

Impact of wind and thermal forcing on the seasonal variation of three-dimensional circulation in the Caspian Sea

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A three dimensional hydrodynamic model (COHERENS) has been used to study monthly circulation and water mass properties of the Caspian Sea. Boundary conditions given to the model were river discharge, wind speed, air temperature, relative humidity, cloud cover and precipitation rate. Model simulation showed cyclonic circulation in December and January especially in the south and middle of the Caspian Sea. Moreover, wind velocity and temperature had an important role in the formation and variations of currents in the Caspian Sea. The thermocline that was established in the southern coast of the Caspian Sea according to field data and results of model simulation, showed relatively similar trends, such that the thermocline is created at the depth of 30 to 40 meters in the Anzali port region during autumn and then the thermocline vanishes in winter with the decrease in temperature. In spring the thermocline layer is recreated at a depth of about 10 to 20 meters.

[**Keywords:** Caspian Sea, thermocline, circulation, COHERENS]

Introduction

Caspian Sea is the largest isolated body of water on earth that can be divided into three regions: north (covering 80000 km²), middle (covering 138000 km²) and south (covering 1648400 km²)¹.² The shallow north region has a maximum depth of about 20 m, but the middle and south regions have maximum depths of 788 m and 1025 m, respectively. Underwater extension of the Apsheron Peninsula forms a sill separating the middle and southern regions, with a maximum depth of about 180 m. South region contains two thirds and the north 1% of the total volume of the Caspian Sea waters³.

Because of the distinct features of the Caspian Sea such as its size, depth, chemical properties, and peculiarities of the thermohaline structure and water circulation it is classified as a deep inland sea. In addition, the longitudinal of the Caspian Sea is three times longer than its latitudinal and that gives rise to the great variability of climate condition throughout the sea⁴.

Caspian Sea has low salinity and deep water regions change with depth (12.8-13.08 PSU); also density stratification largely depends on temperature changes⁵. The range of salinity in the south Caspian Sea is between 12 and 13^{6, 3}. Minimum sea surface temperature in the south Caspian Sea is about 7°C in February and during the summer the maximum sea surface temperature it is about 27°C^{6, 7}.

The form of general circulation in the Caspian Sea has been reported to be anti-clockwise⁵. Isolated water and its inland position of the Caspian Sea are mostly responsible for significant outer thermohydrodynamic factors specifically heat and water fluxes throughout the sea surface, river discharge for sea level variability, formation of its 3D thermohaline structure, and water circulation⁴. In addition, shallow water region circulation in the Caspian Sea is almost completely controlled by local winds^{8, 5, 3}.

Many rivers (about 130) of various sizes drain into the Caspian Sea with an annual input of about 300 km^{3, 2}. Important rivers are the Volga (80% of

the total volume of inflow), the Ural (5%), the Terek, Sulak, and Samur (total up to 5%), the Kura (6%), and Iran's small rivers of the Caucasus and several others (45%)⁹. The aims of this study are to investigate the main circulation features and the seasonal variability of the circulation and impact of thermal and wind forcing in formation of surface and subsurface currents.

Materials and Methods

Model is based on the hydrostatic version of the Navier-Stokes equations. Hydrodynamic part of the model uses the equations of temperature and salinity, and the momentum equations use the Boussinesq approximation, the assumption of vertical hydrostatic equilibrium, and the continuity equation¹⁰. Equations of the model are discretised on an Arakawa C-grid¹¹. The equations of momentum and continuity that are solved numerically use the mode-splitting technique.

Grid resolution of the model is $(0.046^\circ) \times (0.046^\circ)$ (latitude $\times$ longitude), which gives a grid size of about 5 km. Maximum depth in the model is 1000 m and a minimum depth of 7 m occurs in the shelf region of the northern region. Model is configured with 30 vertical sigma levels (the layers' numbers are represented as K so that the bottom layer begins with 1 and as the layers go up towards sea level the number increases). Bathymetry and coastline locations are based on GEBCO data that has been interpolated and slightly smoothed (Fig. 1).

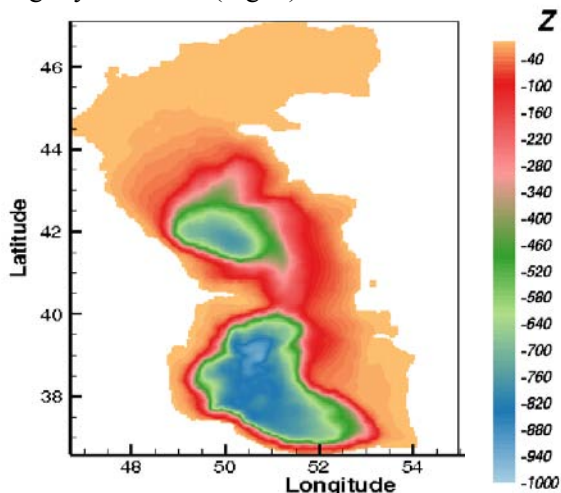


Fig. 1— the modeling domain and bathymetry used in this study.

Model was initialized in winter (January) using monthly mean temperature and salinity climatologies obtained from¹². Surface boundary condition for horizontal currents is

$$(\tau_{s_1}, \tau_{s_2}) = \rho_a C_D^s (U_{10}^2 + V_{10}^2)^{\frac{1}{2}} (U_{10}, V_{10}) \quad (1)$$

where, τ_{s_1}, τ_{s_2} a directional wind stress at the sea surface, $\rho_a = 1.2 \text{ kg/m}^3$ is the density of air, U_{10}, V_{10} are the components of wind vector at a reference height of 10 m and C_D^s is the surface drag proposed by¹³;

$$C_D^s = 10^{-3} (0.43 + 0.097 |U_{10}|) \quad (2)$$

boundary condition for the horizontal current at the bottom is according to the quadratic friction law

$$(\tau_{b_1}, \tau_{b_2}) = \rho_0 C_D^b (U_b^2 + V_b^2)^{\frac{1}{2}} (U_b, V_b) \quad (3)$$

Where τ_{b_1}, τ_{b_2} are the components of the bottom stress, and (U_b, V_b) are bottom velocities that are evaluated at the grid point nearest to the bottom. quadratic bottom drag coefficient is a function of roughness length according to

$$C_D^b = \left\{ \frac{k}{\ln(z_r/z_0)} \right\}^2 \quad (4)$$

Where z_r is a reference height taken at the grid centre of the bottom cell, z_0 represents the bottom roughness length and $k=0.4$ is von Karmen's constant.

Horizontal diffusion coefficients ν_H and λ_H , are taken proportional to the grid spacing and the magnitude of the velocity deformation tensor in analogy with¹⁴ parameterization

$$\nu_H = C_{m_0} \Delta x_1 \Delta x_2 D_T \quad (5)$$

$$\lambda_H = C_{s_0} \Delta x_1 \Delta x_2 D_T \quad (6)$$

where

$$D_T^2 = \left(\frac{\partial u}{\partial x_1} \right)^2 + \left(\frac{\partial v}{\partial x_2} \right)^2 + \frac{1}{2} \left(\frac{\partial u}{\partial x_2} + \frac{\partial v}{\partial x_1} \right)^2 \quad (7)$$

and $\Delta x_1, \Delta x_2$ are the horizontal grid spacing.

