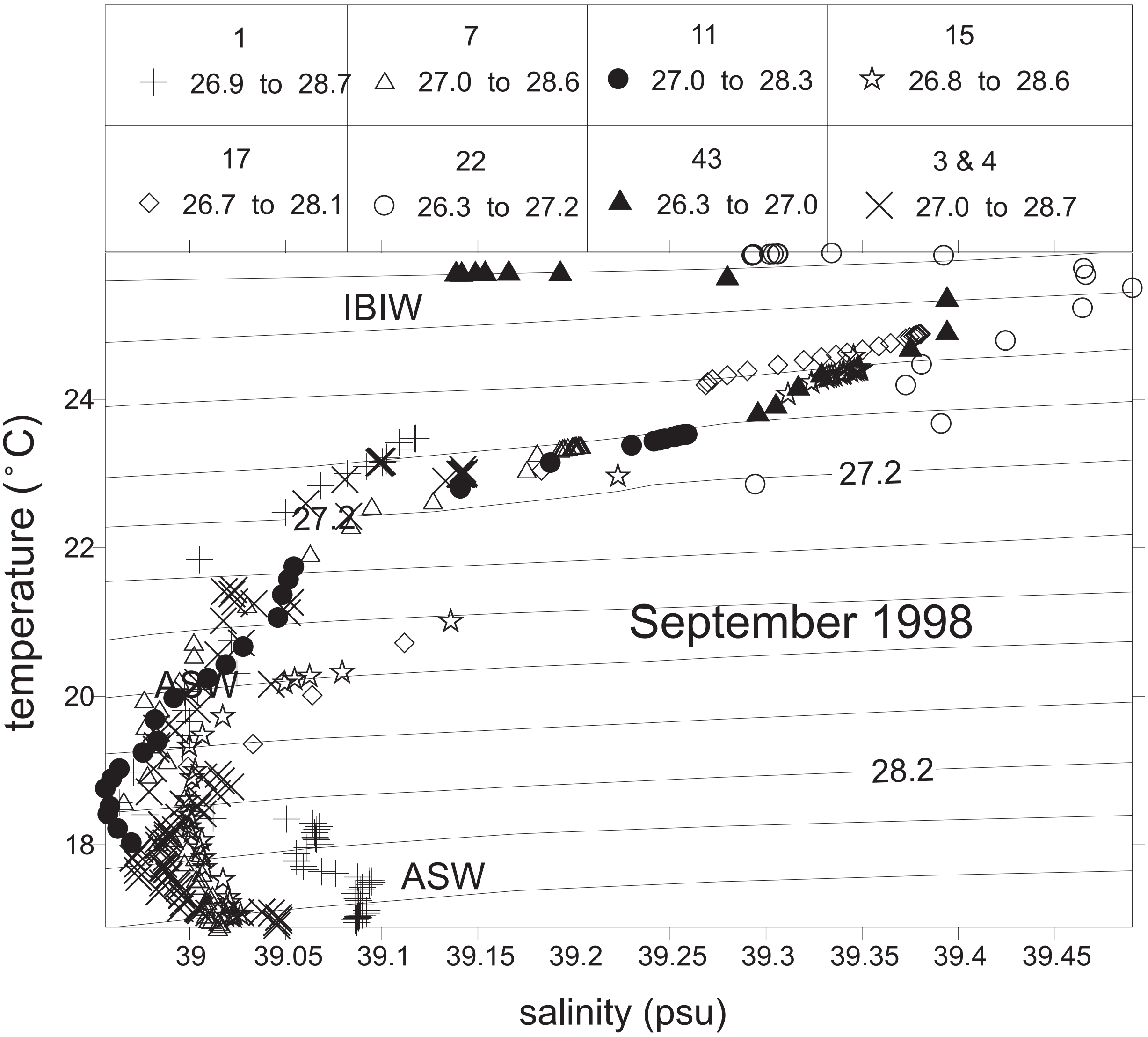



**Figure 24.** T-S diagrams of representative stations for distinct water masses in September 2000, + – St.1 (ASW), x – St.3 & St.4, Δ – St.7 (Foça), ● – St.11 (Gediz), ✻ – St.15 (cyclonic middle gyre), ◇ – St.17 (outer II), ❍ – St.22 (middle bay), ▲ – St.23 (inner bay).

simulated barotropic response of the flow pattern with in-situ data analysis provides new information about water masses in İzmir Bay. Throughout this study three primary water masses are recognized to exist in İzmir Bay: Two of them are Aegean Sea Water (ASW) and İzmir Bay Inner Water (IBIW); these are very distinct water masses. İzmir Bay Water (IBW) is formed between these two water masses and is under several local influences. Gediz River and the salt production area at Tuzla can influence the surface water of the IBW. Although three distinct water masses exist in winter, no distinct division is found between the ASW and IBW in summer especially in the lower layer of the water column.

In winter, ASW and IBW show a homogenous vertical distribution due to the winter convection and wind mixing. Fresh water discharge forces the establishment of a vertical and horizontal stratification all year around in IBIW. Besides seasonal heating, the strong evaporation plays an important role in the two-layered system in the summer. The temperature in winter decreases gradually towards the inner Bay. The IBIW mass is always colder, denser, and fresher than the other water masses and the ASW is always warmer, more saline and lighter than the water masses of other regions in winter. Temperatures decrease in summer from inner Bay to Aegean Sea, because of differential warming. As a result of variation in temperature, density also changes in a similar manner. It decreases from the middle bay to outer III in winter, but increases in summer. April and October are the transient months between winter and summer. The upper and lower layers show summer and winter characteristics, respectively, in April, except for the surface of ASW. Because of its large volume, ASW water preserves its winter character. In the late April, the stratifications start to be stronger, but gradually, horizontal homogeneity is approached in time.

Seasonal change influences water exchange between the Aegean Sea and İzmir Bay. The current structure in İzmir Bay indicates that vertically homogenous ASW enters the bay near Karaburun in winter and horizontally homogeneous ASW inflow occurs above the pcynocline through the vertical section VS4 in summer. The outflow occurs in the surface and bottom layer near the coast of Foça in winter. As a result of thermohaline behavior of stratified water in summer, it flows to the Aegean Sea under the pycnocline. The density surfaces are horizontally parallel to each other in summer.

The most pronounced characteristic of circulation in the İzmir Bay is the development of the middle gyre in the middle of the bay. The model approach to obtain a representation of the spatial variability of İzmir Bay circulation is successful in evaluating the middle gyre which occurs mainly as a result of wind-driven circulation in the bay. While the southerly winds cause a cyclonic gyre in the middle of the İzmir Bay (southeast of the Uzun Island), the northerly winds cause an anticylonic gyre. The winds from northerly direction (Etesians in summer), that are a dominant feature over the İzmir Bay area, produce southerly coastal barotropic currents.

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