The effect of Ekman and geostrophic surface current on the distribution of SST variability over the Persian Gulf

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Abstract

Ekman and geostrophic surface currents are often associated with mesoscale eddy activity and upwelling jets, due to their effect on the variability of SST, in the Persian Gulf. Therefore, understanding the distribution of geostrophic and Ekman surface currents and how they are related to SST variability is a vital step for understanding circulation dynamics in the Persian Gulf. This study aims to quantify the importance of components of current on the distribution of SST variability over the Persian Gulf. To this end, Intra- annual variability of Ekman, geostrophic and total currents, and SST have been investigated based on the daily time series of 21 years (2000-2020). As well, a correlation analysis was done on the components of current and SST, the results indicated that Ekman current has more intensity in the winter months than the summer months due to the Winter Shamal events, and the maximum value of this current component is seen in the center of the Persian Gulf in all months. In addition, the direction of the Ekman surface currents is toward the sea in the northern region of the Persian Gulf so the Ekman current gives rise to the formation of coastal upwelling currents. The maximum value of the geostrophic component is seen in the northwestern part of the Persian Gulf (near the mouths of rivers) as well as the easternmost region of the Persian Gulf (Strait of Hormuz) in all months due to the difference in surface density in these areas and geostrophic component plays an important role in the formation of the total and main current in this region. The maximum value of total current is seen in the northwestern Persian Gulf in June. A negative (positive) correlation between Ekman (geostrophic) current and SST is found over the Persian Gulf (in the northern coastal regions) and certain parts of the northern Persian Gulf (about 52.5° E – 53.5°), which have the strongest relationship between the components of current and SST, implying that there is a possibility of the upwelling and mesoscale eddy creation at the same time.

Keywords: Ekman current. geostrophic current. SST. the Persian Gulf.

Introduction

The Persian Gulf is a semi-closed and shallow-water basin (mean depth of 36 m), located about 47.5°58' E and 23°31' N, which is connected to the Gulf of Oman by the Strait of Hormuz. The Persian Gulf benefits from a special location due to its specific climatic features, Thus study of currents of the Persian Gulf is vital because of their effects on the regional climate, the environment, fisheries, shape change of coastal areas, maritime transportation as well as affecting oil and non-oil pollution movements (Farzaneh et al., 2018).

Ocean surface currents are mainly due to winds and their effects are dominant in the upper layers, while the density-induced currents mainly affect deeper parts of the ocean (Van Aken, 2007). Two important factors standing out the most are the wind force and the water density difference giving rise to the creation of sea surface currents (Dawe and Thompson, 2006). In this regard, the knowledge of Ekman and geostrophic surface currents changes is essential for understanding the ocean dynamics and mechanism as well as mass and heat transfer.

Geostrophic current results from the balance between the horizontal pressure gradient and the Coriolis force that historically was deduced by the geopotential anomaly determined from density profiles. The relief of the sea surface also defines the streamlines of the geostrophic current at the surface relative to the deep reference level. The hills represent high pressure, and the valleys stand for low pressure. Clockwise rotation in the Northern Hemisphere with higher pressure in the center of rotation is called an anticyclonic eddy. Counterclockwise rotation with lower pressure in its center is cyclonic eddy. In the Southern Hemisphere, the sense of rotation is the opposite, because the effect of the Coriolis force has changed its sign of deflection (Stewart, 2008).

Mesoscale eddies play an important role in modifying the distribution of SST. With the ability to transport physical properties over long distances away from their formation region, mesoscale eddies can presumably transport upwelled water as well as its chemical and biological properties (Chelton et al., 2011; Nagai et al., 2015; Yuan and Castelao, 2017). A/an cyclonic/anticyclonic eddy is usually associated with a cold/warm-core caused by the eddy-induced divergence/convergence motion (Sun et al., 2019). Thus the cyclonic eddy is associated with a negative SST anomaly, while the anticyclone is characterized by a positive SST anomaly (Yuan and Castelao, 2017).

On the other hand, Ekman current results from the balance between the frictional stress due to the wind and the Coriolis force. Theoretically, the wind-driven component of mass transport in the surface (Ekman) layer is perpendicular to the mean wind stress, to the left of the wind stress in the southern hemisphere, and the right in the northern one. At the surface, the current associated with this transport deviates from the wind direction by 45°, and the amplitude decreases down to the Ekman layer depth following a spiral. The average water particle within the Ekman layer moves at an angle of 90° to the wind; this movement is to the right of the wind direction in the Northern Hemisphere and to its left in the Southern Hemisphere. This phenomenon is called Ekman transport, and its effects are widely observed in the oceans. Since the wind varies from place to place, so does the Ekman transport, forming convergence and divergence zones of surface water. A region of convergence forces surfaces water downward in a process called downwelling, while a region of divergence draws water from below into the surface Ekman layer in a process known as upwelling. Upwelling and downwelling also occur when the wind blows parallel to a coastline (Price et al., 1987; Stewart, 2008).