The values of the numerical coefficients C_{m_0} and

C_{s_0} are assumed to be $C_{m_0} = C_{s_0} = 0.1$

Model was forced by climatologic six hourly atmospheric forcing such as wind speed, air temperature, air pressure ($0.5^\circ \times 0.5^\circ$) in 2004 derived from ECMWF (ERA-Interim) projects, and precipitation rate, cloud cover and relative humidity ($2.5^\circ \times 2.5^\circ$) in 2004 derived from

Table 1—Mean monthly climatological data.

Month	Wind Speed (m/s)	Air temperature (c)	Cloud Cover (%)	Air pressure (Pa)	Precipitation Rate (Kg/m ² /s)
Jan	2.35	5.71	0.43	98921	7.136×10^{-6}
Feb	1.15	6.33	0.48	99026	9.158×10^{-6}
Mar	0.93	8.50	0.69	99395	1.11×10^{-5}
Apr	1.07	11.61	0.44	98901	2.04×10^{-5}
May	1.09	17.72	0.53	98502	4.76×10^{-6}
Jun	1.28	22.79	0.26	98423	2.015×10^{-6}
Jul	2.25	24.06	0.29	98371	4.5×10^{-6}
Aug	2.17	26.40	0.22	98303	1.932×10^{-7}
Sep	1.88	22.71	0.27	98949	5.418×10^{-6}
Oct	1.22	17.17	0.34	98373	1.306×10^{-5}
Nov	1.17	12.91	0.49	99150	2.314×10^{-5}
Dec	1.37	6.06	0.50	99389	2.108×10^{-5}

and the monthly mean values of the flows for the Volga (has three locations for discharge into the Caspian Sea in the model), Ural, and Kura are given. Salinity of river flow waters was considered to be 0‰. Monthly mean discharge value for each river was obtained from the GRDC (The Global Runoff Data Centre).

In this simulation, the time steps of barotropic and baroclinic models are 15 s and 150 s, respectively. Total simulation time of the model was five years. The model first ran for four years with six hourly varying climatologic forcing at the sea surface boundaries until a quasi steady state was reached and then extended for another year (2004).

Between November 2004 up to the end of January 2005 in the southwest of the Caspian Sea, between the estuary of the Sefidrood river and Anzali port at the width of the continental shelf the current in line vertically to the coast up to a depth of 200 m was measured using moorings with three current meters (RCM9-MKII) at three points which were placed 20 m, 50 m, and 200 m deep in order to

NCEP/NCAR re-analysis. Monthly average of each atmospheric force that was calculated by data recorded every six hours is shown in Table 1.

There are three major rivers used in the model

measure the currents, so that at the 20 m mooring point two devices at 5 and 18 m depth; at the 50 m mooring point, two devices at 5 m and 47 m depth; and at the 200 m mooring point, three current measuring devices at 3 m, 58 m and 122 m were placed. However, in this study due to size grids, the model is about 5000 m after the actual location of the three current measuring devices (20, 50, and 200 m) on one of the grid borders. It is because of this, in order to compare the data of this area with the model, the data point at a

depth of 200 m (due to it being the best choice) has

been used. Furthermore, the CTD measurements along the major axis of the current measurements along and towards the moorings in 9 stations with a distance of 1000 m from each other in May, October, and January were taken.

Results

Result of current model simulation due to wind forcing

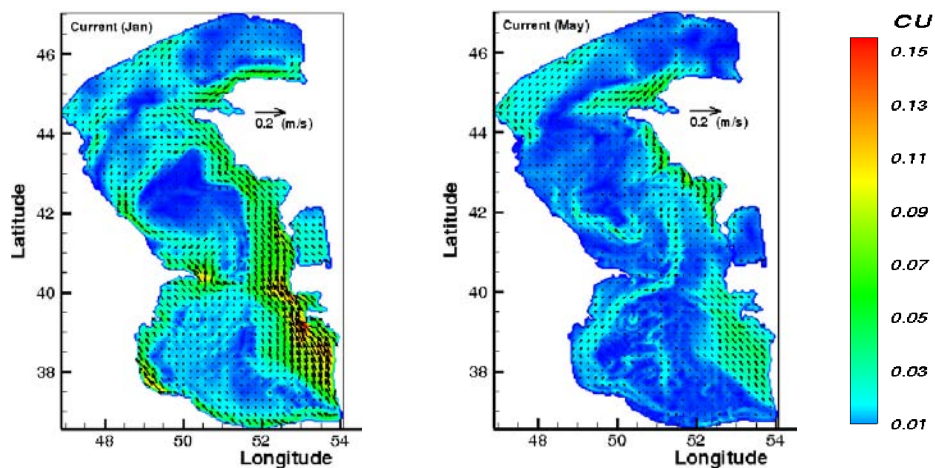
Initially the model was affected by wind force and the results of the wind-driven currents are shown in Fig. 2. The wind scheme of January were stronger than the other months and it resulted in increased compression and intensity of the currents in the Caspian Sea, specifically it was stronger in the south, southwest, and east coast. In January, because of wind direction, the direction of the currents on the east coast of the south and middle Caspian Sea was from the south to the north, while on the west coast of the middle Caspian Sea it was towards the south. Hence, the current scheme of the middle Caspian Sea was cyclonic. After January, the intensity of the currents decreased due to wind scheme changes. From May to July the wind scheme changed from the north to the south of the Caspian Sea. Consequently, the direction of the currents in the east of the middle Caspian Sea became horizontal from the east to the center of the middle Caspian Sea region and these current schemes continued until September. Thus, upwelling phenomenon was created on the east coast of the middle Caspian Sea.

Starting in June, in the southern Caspian the cyclonic current scheme increased proportional to the direction and wind schemes, while the currents became stronger in July. The currents in the southern Caspian became weak in August and September and starting in October, the currents were recreated so that they became stronger and more organized in December (not shown).

Results of the simulation of the general circulation model (under all external forcing)

By applying other atmospheric forcing, river entrances, and increasing the temperature and salinity of the water to the circulation model as initial conditions, the structure and circulation scheme had some intensity in some places, and on the other hand, eddy structures were created in the central and south regions of the Caspian Sea in a way that the flow rate of the eddies decreased when moved towards the center of the sea.

