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The dynamics of İzmir Bay under the effects of wind and thermohaline forces

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Abstract. The dominant circulation pattern of the İzmir Bay by the Aegean Sea coast of Turkey is studied under the influence of wind and thermohaline forces. İzmir Bay is discussed by subdividing the Bay into outer, middle and inner areas. Wind is the most important driven-force in İzmir coastal area. There are also thermohaline forces due to the existence of water types of different physical properties in

10   the Bay. Instead of the two-layered current system prevailing during summer, a horizontally shared current system exists in winter. The free surface version of the Princeton model (Killworth's 3D general circulation model) is applied with the input data obtained through the measurements made by the research vessel K. Piri Reis. As a result of model experiments the basin-wide circulation in İzmir Bay is cyclonic. Although the stratification in the bay changes the behaviour of the circulation, the recirculation pattern

15   does not change seasonally, but changes under the influence of wind forcing. Wind-driven circulation causes cyclonic or anti-cyclonic movements in the middle bay where the distinguished İzmir Bay Water (IBW) forms. 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 in the Middle Bay. Outer and Inner Bay have also certain wind driven recirculation patterns.

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Key words: Circulation, 3D numerical model, İzmir Bay

1 Introduction

İzmir Bay, located on the Aegean Sea coast of Turkey, was formed as a part of the Aegean Sea during the Pleistocene period. Later, it was partially filled with the silt carried by Gediz River (Maddy et al., 2012).

25   It can be divided into three areas according to their physical characteristics: Outer, Middle and Inner Bays, as indicated in Fig. 1. The average depth in the Outer Bay is about 70 m. It decreases significantly towards the Inner Bay to an approximate depth of 10 m. The reason of extra-shallowing towards the Inner Bay and shallow area along the eastern coast of the Middle Bay is the silting process of Gediz River since the formation of the Bay: Gediz River used to join the sea through a delta, with several small

30   mouths, extending from Inner Bay to Middle Bay until about 1890. At that date, the river was artificially diverted northwards to join the sea at the Outer Bay, at a location south of Foca in an effort to save the harbour.

The water input through Gediz River is relatively small (averaging about 40.3 m3/s) over 30 years compared to the water exchange with the Aegean Sea (approximately 7000 m3/s). Since Gediz River used

35   to discharge into the Inner and Middle Bays until 1890, there is an important accumulation of

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sedimentation in the Inner and Middle Bays (Karahan, 2002). This situation, causing major differences in the bathymetric structure of the Inner Bay, has a very important role on the circulation there and avoids massive water exchange water between the Inner Bay and the Middle Bay.

The main driving forces of the circulation system of the Bay are the wind force and the elevation gradient
40   maintained in the sea level. The stratification is also important in the Bay.

In the Bay, three distinguished water types exist: Aegean Sea Water (ASW), İzmir Bay Water (IBW) and İzmir Bay Inner Water (IBIW) (Sayın et al., 2006). On the other hand, the transport processes through some vertical sections can give a good estimate about renewal time for the selected regions in the İzmir Bay (Sayın, 2003). It is important also from the biological point of view to know the exchange between
45   the Aegean Sea and the Bay and the volume of the Bay in order to calculate the renewal time for the İzmir Bay water.

The current from the Karaburun area carries fish eggs and larvae into the small Gülbahçe Bay through the Mordoğan Passage and even further to the Middle Bay, depending on the wind condition and stratification in the water column. This feature adds to the diversity of marine life, as can be observed
50   from various larvae found in Gülbahçe Bay. Suspended material and food can be trapped in the interfacial area between the water masses from the Aegean Sea and the interior parts of the Bay. Therefore, these places are the attraction locations for fish (Sayın and Öztürk, 2006).

One can increase the number of examples in which the currents and background-forming horizontal and vertical stratification are crucial for marine environments. The analysis of current system in the Bay is
55   quite recent: The first mathematical model study is related to the circulation pattern of the İzmir Bay: It is the depth-averaged two dimensional mathematical model given in Karahan (1988). The current system in the Bay has been examined by Saner (1994). He has calculated the circulation pattern and water exchange between the different regions of the İzmir Bay using two and three dimensional wind-driven mathematical models. Saner (2005) has also compared his two models: The two dimensional model
60   solving the equations using standard 2D-ADI method with the 3-D dimensional sigma coordinate model. Pazı (2000) has studied the current system of the Bay mainly related to the observations and has found that the current is driven by wind and also by thermohaline forces. Sayın (2003) has investigated the important physical features based on observations and modelling studies. Beşiktepe et al. (2011) calculated the circulation pattern of the İzmir Bay with a primitive equation model of the Harvard Ocean
65   Prediction System. Eronat (2011) and Eronat & Sayın (2014) studied on the temporal evolution of the water characteristics, in addition to effort on the current system in the Bay.