The seasonal features of the sea surface circulations are also variable and have effects on seasonal patterns of SST. In warmer oceanic regions, where sea temperature decreases rapidly with depth, upwelling can be identified from drops in SST (Goela et al., 2016; Barzandeh et al., 2018). Apart from these, the shallowness of the basin causes rapid responses of the oceanic properties to atmospheric conditions. During coastal upwelling, warm surface waters are carried oceanward and, consequently, cold waters come up from the depths, in the Shallow areas. There are two significant features of the upwelled waters: coldness and richness in nutrients. The coldness alters the temperature of coastal waters and results in an alteration of the coastal climate (Kämpf and Chapman, 2016).

Although many previous studies have focused on mesoscale eddy activity (Reynolds, 1993; Thoppil and Hogan, 2010; Pous et al., 2013; Raeisi et al., 2020; Raeisi et al., 2020), the occurrence of coastal upwelling (Sadrinasab, 2009 Barzandeh et al., 2018; Al Senafi and Anis, 2020), and the distribution of SST in the Persian Gulf (Shirvani et al., 2015; Noori et al., 2019), there are only a few previous studies including research on the variability of the surface current components (geostrophic and Ekman currents). Furthermore, the direct relationship between the surface current components and the distribution of SST in the Persian Gulf has not been systematically investigated.

Thoppil and Hogan (2010) focused on mesoscale eddy activity using results from a high-resolution numerical simulation for one year. As a result, they found that the meanders in the Iranian coastal current evolve into a series of mesoscale eddies, which are denoted as the Iranian coastal eddies. These eddies are consistent with the buoyancy plus Ekman drift forcing including two significant cyclonic eddies in the western part of the Persian Gulf and two other cyclonic eddies in the eastern. Also, in the Iranian coastal regions, located about 52˚ E, often an anticyclonic eddy appears in between the cyclonic eddies. The remnants of eddies are seen until November, and they dissipate thereafter as the winter cooling causes the thermocline to collapse. They also confirmed the existence of upwelling along the north-Iranian coast of the Persian Gulf. Barzandeh et al. (2018) investigated the coastal upwelling in the northern Persian Gulf by using the long-term wind time series. They found that the most intense coastal upwelling in the central areas, located about 51˚ E - 53˚ E, including three peaks in June, November, and February, and the SST decreases more in the segments with more intense coastal upwelling along the northern shoreline. Also, their results show the sea level anomaly responds to wind-driven coastal upwelling so that coastal upwelling causes negative coastal sea level anomaly (SLA). Coastal sea level drops due to an offshore Ekman transport, causing a geostrophic alongshore jet, and the associated onshore flow within the bottom Ekman layer accounts for the appearance of cold water at the surface. In other words, the direction of prevailing winds causes the positive sea level anomalies by Ekman suction which could be related to the barotropic and steric sea-level changes in the Persian Gulf, the northern Arabian Sea, and the Gulf of Oman, as it has been shown by Eshghi et al. (2020); Piecuch et al. (2021) also, SST has a strong effect on SLA in the Persian Gulf (Siddig et al., 2021). Farzaneh et al. (2018) investigated Ekman and geostrophic currents and their velocities based on the solution of Ekman and geostrophic equilibrium equations in the region of the Persian Gulf and the Gulf of Oman and using data of altimetry and surface wind satellites, values of velocity components v and u as well as the value and the direction of Ekman and geostrophic currents were extracted in forms of monthly data for one year (2014). The results were compared with measurements by AVISO and NOAA for the region of the Persian Gulf and the Gulf of Oman, and based on the obtained results of their study, the difference in the value of these currents is about 1 cm/s. In the surface layer of the Persian Gulf and the Gulf of Oman, eddies are formed indicating the compatible clockwise or anti-clockwise circulation of water. The dominant direction in geostrophic currents is toward the southern coastal region of the Persian Gulf, which is along the direction of the main current of the Persian Gulf. Hence, geostrophic currents can play a determining role as the main component of the Persian Gulf. The average values of geostrophic currents reach the maximum value in December, while its nadir is in February. In the northern regions of the Persian Gulf and northwestern regions of the Gulf of Oman, the Ekman current leads to the creation of upwelling making cold waters of the lower layer move to the surface of the sea. Average values of Ekman currents are maximum and minimum in June and October respectively.

This study aims to quantify the importance of geostrophic and Ekman surface currents on the distribution of SST variability in the Persian Gulf. Geostrophic and Ekman surface currents and SST variability in the Persian Gulf are often associated with mesoscale eddy activity and upwelling jets. Therefore, understanding the distribution of geostrophic and Ekman surface currents and how they are related to SST variability, is a vital step toward understanding circulation dynamics in the Persian Gulf.

Data methods

In this study, the data of daily geostrophic (u_g) and Ekman (u_e) components of sea surface current with a spatial resolution of 0.25° × 0.25° were extracted from the geostrophic and Ekman current observatory (GEKCO) for 21 years (Jan 01, 2000 - Dec 31, 2020). The GEKCO2 model is developed by Sudre et al. (2013) which provides both geostrophic and Ekman currents based on the following equations, remote-sensing altimeter, and scatterometer datasets.