Birol Kara et al. (2010) investigated the sea surface circulation of the Caspian Sea using a three-dimensional numerical ocean model (HYCOM). He showed that currents can be as weak as a few cm s^{-1} in the north, while they can reach strengths of tens of cm s^{-1} in the south. He also showed the circulation in



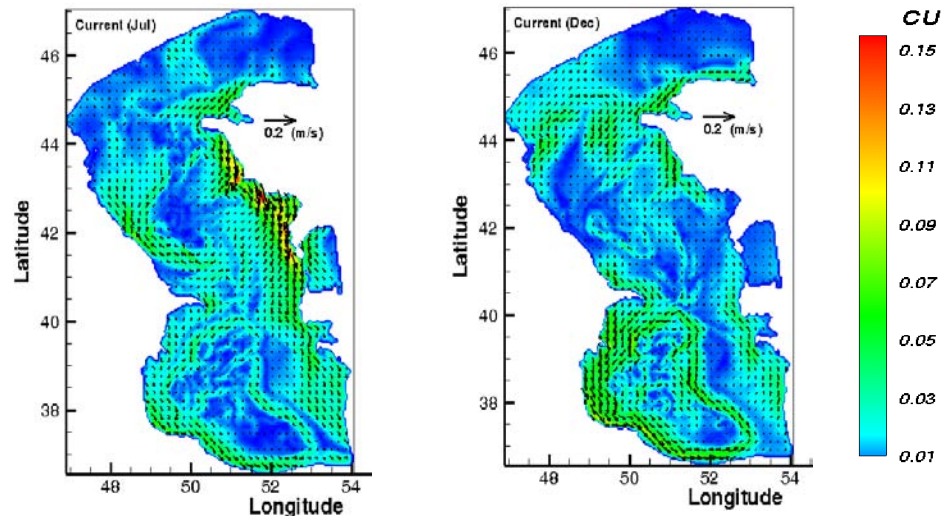


Fig. 2— Monthly mean sea surface currents (m/s) obtained from wind forced Caspian Sea COHERENS simulation in 2004.

the middle of the Caspian Sea was generally cyclonic during winter, some features evident in the COHERENS simulation as well.

The average annual scheme of the surface flow by model simulation is shown in Fig. 3. The figure indicates the weakness of flow rate in the northern region of the Caspian Sea and how the flow rate became stronger in the center of the sea and in the south of the Caspian Sea in the high-speed streams.

In the western region of the middle Caspian Sea, anticyclonic eddy was created and this existed during all of the months of the year. However, in some months, due to the weakness of the wind and changes in wind directions, respectively it either became smaller or it oriented towards the south (Fig. 4). In terms of size and compressible flows, this eddy became larger and stronger from August to December. The existence of this eddy that was located over the deep depression of the bathymetry was showed by Birol Kara et al. (2010) as well. But in HYCOM simulation this anticyclonic gyre began to develop in August and disappeared at the end of December. Also, he stated that it seems the feature of this eddy was strongly controlled by bathymetry. Birol Kara et al. (2010) indicated another important eddy that was located in the southern Caspian Sea (that was revealed by HYCOM simulation), which was a cyclone

centered near (38°N, 51°W) and the intensity of this gyre was strong during winter. In addition, the

figures of the HYCOM results, done according to Birol Kara, show that in some of the months such as October and September, an anticyclonic eddy in the southeast and a cyclonic eddy (38°N, 51°W) appeared. These two eddies in the COHERENS modeling results were also apparent, although the anticyclonic eddy was observed in the COHERENS modeling results were also apparent, although the anticyclonic eddy was observed in the COHERENS modeling in almost all of the months and in September and October they became stronger, but the cyclonic eddy was observed only in some of the months, although the location compared to the eddy in Birol Kara's results were a little oriented towards the north and strength and structure were weaker.

In January, on the southwest coast of the Caspian Sea there was a strong anticyclonic eddy and on the west of the Sea the cyclonic eddy was larger

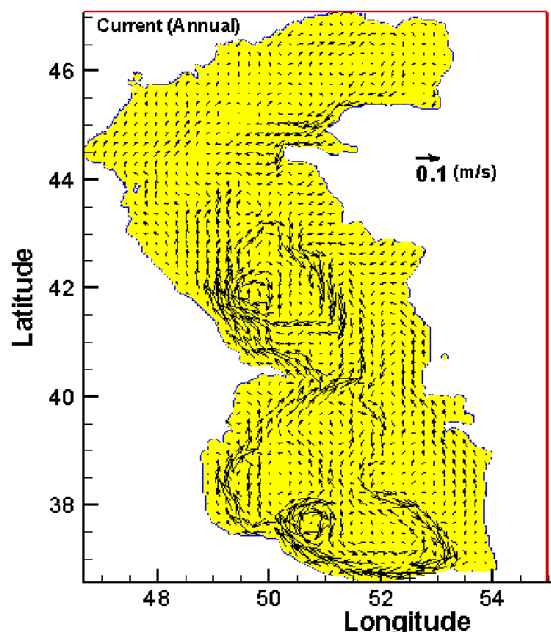


Fig. 3—Annual mean surface currents (m/s) obtained from climatologically forced Caspian Sea COHERENS simulation in 2004.

than the anticyclonic eddy, although weaker. The cyclonic eddy was fed from the anticyclonic eddy (Fig. 4a). In February the cyclonic eddy oriented to the east of the sea, in a way that it was placed on the upper side of the anticyclonic eddy. In September and October the anticyclonic eddy became stronger and larger and the cyclonic eddy, which was placed on the anticyclonic eddy, ceased to exist.

Seasonal variability in the Caspian Sea for a year (1982) based on a three-dimensional primitive equation model was described by Ibrayev et al. (2010). He showed in autumn and winter the shelf areas were always 5-6°C cooler than the interior region, because of the smaller heat capacity of shallow waters. However, in our simulation model the shelf areas are about 4-7°C cooler than the interior regions. Also, he showed

that in winter time SST increased from lower temperatures near the coasts to about 12°C in the interior of the southern Caspian Sea. In the COHERENS simulation, the different temperature between near coast areas and the interior area is about 14°C.

According to water surface temperature, from December to February there was a tangible temperature gradient from the south of the sea towards the north. From the east coast of the south Caspian, to the coasts with higher latitude the flows became stronger. In fact, these flows of warm water rose along the east coast of the Caspian Sea to near the north Caspian Sea and at the west coasts of the middle Caspian Sea there were currents of cold water towards the south Caspian Sea. These currents caused by temperature gradient made the cyclonic currents stronger, which have also been noted by ¹⁵. These types of currents during these months of the years have been preserved on the subsurface layers and parts of the deep sea, although the intensity and the magnitude of the speed of the current have been reduced (Fig. 5a, 6). From June to August, in which the upwelling phenomenon occurred on the eastern coasts of the middle Caspian Sea, the temperature of the surface water in this area decreased and there were currents from the east coast of the middle Caspian Sea to the west and southwest (Fig. 4b,c). However, the subsurface layers were weakened because of the effect of wind stress and because of the existence of the temperature gradient between the south Caspian Sea (higher temperature) and north Caspian Sea (lower temperature) the subsurface currents were created in a direction that would guide warm water from regions of the south Caspian Sea towards the northern regions (Fig. 5b).