In present study, emphasis is given to the dynamics of recirculation maintaining in İzmir Bay. These circulation patterns are formed under special wind conditions depending on background stratification. The seasonal regime of current system and forming of persistent or quasi-permanent water movements in
70   the Bay are the information relevant to studies on the biological or chemical oceanography of the Bay.

Materials and methods of this study are explained briefly in the second section. The third section examines the recirculation patterns that are frequently observed in the İzmir Bay environment. The last section is the conclusion.

2 Material and methods

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The physical oceanographic measurements have been initiated in 1988 in İzmir Bay. The regular measurements have been conducted since 1996 with Seabird CTD (Conductivity, Temperature and Depth) system.

A z-level Killworth's 3-D general circulation model based on the primitive equations described by Bryan

80 (1969) and Cox (1984) is applied to the İzmir Bay. The specific model configuration used here is an explicit free surface version of the Princeton model, developed by Killworth et al. (1989). The Killworth model filters the fast oscillations, letting geostrophic balance remain behind after the establishment of the steady current. The steady current is achieved by controlling the kinetic energy of the system. The integration is stopped as soon as the kinetic energy level reaches to a plateau. To set a realistic

85 stratification, selected winter and summer hydrological cruise CTD data is prescribed in the model as an initial condition. The winter and summer initial temperature and salinity values are shown in Fig. 2. The simulations were used to define the general circulation patterns of the Bay.

The chosen model parameters are given in Table 1. No tidal and heat forcing is included in the model. The density-driven experiment is conducted using the temperature and salinity fields (no wind) to

90 understand the effect of the stratification on the circulation pattern. The wind-driven experiment is conducted using persistent wind from four main directions (wind intensity is chosen constant 5 m/s) to simulate the lasting wind condition.

The model domain is connected to the Aegean Sea. At the boundary, Stevens (1990) active open boundary condition for the tracer field, Orlanski (1976) radiation condition for the external mode was

95 applied. Stevens active boundary was chosen to force the model with observed temperature and salinity values at the boundary. It was deemed suitable to choose radiation condition for the barotropic part due to lack of consistent surface elevation information related to the Aegean Sea general circulation dynamics.

The numerical experiments which were done can be summarized into two groups: One group deals with

100 the thermohaline circulation (thermohaline circulation is defined as the circulation evolved under the influence of the density-induced forces generated as a result of background temperature and salinity stratifications) and the other group with the wind-driven circulation.

It is certain that the open sea flow is very influential for the existence of features in the real sea. In our case, we have no sea level measurements. It is not possible to get reliable sea level information from

105 satellite data (TOPEX/POSEIDON) due to its coarseness. On the other hand, although the İzmir Bay has a link with the Aegean Sea, cape and islands off the northern part of the Bay probably form a barrier for the development of a big sea level gradient extending from north up to İzmir Bay mouth opening to the Aegean Sea.

3 Results and discussions

The representation of recirculation patterns that are formed by existence of winter and summer stratification in the water column are given as a result of thermohaline circulation in Fig. 3.

First we describe the water types related to the stratification in the Bay. The existing water types (Sayın et al., 2006) in the Inner, Middle and Outer Bay evolving under the different physical processes and mechanism influence the water circulation in the Bay. From the water types, the İzmir Bay Water (IBW) is denser than the Aegean Sea Water (ASW) in winter and the expected thermohaline circulation is cyclonic along the basin width (Fig. 3 upper panel). It means dense water of IBW tends to flow along the east coast towards Aegean Sea and less dense ASW that enters near Karaburun flows through the Mordoğan Passage into the Middle Bay.

The flow from Aegean Sea follows the path in the middle of the Outer Bay and turns to the direction to Gediz River and then flows near the east coast of the Uzunada Island and bifurcates in summer (Fig. 3). One branch combines with the current at the west coast and other branch complete the cyclonic circulation in basin wide. This flow leaves the İzmir Bay near the coast of Foça. The summer circulation pattern is complicated comparison to the pattern obtained for winter circulation. Instead of being vertically homogeneous, it is almost horizontally homogeneous; but vertically stratified water column changes the behaviour of the current during summer.

If the circulation patterns in winter are compared with the patterns formed in summer, except the cyclonic circulation patterns **A** (Aegean Recirculation Pattern) and **O** (Outer Bay Recirculation Pattern) in the outer Bay, the pattern **M** (Middle Bay Recirculation Pattern) changes sign. Thermohaline circulation **I** (Inner Bay Recirculation Pattern) is very weak in the Inner Bay in both seasons with a dipole shape that changes signs from winter to summer (Fig. 3).