Geostrophic velocities are given by

$$u_g = -\frac{g}{f}\frac{\partial h}{\partial y} \quad (1a)$$

$$v_g = -\frac{g}{f}\frac{\partial h}{\partial x} \quad (1b)$$

$$U_{geo} = \sqrt{{u_g}^2 + {v_g}^2} \quad (1c)$$

Where y and x are the latitude and longitude positions, $f = 7\times10^{-5}$ s^{-1} is the Coriolis parameter and equals 2Ω sinϕ (Ω is the rotation rate of the Earth and ϕ is the latitude), g is the acceleration due to gravity (9.807 m s^{-2}), and h is the map of absolute dynamic topography (MADT) that results from the elevation of the sea surface height referenced by the geoid.

Ekman velocities are given by

$$f h_e\, u_e + r_e v_e = {}^{\tau_y}/_{\rho} \tag{2a}$$

$$r_e u_e - f h_e\, v_e = {}^{\tau_x}/_{\rho} \tag{2b}$$

$$U_{ekm} = \sqrt{{u_e}^2 + {v_e}^2} \tag{2c}$$

Where $\tau\ (\tau_x\ , \tau_y)$ is the wind stress field, $\rho = 1025$ kg m^{-3} is the water density, and h_e , and r_e are, respectively, the thickness of the Ekman layer and the linear drag coefficient that represents the vertical viscosity terms as a body force on the Ekman components. The improvement for the Ekman component was needed to account for the strong variability of the Ekman layer. This is a very complex problem that could be addressed, pragmatically, by estimating $(h_e\ , r_e)$ from observations. Indeed, once the geostrophic component has been removed from the current observed by surface drifters, the residual is assumed to represent the Ekman current. Based on the equilibrium as stated by Eq. 2a and 2b, the $(h_e\ , r_e)$ parameters could be expressed as

$$h_e = \frac{1}{f}\frac{\tau_y u_e - \tau_x v_e}{\rho\ ({u_e}^2 + {v_e}^2)} \tag{3a}$$

and

$$r_e = \frac{\tau_x u_e + \tau_y v_e}{\rho\ ({u_e}^2 + {v_e}^2)} \tag{3b}$$

Using these daily data time series, Intra- annual (monthly) variability of Ekman and geostrophic surface currents were investigated over the Persian Gulf. Then, based on the surface current components (u_{total}, v_{total}), the total surface current $(\ U_{total})$ was estimated using the following equations, and Intra- annual variability of $(\ U_{total})$ was investigated over the Persian Gulf.

$$u_{total} = u_e + u_g \quad (3a)$$

$$v_{total} = v_e + v_g \quad (3b)$$

$$U_{total} = \sqrt{{u_{total}}^2 + {v_{total}}^2} \quad (3c)$$

The Persian Gulf is a shallow and quasi-narrow basin and these features can cause the instability of SST. Indeed, the shallowness and quasi-narrowness of the Persian Gulf cause fast heat exchanges across the region and as a result, the SST patterns are influenced frequently. Therefore, to investigate the variability of SST over the Persian Gulf, the Optimum Interpolation (OI) Daily SST Analysis data were obtained from the National Oceanic and Atmospheric Administration (NOAA) with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ for 21 years (2000-2020) (Banzon et al., 2016; Reynolds et al., 2007).

Eventually, a correlation analysis (Pearson's coefficient) was applied between two time series of components of current and SST to evaluate the relationship between the geostrophic and Ekman surface current**s** intensity and the SST fluctuations and quantify the importance of components of current on the distribution of SST variability and their effect on the possibility of the formation of eddy activity and upwelling current over the Persian Gulf.

Results and discussion

Intra- annual variability of Ekman, geostrophic, and total surface current

Using the daily Ekman and geostrophic surface currents data time series of 21 years, Intra- annual (monthly averaged) variability of them is shown in Fig. 1, and 2, respectively. In Fig. 1, which shows the directions (as a vector) and values (as the background color) of the Ekman surface current in the Persian Gulf in form of monthly data for 21 years, the Ekman current average variabilities observed in different months of the time series. During the two winter months (January and February), the Ekman current is almost uniformly distributed throughout the Persian Gulf and it has more intensity than the summer months. The reason for this behavior is the Winter Shamal that blows from the northwest during the cold months of the year and commonly generates significant dust storms, spreading to the southeast and covering the entire Persian Gulf (Thoppil and Hogan, 2010). In particular, the northern part of the