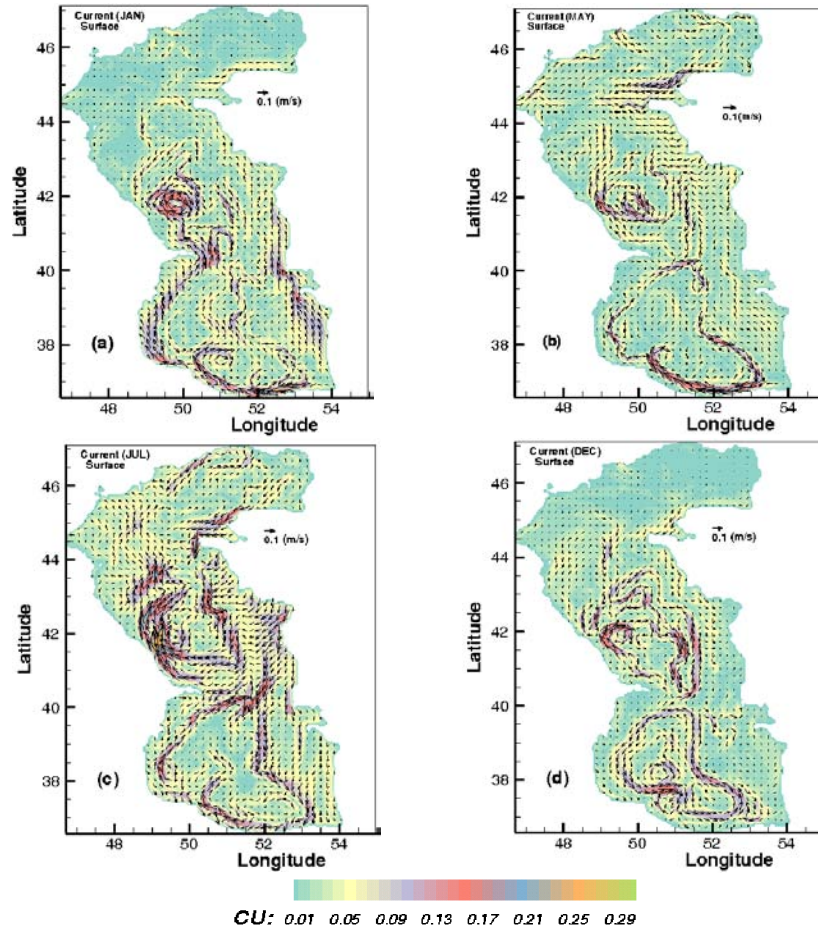


Fig. 4—Monthly mean surface currents (m/s) obtained from climatologically forced Caspian Sea COHERENS simulation for the months of a) January, b) May, c) July, d) December (2004).

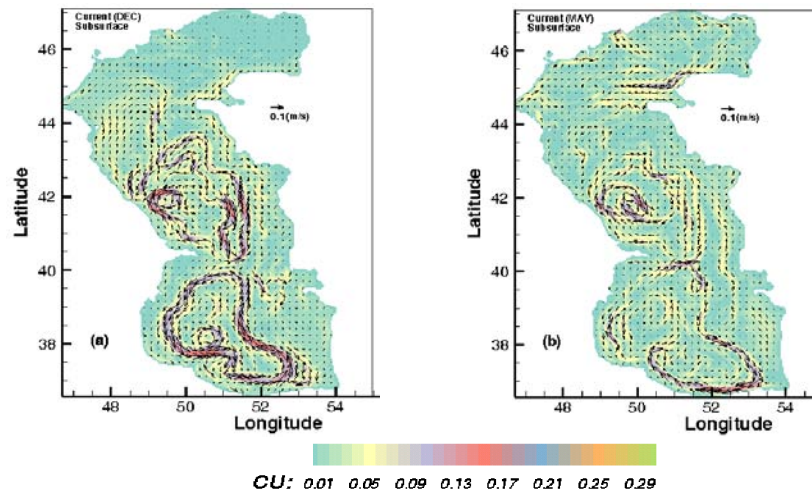


Fig. 5—Monthly mean subsurface (number of layer "k=27") currents (m/s) obtained from climatologically forced Caspian Sea COHERENS simulation for the months of a) December and b) May (2004).

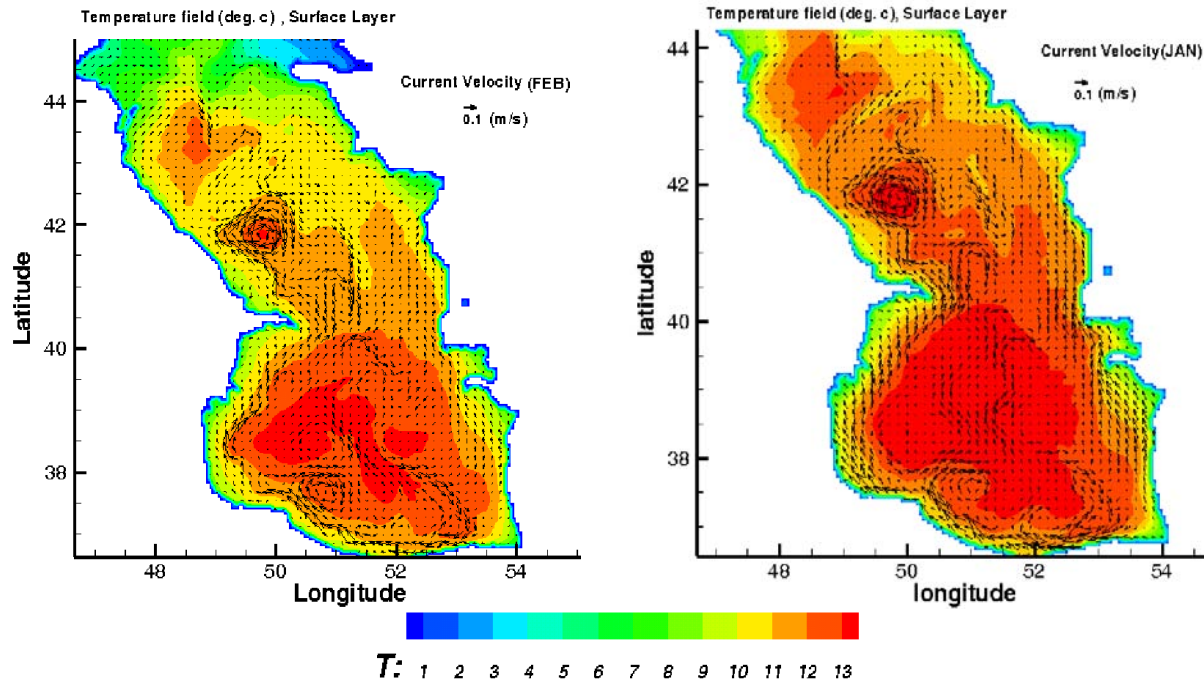


Fig 6—The mean monthly horizontal temperature (degrees Celsius) and velocity (m/s) fields at sea surface in February and January obtained from climatologically forced Caspian Sea COHERENS simulation in 2004.