After analysis of thermohaline circulations, some model experiments are conducted using the winds from four main directions: westerly, easterly, northerly and southerly. Persistent westerly wind changes thermohaline cyclonic circulation and winter homogeneous water is immediately under the influence of wind force (Fig. 4). Coastal jets are produced along both coasts in the wind direction and a slow return flow compensates this transport in the central area of the basin as explained in the literature. In the case of a westerly wind, as expected, characteristic flows near both coasts are in the wind direction. The recirculation pattern **M** is anticyclonic due to establishing a stronger current near the east coast of the Bay relative to the coastal current near the east coast of Uzunada Island. This pattern **M** is also anticyclonic in summer, but it is not well developed. It means that the stratification can play an important role on the current system.

In the Inner Bay, recirculation dipole pattern **I** is observed both in summer and in winter with a same sign. There is no significant communication between Inner and Middle Bays because of the existence of a narrow passage (Yenikale passage). The numerical experiment was conducted to show the development of circulation in the Inner Bay by increasing the wind intensity from zero to 5 m/s. The current, not only in the Inner Bay, but also in the other regions of the Bay starts to set up after a certain wind speed is exceeded. The current is very weak in the Inner Bay without the existence of wind force. The currents get

stronger with increasing wind speed. Recirculation patterns which exist in the Middle Bay become well-developed after the increase of wind intensity above approximately 2.5 m/s and are observable both in the

150   barotropic field and in the certain layers.

In a similar manner, the current pattern of the Bay can be analyzed for the other wind conditions as was already done for the westerly wind. It is prefered to explain the current system giving emphasis on the recirculation patterns form in the Bay. For example, closed circulation pattern **M** has an anti-cyclonic character in westerly and northerly wind conditions (Fig. 4 and Fig. 6); and has cyclonic character in

155   other wind conditions; easterly and southerly (Fig. 5 and Fig. 7) for both seasons. Because of existing strong stratification in summer, a dipole forms in the middle area instead of one anti-cyclonic circulation (Fig. 4 and Fig. 6).

Circulation pattern **I** generally has dipole character in westerly and easterly wind conditions (Fig. 4 and Fig. 5). These poles change places (signs) with each other depending on changing wind directions. It has

160   anti-cyclonic character in southerly wind condition and cyclonic character in northerly wind condition for both seasons (Fig. 6 and Fig. 7).

Circulation pattern **O** forms mainly cyclonically in case of westerly and northerly wind conditions (Fig. 4 and Fig. 6) and anti-cyclonically in case of easterly and southerly winds in both seasons (Fig. 5 and Fig. 7).

165   Circulation pattern **A** is not persistent. If it forms, it will be in cyclonic form. This cyclonic behaviour is seen both in summer and winter thermohaline circulations.

The small pattern formed above the **M**, most of time has the same sign as **M**. This circulation is formed at first in the Middle Bay area and later it moves towards the north. It sometimes combines with the patterns in the Outer Bay forming one big recirculation pattern.

170   The results obtained by the numerical method can be summarized schematically with respect to frequently seen recirculation patterns (Fig.8). İzmir Bay is very sensitive to wind intensity and direction. A central recirculation pattern **M** is frequently present in the Middle Bay. Its direction of vorticity depends strongly on the recently blowing wind condition. The other recirculation patterns, **A**, **O**, and **I**, are quasi-stationary. For example, the recirculation patterns seen in Outer Bay near the Aegean Sea **A**

175   and **O** are developed mainly in the Middle Bay area. Sometimes they combine with the features in that area forming a larger cyclonic or anti-cyclonic pattern. They are mainly related to strong currents maintained near coastal shallow areas and gain velocity-shear related to topography. The velocities are stronger in shallower areas compared to the velocities in relatively deeper parts. Recirculation Pattern **I** is observed in the Inner Bay generally with dipole shape.

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4 Conclusions

The circulation and water movements of İzmir Bay can be summarized as follows:

The expected basin-wide circulation in İzmir Bay is cyclonic. The Izmir Bay Water flows along the east coast towards Aegean Sea while the Aegean Sea Water enters through the Mordoğan Passage into the

185 Bay in winter. However, in summer, although the circulation is cyclonic again, Aegean Sea Water flows into the Middle Bay near the east coast of the Uzunada Island.

A (Aegean Recirculation Pattern) and **O** (Outer Bay Recirculation Pattern) form in the Outer Bay. The most often observed **M** (Middle Bay Recirculation Pattern) forms in the Middle Bay and **I** (Inner Bay Recirculation Pattern) is observed in the Inner Bay generally with dipole shape.