Persian Gulf in Iran has been exposed to dust in recent years (Yazdani et al., 2020). In March, approaching the spring, the value of Ekman current is reduced in the northwest areas of the Persian Gulf, but the maximum of Ekman current is seen (about 0.06 ms^{-1}) along the northern coast of the area in this month. This region is located near Ra's-e-Motaf which is famous as Iran's Bermuda triangle due to its stormy conditions and lots of ship sinking, as well as containing the highest wave energy in the Persian Gulf (Kamranzad et al., 2013). In April and May, the minimum of Ekman current is seen in the northwest regions of the area, so that by moving towards the east, its value increases. During spring and summer, the maximum value of Ekman current is observed in June. This is due to the effect of Summer Shamal winds, prevailing during June in this area (Thoppil and Hogan, 2010; Kamranzad et al., 2017). In the warmer months of the year (July to September), when the wind speed decreases, the intensity of the Ekman current reduces. This is significantly more evident in August. However, by moving toward the autumn months, the intensity of the Ekman current increases, and the maximum value is observed in November and December (about 0.09 ms^{-1}). Also, the maximum value of this current component is seen in the center of the Persian Gulf during all months. The central part of the Persian Gulf has a high monthly variation of wind speed among the other regions (Kamranzad et al., 2013), and the minimum value of Ekman current is seen in the northwest regions of the Persian Gulf in most months of the year. Although the mean, absolute wind speed is considerable in this area but the mean, vector-average speed is negligible. Thus, the minimum wind-driven component of current is observed in the northwest regions of the Persian Gulf so this part of the Persian Gulf is known as the 'low energy' area (Reynolds, 1993).

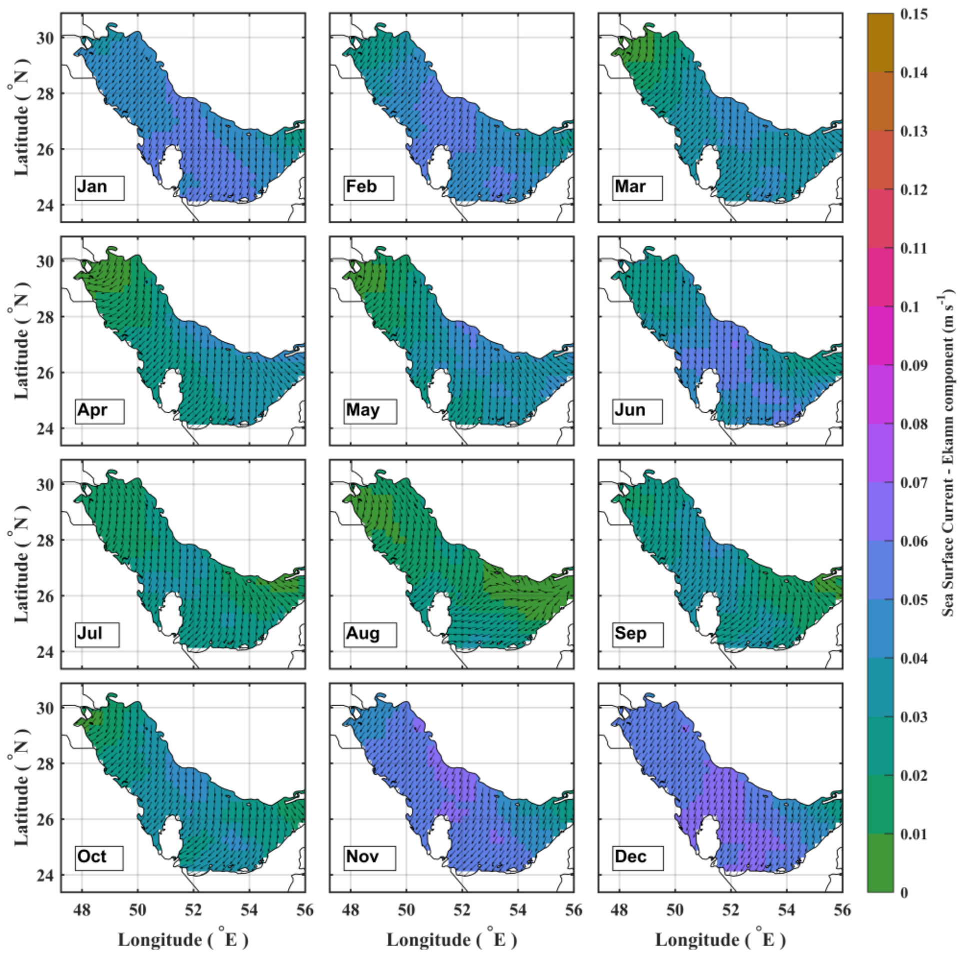

Fig. 1 Intra- annual cycle of Ekman surface current (2000-2020)

On the other hand, the Ekman current can intensify some physical phenomena such as upwelling and downwelling which thereby can lead to certain effects on the environment fisheries, and fishing on a small scale (Vignudelli et al., 2011). The direction of the Ekman surface current**s** is toward the sea (coast) when westerly (easterly) wind is blowing and an upwelling (downwelling) current is formed as a result (Farzaneh et al., 2018). so according to Fig. 1, in the northern region of the Persian Gulf, the Ekman current gives rise to the creation of coastal upwelling currents, and consequently, cold waters come up from the depths, near the coastal areas. The coldness alters the temperature of coastal waters and affects the regional oceanic and atmospheric properties. In addition, the water vertical movement carries nutrients to the surface and causes changes to the chemical and biological characteristics of a coastal region (Allen, 1973; Bakun, 1990). Following the previous study focused on coastal upwelling in the Persian Gulf, SST decreases more in the segments with more intense coastal upwelling along the northern shoreline (Barzandeh et al., 2018).