Upwelling phenomenon at the east coast

In the summer the middle Caspian Sea experiences an upwelling that is considered to be the most important thermal and dynamical phenomenon¹⁶. The upwelling (5-20 km) is towards the coast and in the long shore direction it extends tens of kilometers; also the temporal scale lasts only a few days¹⁷. Along-shore current in the direction of the equator is considered to be an important characteristic of upwelling off the eastern coasts of seas, including the Caspian Sea. From June to August the advection of cold upwelling waters occur in the direction of the southern Caspian from the east to the middle Caspian⁷. In this phenomenon, the temperature of the lower water, which is less, will come to the surface of the sea and this will cause a decrease in the temperature of the

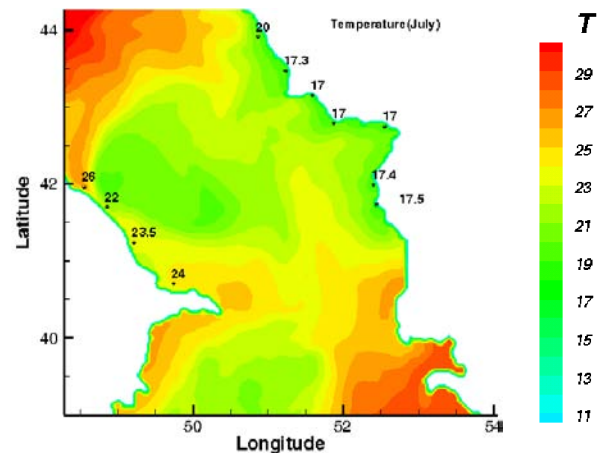


Fig 7— Climate fields of the water temperature (degrees Celsius) in the surface layer of the Caspian Sea in July obtained from climatologically forced Caspian Sea COHERENS simulation in 2004.

surface water. According to Fig. 7, the temperature of the east coast was lower than the west coast at the time upwelling occurred, which was similar to Tuzhilkin and Kosarev's study (2005). Also, this phenomenon occurred at a depth of less than 40 m (Fig. 8), which is nearly consistent with Tuzhilkin and

Kosarev's study (2005), which showed the summertime upwelling off the eastern coast of the middle Caspian operates in the upper 50-m layer.

Hence, the cold water under the lower layers moved upwards and it made the depths of the thermocline, which is close to the east coast, to be almost 20 m (Fig. 8). The vertical flow rate in this area represents the phenomenon of upwelling in the east coasts (Fig. 9). According to Fig. 10, in August, the extent and intensity of the horizontal flow became weaker and at

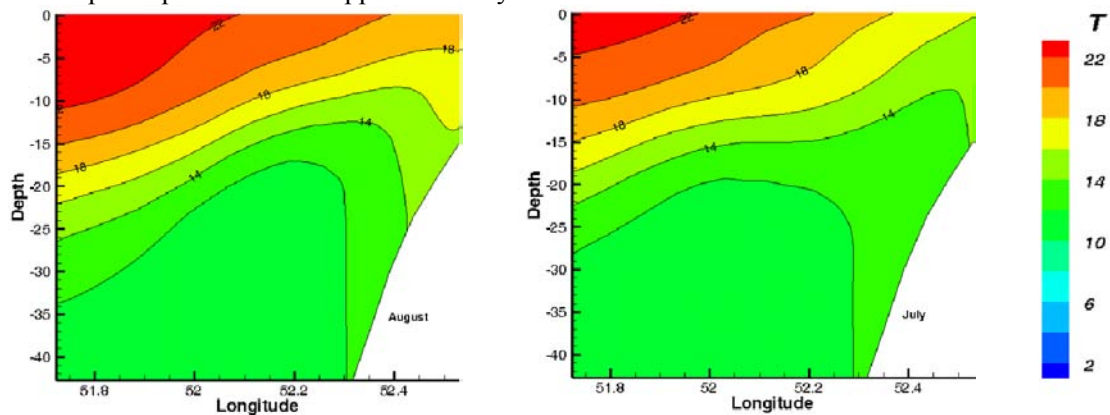


Fig 8— Vertical cross section of temperature (degrees Celsius) along 42.5° N in July and August obtained from climatologically forced Caspian Sea COHERENS simulation in 2004.

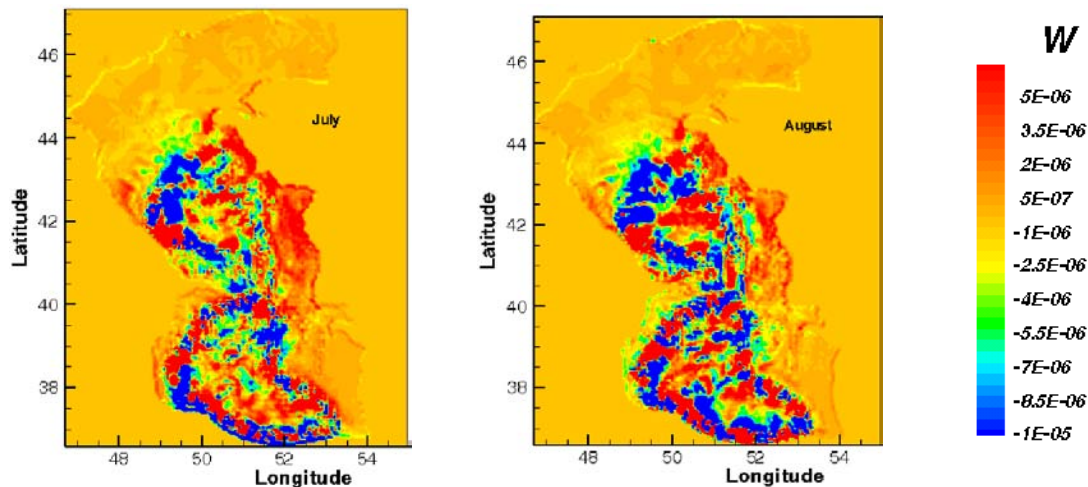


Fig 9— Vertical current velocity (number of layer "k=28") obtained from climatologically forced Caspian Sea COHERENS simulation in 2004. The units are in m/s.

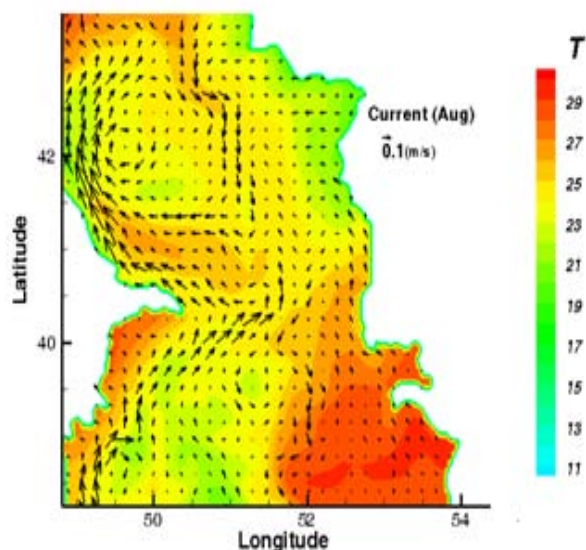


Fig 10— The mean monthly horizontal temperature (degrees Celsius) and velocity fields on the surface in August obtained from COHERENS simulation in 2004.

the end, the size of the vertical flow rate of this area from July and August decreased, which was about 12 and 7 m respectively in a month (Fig. 9).