190 Pattern **M** has a cyclonic character in case of southerly and easterly winds and has an anticyclonic character in case northerly and westerly winds. Sometimes in summer, anticylonic circulations cannot be developed well because of the strong background thermohaline cyclonic circulation. The recirculation pattern formed above the **M** towards the Aegean Sea has always the same sign as **M**. This pattern forms at first in the Middle Bay area and it moves to the north. It sometimes combines with the other pattern in

195 the Middle Bay remaining one big pattern behind. This shows us that the Middle Bay area plays important role in the generation of closed recirculation patterns in the Bay.

Outer Bay Recirculation Pattern **O** forms mainly anti-cyclonically in case of southerly and easterly winds and cyclonically in case of westerly and northerly wind conditions in both seasons.

The wind-driven recirculation pattern **I** almost has double poles in easterly and westerly wind conditions.

200 These poles change places with each other depending on the wind direction. The dipole character of circulation gains cyclonic or anti-cyclonic behaviour, in turns, in northerly and southerly wind condition.

Circulation pattern **A** is not persistent. Its shape changes depending on the Aegean Sea boundary condition.

205 **Acknowledgements**

210 **References**

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Tables

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 coeff for momentum:	$1.0E5 \ cm^2/sec$
Vertical eddy coeff for momentum:	$1.0 \ cm^2/sec$
Horizontal eddy coeff for heat:	$1.0E5 \ cm^2/sec$
Vertical eddy coeff for heat :	$0.1 \ cm^2/sec$
Baroclinic time step:	200 sec
Barotropic time step:	5 sec
Bottom drag coefficient	2.2E-3

Table 1. The chosen model parameters for the wind-driven circulation experiments.