According to Fig. 2, which shows the directions (as a vector) and values (as the background color) of the geostrophic surface current in the Persian Gulf in the form of monthly data for 21 years, the geostrophic current average variabilities observed in different months of the time series. During the winter and spring months (January to May), the geostrophic current is non-uniformly distributed throughout the Persian Gulf and its intensity decreases compared to the summer months. In the warmer months of the year (June to September), the intensity of the geostrophic current increases, and by moving towards the autumn, the value of the geostrophic current decreases again, however, the maximum value is observed in December. Also, the maximum value of this current component is seen in the northwestern part of the Persian Gulf (near the mouths of rivers) and the easternmost region of the Persian Gulf (Strait of Hormuz) in all months due to the difference in surface density in these areas because of the entry of freshwater through river discharges and less salty water inflow through the Strait of Hormuz to the Persian Gulf. This is primarily the consequence of density-driven outflow–inflow through the Strait of Hormuz and strong stratification. The relaxation of warmer and fresher water inflow through the Strait of Hormuz could generate a perturbation in the cross-shelf density field and trigger the baroclinic instability process (Thoppil and Hogan, 2010).

In the northwestern part of the Persian Gulf, by moving away from the mouths of rivers and moving towards the northern central parts, the intensity of the geostrophic current decreases. Due to the strong northwest winds and prevailing dynamic conditions in the region, the salinity and temperature of the water column from the surface to the bottom are uniform and the water column is well mixed during the year. The shallowness of this area and the relatively strong tidal currents prevent stratification in all months of the year (Afsharian et al., 2021).

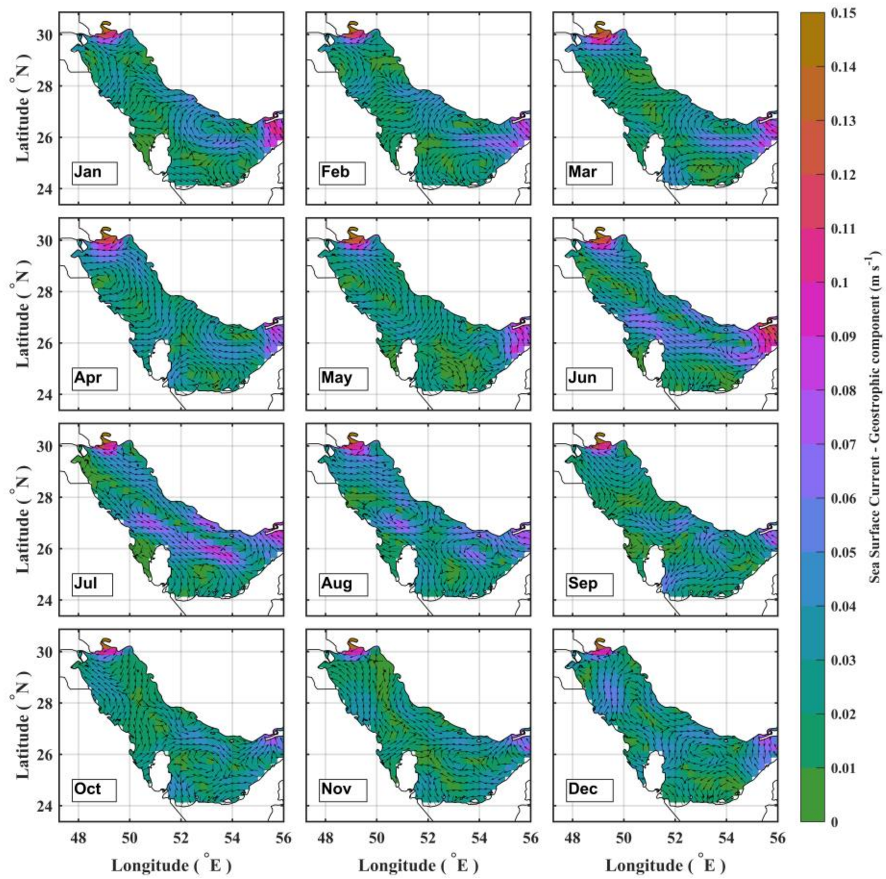

Fig. 2 Intra- annual cycle of geostrophic surface current (2000-2020)

On the other hand, the existence of eddies is obvious in the region of the Persian Gulf indicating the existence of clockwise and anti-clockwise circulations. The circulation pattern in the east of the Persian Gulf is anti-clockwise. In the Strait of Hormuz, this circulation originated from costs of Iran and near the coast of Arabian countries (mostly from the surface) and exists from the inner part of the Persian Gulf (Reynolds, 1993; Swift and Bower, 2003). The progression of a salinity front that separates the low-salinity water from the Gulf of Oman and high-salinity water in the Persian Gulf is accompanied by the development of eddies (Thoppil and Hogan, 2010).