Comparison between the field measurements and model simulation of the thermocline

Temperature and salinity profiles of the data measured at nine stations in autumn (October), spring (May) and winter (January) are shown in Fig. 11 and 12. Based on the measured field data in Fig. 11, in autumn because of a decrease in the weather temperature, the thickness of surface layer had a large thickness. The thermocline in October was around 30 to 40 m. The change of the temperature in the width of the layer was 7°C , so that the upper layer was about 19°C and the lower level was about 11.5°C . But in the model simulation the temperature of the upper layer and the lower level were about 17°C and 12°C respectively. So the thickness of the thermocline measured by the model simulation is comparable with measured data (Fig. 13). In winter, according to the field data, season thermocline was eliminated and the temperature was uniform up to a depth of 100 m, which was between 9.5°C to 10.5°C and the temperature in the model

simulation recorded approximately the same amount, which is very close to the measured data. After destroying of surface thermocline in winter, this layer was recreated in spring. Thermocline was situated at a depth of 10 to 20 m in May. The measured temperature of the upper layer and lower layer were 16°C and 11°C respectively, which is comparable with the measured temperature by model simulation which were 14°C and 11.5°C for the upper and lower layer respectively. According to Fig. 12, in all of the seasons there was very little vertical gradient saline change in this coastal region. As a result of the structure of the vertical density considering the little saline change was in harmony with the temperature change.

Comparison of currents resulting from model simulation and measured currents (field data)

According to Fig. 14, the measured predominant currents (field data) on the southwest coast of the Caspian Sea moved from the west to the east. In terms of amount and direction, these currents are similar to the results of the currents of the model simulation, even though the reason for differences between these values in this area is due to the use of interpolated bathymetry and wind data from the model.

The data (ECMWF wind data) was at intervals of 0.5×0.5 degrees and in all of the fields and these grids were interpolated at 0.046×0.046 degrees. On the other hand, the wind data in the Anzali port region with the synoptic wind data at the Anzali stations had some differences. So an error in the actual measurements of wind speed, because of interpolation and the difference in the amount of actual wind with the data used in the model is inevitable. Also, the bathymetry of the region, which is in the entire field of interpolation and is smooth, is different with the actual form of the coast in the region. Since the slope of the coast has a significant effect on the formation of coastal currents, the shape of the currents resulting from simulation cannot precisely match the shape of the measured currents.

Effect of wind stress on surface current velocity and study of the vertical current velocity transect

In Fig. 15 the relationship between wind and currents is shown. Although in most of the time depicted in this figure there is no strong wind on the coast, but large currents that are parallel to the coast were observed. At specific times in which there were strong winds, the effects of this wind

on coastal currents were completely obvious and perceptible. However, in general it is not possible for coastal currents in this area to be solely affected by wind. Also, due to the severe gradient of the coast in this area the current's shape is affected as a result of this gradient and geometric coast.

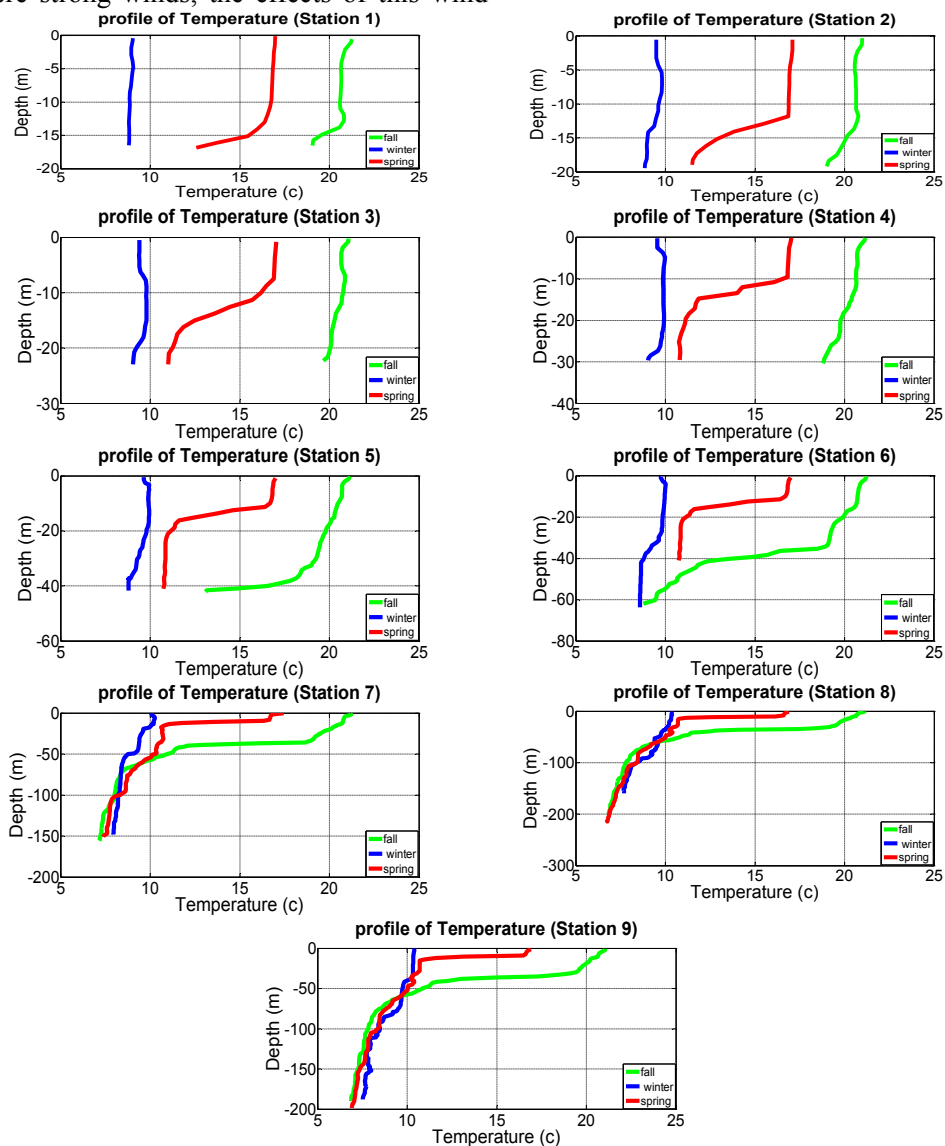


Fig 11— Profiles of temperature measurement in 9 stations.