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Figures
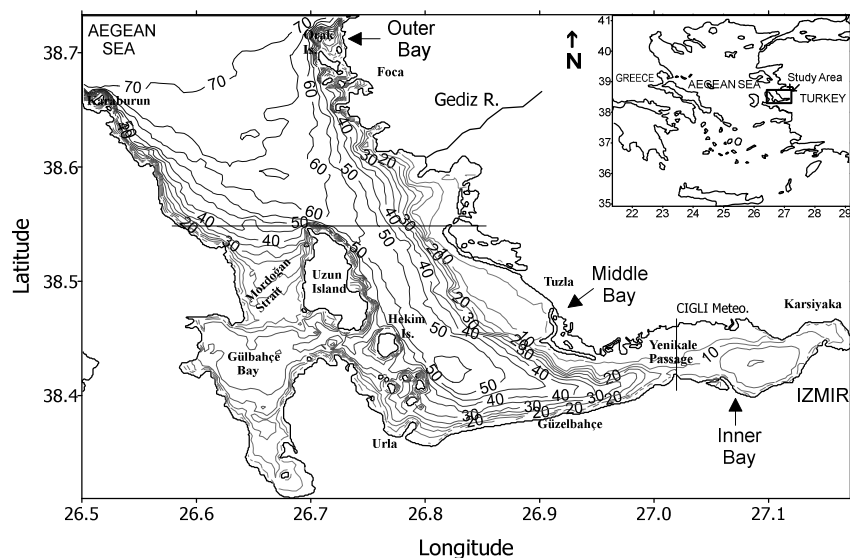
Fig. 1. Location of İzmir Bay and study area bathymetry.
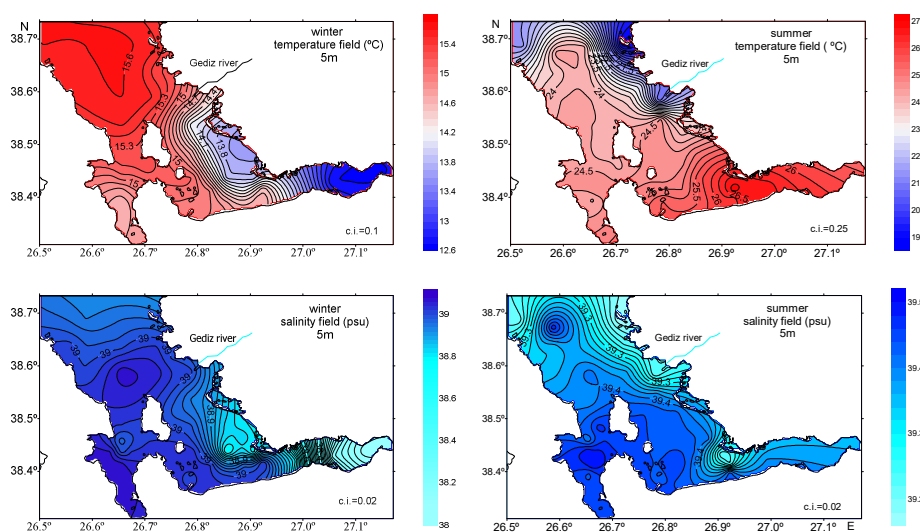
Fig. 2. The winter and summer, temperature and salinity fields are prepared to give to
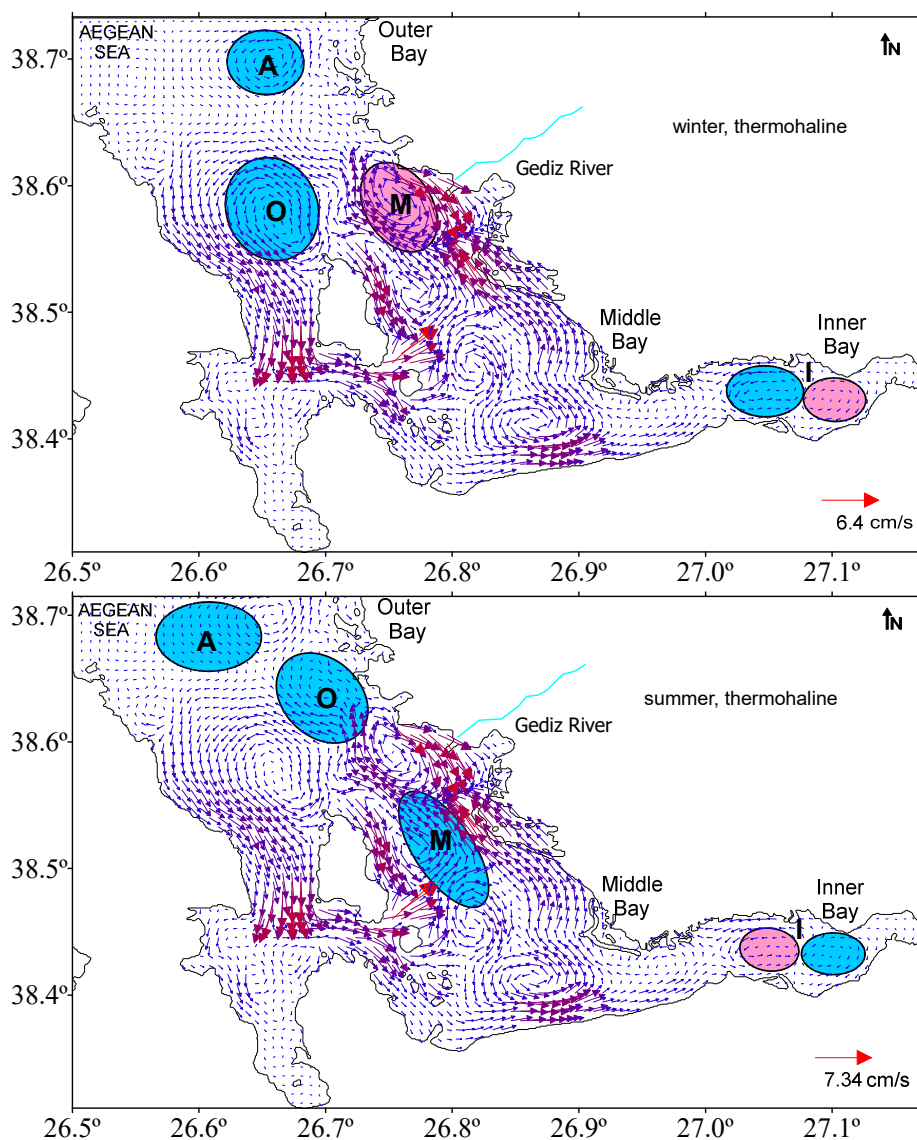265   the model as temperature and salinity distribution of the first level.

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Fig. 3. The winter and summer thermohaline circulation in the Bay.