The direction of the geostrophic current near the Strait of Hormuz in Figure 2 shows the vital role of geostrophic currents in creating the main currents in the Persian Gulf. As can be seen in figure 1, the direction of geostrophic currents is toward the southern coasts of the Persian Gulf which correspond to the direction of the main circulation of the Persian Gulf which is in agreement with the results presented by Farzaneh et al. (2018) in one year (2014). In other areas, clockwise circulations are observed, which are more evident in the cold months, especially January. A warm-core eddy forms when the warmer water moves into the colder and separates into a warm-core, clockwise flow. This eddy drifts toward the coast and usually is dissipated within a few months as it collides with the shallow continental shelf. In the cold months (especially January) the SST difference between eastern and western regions of the Persian Gulf is more than in the warm months (Figure 4), warmer water in the eastern regions of the Persian Gulf moves into the west, separates into a warm-core, clockwise flow and forms an anticyclone eddy.

Figure 3 shows the direction and value of the total surface current(vector addition of Ekman and geostrophic) in the form of monthly data for 21 years in the Persian Gulf.

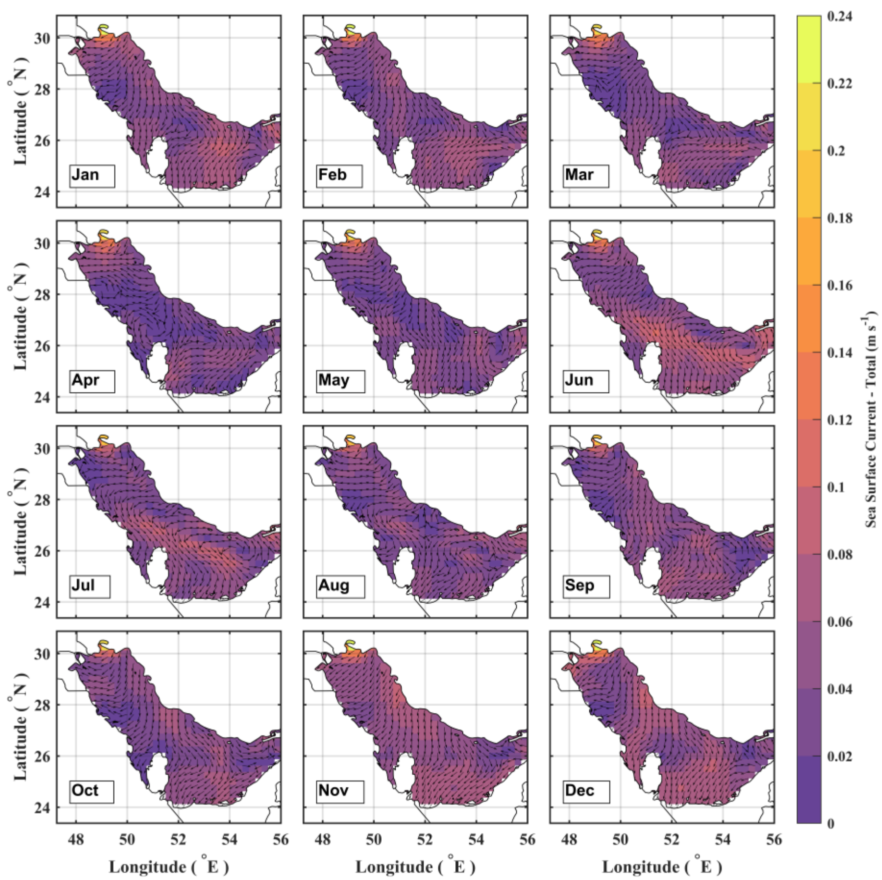

Fig. 3 Intra- annual cycle of total surface current (2000-2020)

According to Fig. 3, the observed mean total current varies in different values, however, the maximum value of total current is seen in the northwestern Persian Gulf in all months where the geostrophic component increases due to variation in surface density through river discharge. Therefore, the geostrophic component plays an important role in the formation of the total current in this region. In addition to the northwestern region, there is an accumulation of the maximum total current in the southeastern regions of the Persian Gulf(where both Ekman and geostrophic components have the highest values) in January. This accumulation is also seen in the next months but its intensity decreases and this reduction continues until May. Then in June, the maximum value of total current and its extent increases in the Persian Gulf, so that the maximum of the total current average occurs in this month. As mentioned, Ekman and geostrophic components reach significant values in June and it causes the mean total current to increase in this month. This is due to the effect of Shamal winds, which are prevailing during June in this area (Kamranzad et al., 2017; Thoppil and Hogan, 2010). In addition, the effect of monsoon waves, generated during monsoon season, off the southern coastline of the Arabian Peninsula in the Indian Ocean, which approach from a southerly direction, can be a factor in creating the highest peak period in June in this area (Khalifehei et al., 2018).