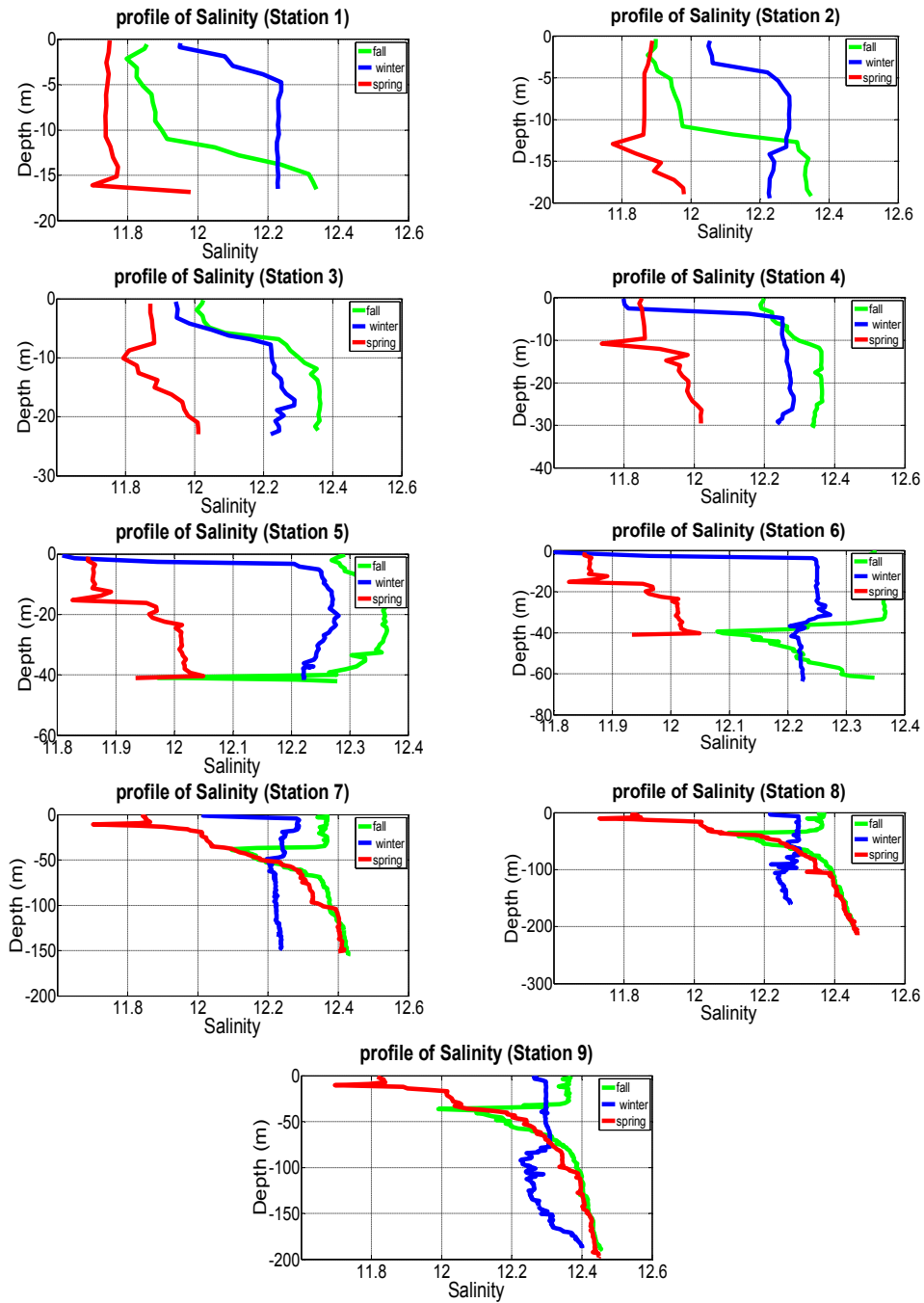


Fig 12— Profiles of salinity measurment in 9 stations.

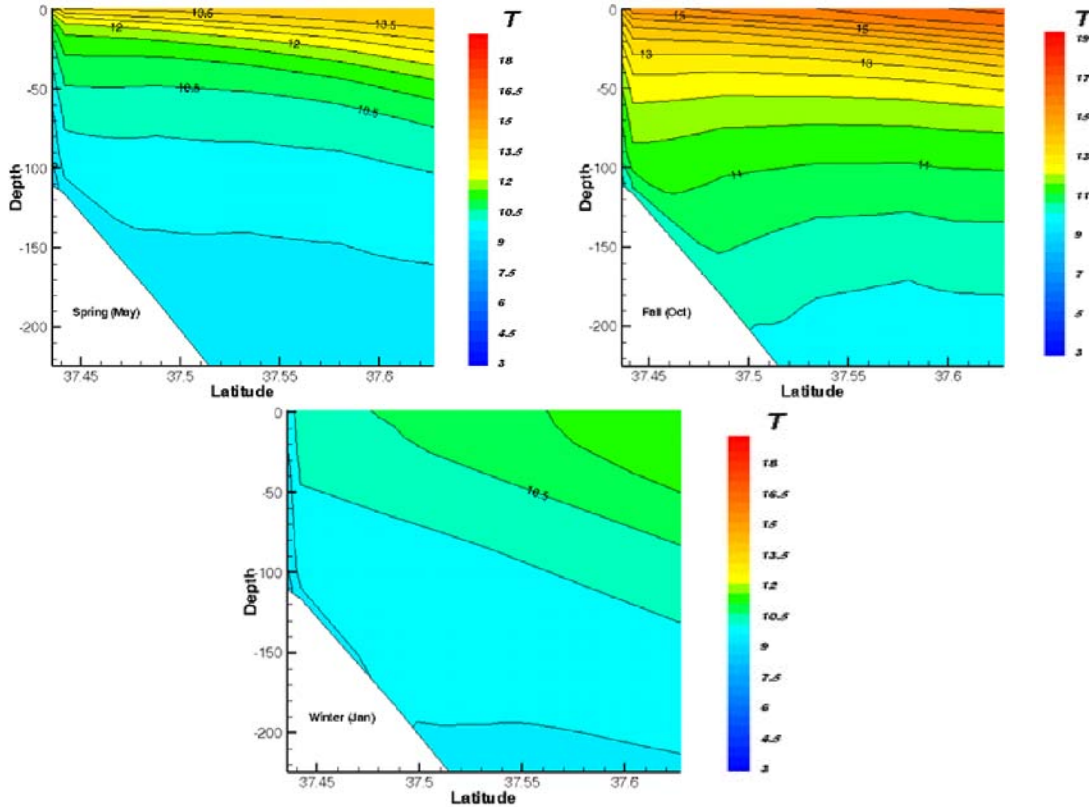


Fig 13— Vertical cross section of temperature (degrees Celsius) along 50°E in May, October and January obtained from COHERENS simulation in 2004.