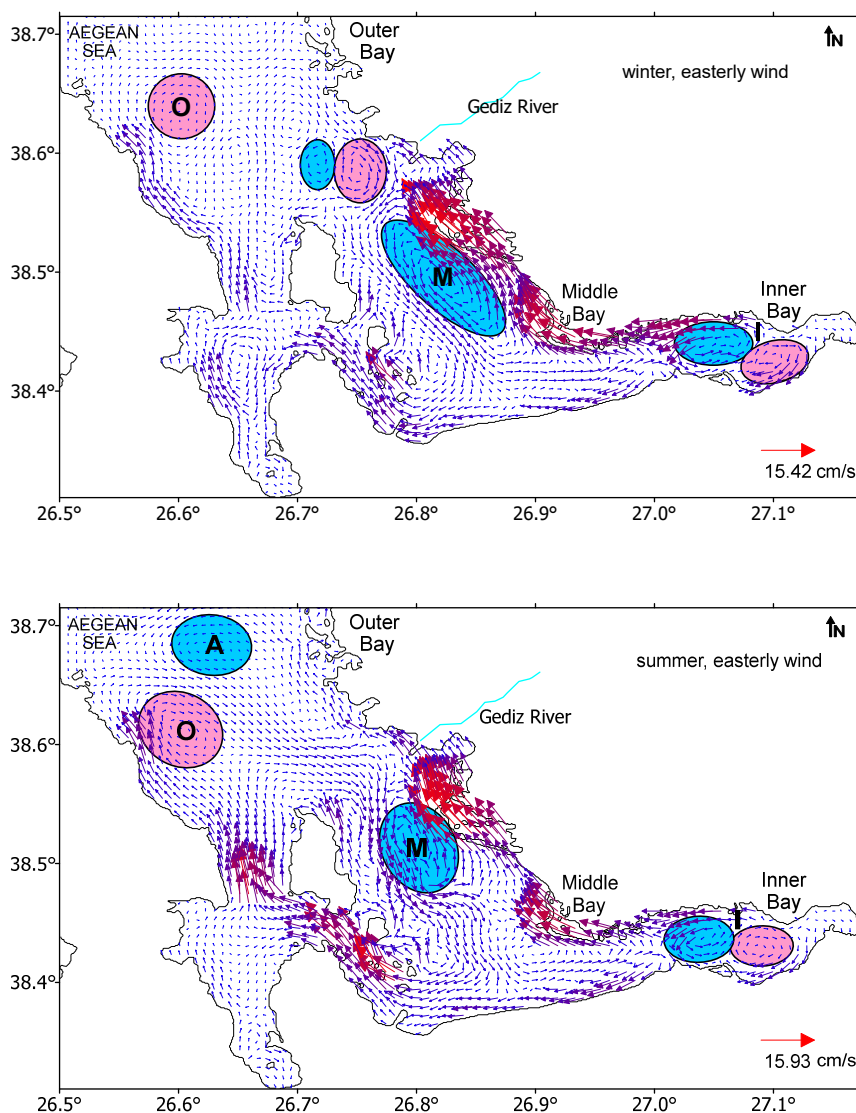Ocean Science
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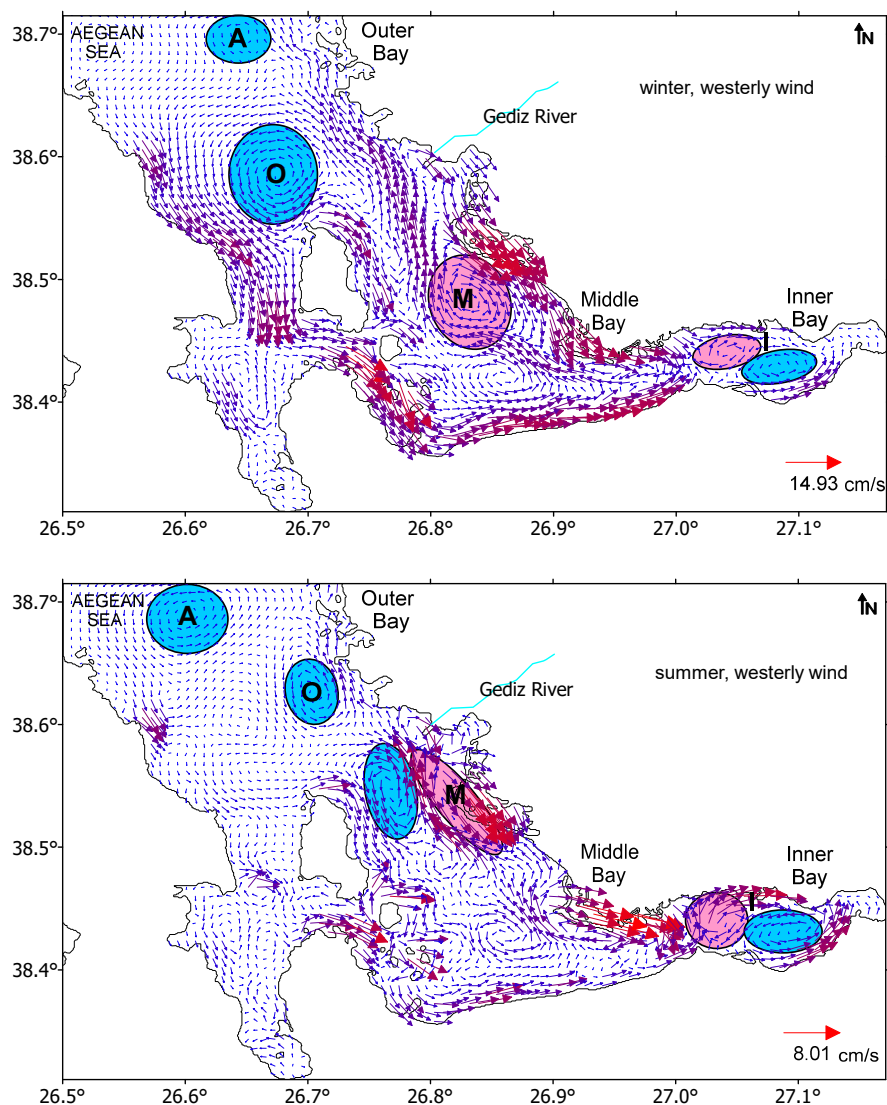
Fig. 4. The barotropic current pattern in case of westerly wind in winter and in summer.