With the passage of June, the maximum value of total current decreases, and the distribution of total current becomes more uniform (especially in November) over the Persian Gulf. As shown in Figure 3, the direction of the total current is more affected by the direction of the geostrophic component which predisposes the surface of the Persian Gulf to the formation of eddies. In other words, the Ekman current is weaker than the geostrophic component because as time and space progress, the prevailing winds (the main cause of Ekman current) that change direction along the shoreline, slow down due to the frictional effect between the wind and the mountain slopes in the Persian Gulf.

Intra- annual variability of Sea Surface Temperature (SST)

The intra-annual variability patterns of SST in the Persian Gulf from 2000 to 2020 are displayed in Fig. 4.

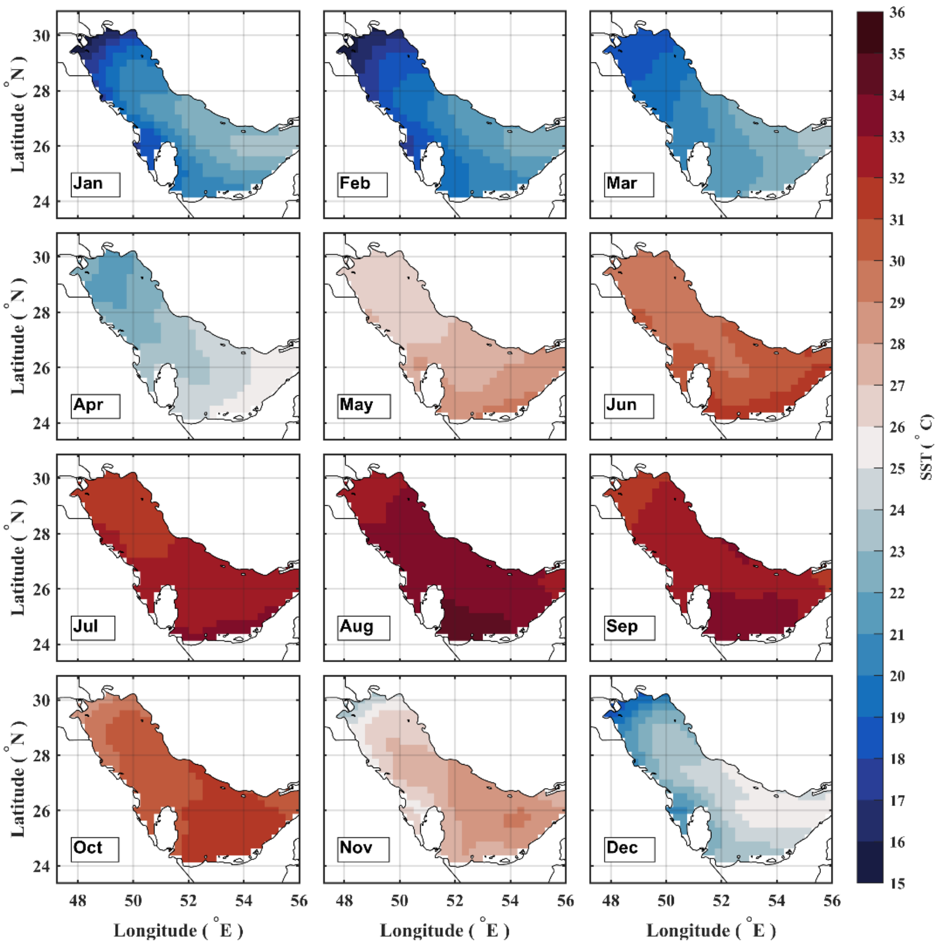

Fig. 4 Intra- annual cycle of SST (2000-2020)

December, January, February, and March exhibit minimum SST over the domain, as expected. SSTs tend to increase gradually from the northwest to the southeast sector of the Persian Gulf during the timescales. The maximum value in SST is identified along with the eastern sector of the Persian Gulf during April and May, which further penetrates the center part of the Persian Gulf and gradually decreases to the north and northwest of the Persian Gulf. A significant intensification in SST is evident from June to September, however, the value of SSTs reaches the maximum value in August. Similar patterns are also evident during October and November, with a significant reduction in SST from that of the summer season. The prevailing wind event caused SST cooling in the northwestern region and the eastern and southern sectors of the domain observe the maximum SST during all months which changes the size structure of the corals and varies the biodiversity in those areas. Bauman et al. (2012) reported that all corals in those areas were significantly smaller, and their size structure was positively skewed and relatively more leptokurtic (i.e., peaky) compared to corals in other regains. They have indicated that sea surface temperature and the recent frequency of mass bleaching are all higher in the southern Gulf, suggesting higher mortality rates and/or slower growth in these populations also SST and surface wind variations cause a change in the density and it is effective on the surface current as well as the stability and mixing of the seawater column.