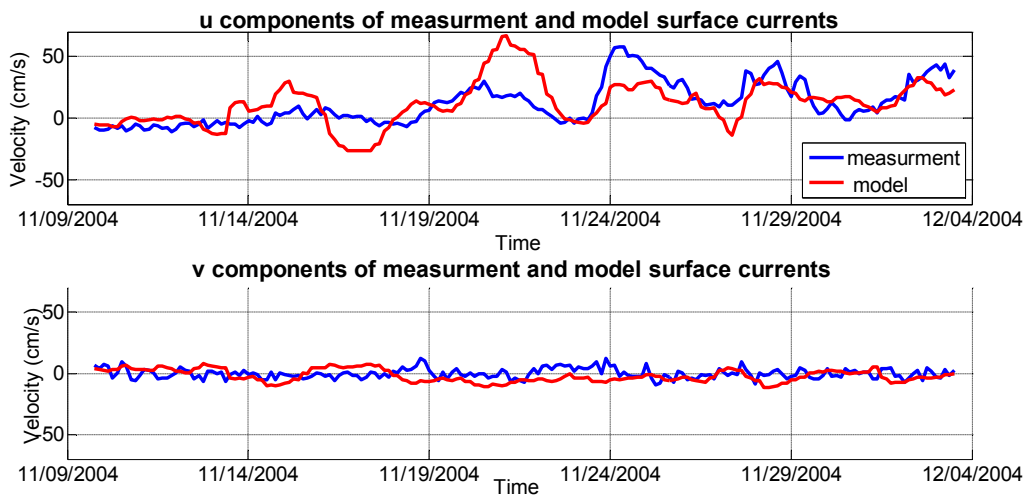


Fig 14— Current velocity at surface layer (comparing model results with observations).

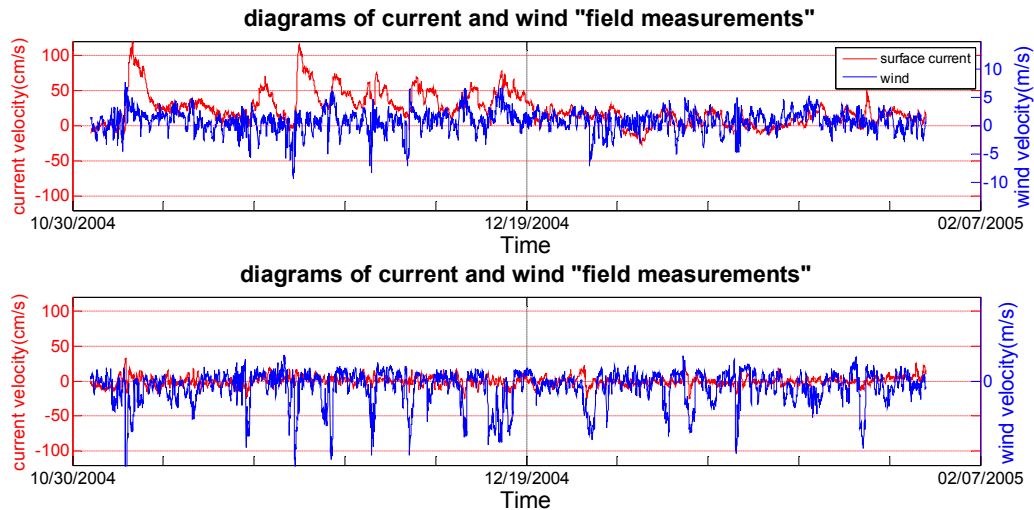


Fig 15— Current velocity at surface and synoptic wind velocity (observations data).

The study of vertical transect of velocity in autumn and winter showed significant differences between these two seasons. In Fig. 16, current velocity that was measured in this region on the surface (3 m from the water surface) and subsurface layer (58 m from water surface) is shown and the depth of these points in autumn on the upper section and bottom layer is consistent with thermocline. It was observed in Fig. 16 in autumn that current velocity in the subsurface layer significantly decreased compared to the surface layer. However, in winter the thermocline layer disappeared and surface and subsurface

currents were almost equal and it can be concluded that this change in the current from surface to depth is a sign of temperature change, and due to the disappearance of the thermocline layer in winter, the change in temperature in the water column was almost insignificant and as a result current velocity change in this water column will be very little.

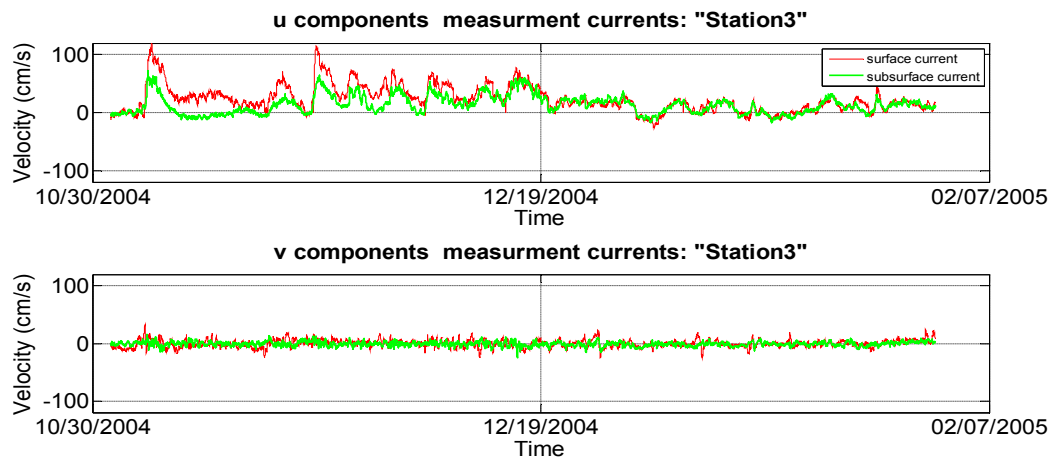


Fig 16— Current velocity at surface and subsurface layer (observations data).

Conclusion

Hydrodynamic part of COHERENS, which is based on a bottom following vertical sigma coordinate, was used to reproduce the seasonal variability of currents. Model result and observational data have been analyzed and show a large number of anticyclonic and cyclonic eddies, especially in the south Caspian Sea (also noted by Kynsh *et al.*, 2008¹⁸). Measurements of speed in the north Caspian Sea were very low and at the central region there was an increase of flow rate. On the south Caspian Sea there were more currents than other regions. In the middle Caspian Sea, the circulation was mostly cyclonic. The effect of wind on the entire region is the most important factor in shaping the scheme of surface and subsurface currents and in the months which wind tension increased, stronger currents were observed. Also, the effect of wind created an upwelling phenomenon in the region.

In the eastern coast of the middle Caspian Sea, due to the effect of wind there was a strong Ekman current from the east coast of the sea to the west that gave rise to upwelling along these coasts during the summer.

In most of the months, circulation schemes from the surface to the deep layer were maintained, but the amount of speed in the currents in the deep sea decreases, although in some of the months (such as May, June, July, August, September) the currents in the deep sea according to the temperature gradient have shown that the temperature with the current direction differed from the levels. Based on this phenomenon the temperature gradient can be counted as another important factor in the role of currents in the entire area.

Another part of this study is comparing thermocline obtained from the simulation with observation data in the south coast. The results of this comparison show that the depth of the thermocline in spring and autumn in the simulation model and the data observed are very similar to each other and in winter this layer in both studies has been eliminated. Furthermore, the temperature obtained by the simulation model of the upper layer of thermocline for spring and

autumn is slightly lower than the observed data, but the temperature under this layer in both is about the same in this study. Furthermore, by studying the vertical velocity transect in the two seasons (autumn and winter) and comparing them with the formed thermocline layer in these seasons, it can be concluded that change in the current from surface to the depth in autumn is a result of temperature change.

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