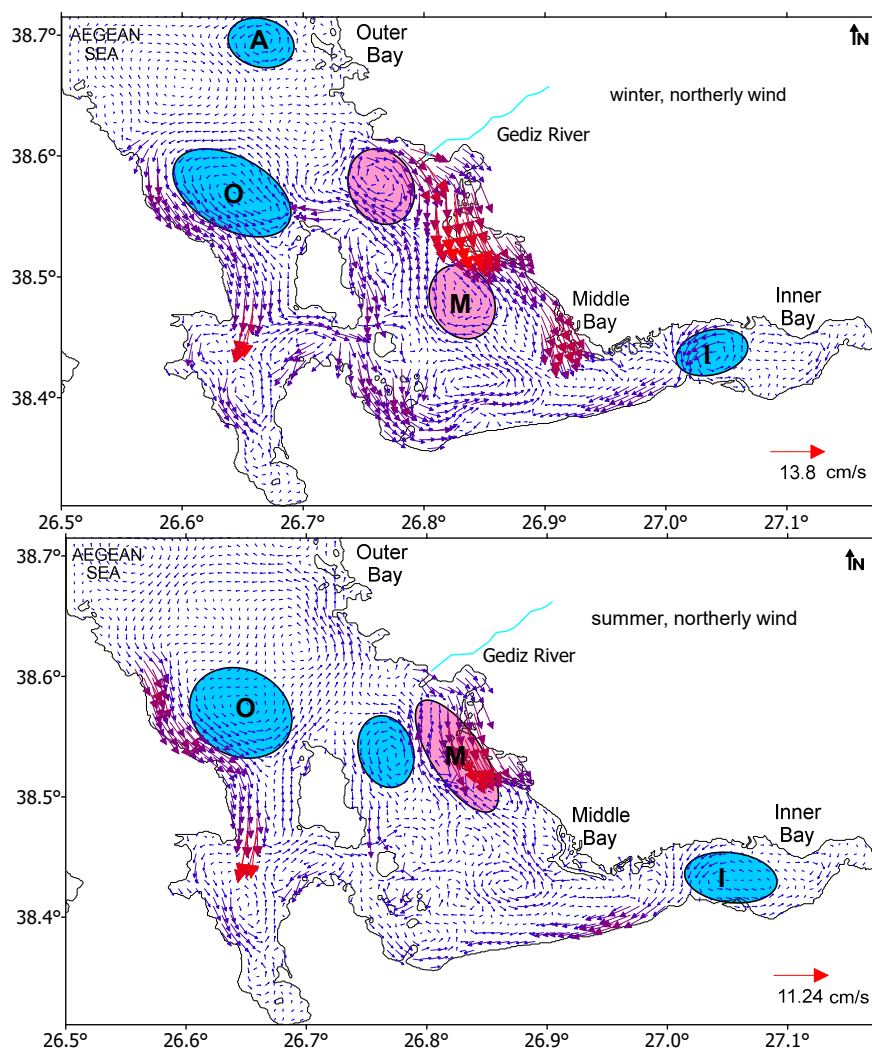**Fig. 5.** The barotropic current pattern in case of easterly wind in winter and in summer.
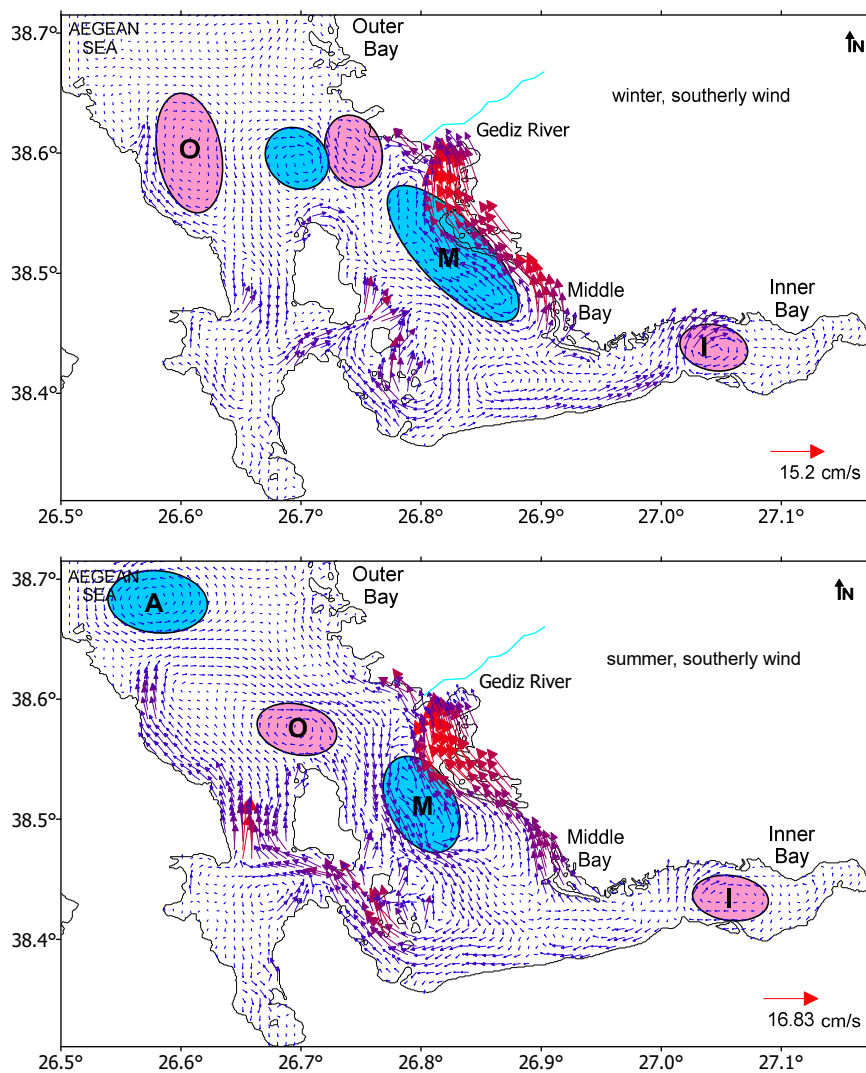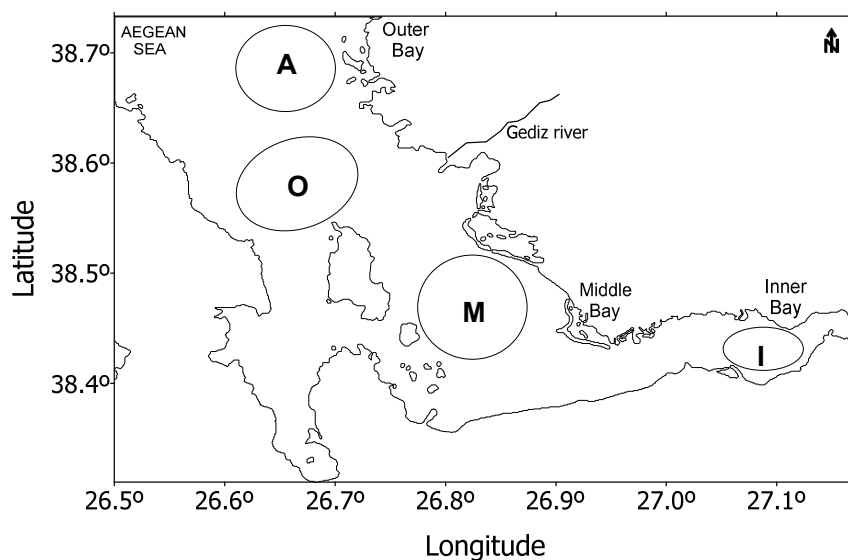
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Fig. 6. The barotropic current pattern in case of northerly wind in winter and in summer.

Fig. 7. The barotropic current pattern in case of southerly wind in winter and in summer.

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285   **Fig. 8.** Frequently seen recirculation pattern in the İzmir Bay.