Influence of Ekman and geostrophic currents on SST

The spatial correlation (with the spatial *p*-value) map between components of current and SST based on timescales from 2000 to 2020 are presented in Fig. 5 and 6. The statistical correlation coefficient is estimated by using Pearson's coefficient for components of current and SST. According to Fig. 5, a negative correlation (*p*-value lower than 0.05) between Ekman current and SST is found over the entire Persian Gulf from 2000 to 2020. SST and wind speed mainly have a negative correlation (Qu et al., 2012) and Ekman current is the wind-driven component of current on the surface. Therefore, the existence of a negative correlation between this component and SST is not unexpected. A significant correlation (about -0.6) between Ekman current and SST exists in the eastern sector of the Persian Gulf including the ports of the Strait of Hormuz and the northeastern coastal region of the Persian Gulf from 2000 to 2020, indicating a strong association between Ekman current and SST during the timescales (2000-2020), which implies that the substantial variations in SST are a consequence of the fluctuations in Ekman current. This significant negative correlation weakens over the southern sector of the Persian Gulf and extends towards the entire Persian Gulf as far as it reaches its lowest value (about -0.3) in areas of the south and southeast of the Persian Gulf. Therefore, the correlation between Ekman current and SST weakens in these areas because the average wind intensity in these areas is not so significant for a great effect on SST variations also the wind direction is not favorable for creating an upwelling current.

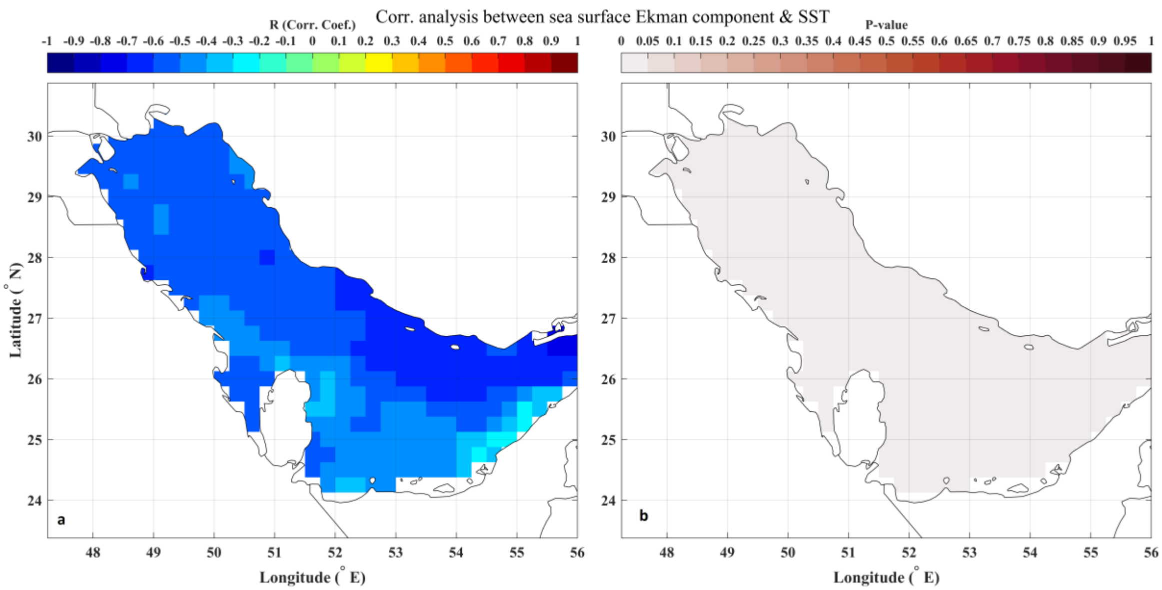

Fig. 5 **a** the spatial correlation and **b** *p*-value map between

Ekman current and SST (2000-2020)

As stated in Section 3.1, in the northern coastal region of the Persian Gulf, the Ekman current gives rise to the creation of coastal upwelling currents which are following the strong negative correlation between Ekman current and SST in these areas (Fig. 5). According to this study, there is a maximum correlation coefficient between Ekman current and SST located at about 52˚ E - 53˚ E where according to previous studies, the most intense coastal upwelling in the northern Persian Gulf, can occur (Thoppil and Hogan, 2010; Barzandeh et al., 2018) and causes a decrease in SST events in this sector.

The wind direction is as effective as the magnitude of wind speed. As a result, the discontinuous (due to the wind direction following the coastline) distributions of coastal upwelling during the year are related to slight variations in wind direction. In fact, at the positions with no significant coastal upwelling, there are two possibilities. Either the magnitude of wind speed is not too high to drive the significant coastal upwelling, or the wind direction for these sectors makes the Ekman current vector far from orthogonal to the shoreline (Barzandeh et al., 2018). so in Fig. 5, at the positions with maximum negative correlation and no favorable conditions for the coastal upwelling occurrence, the wind speed has a significant effect on reducing SST but the wind direction is not favorable for creating an upwelling current.

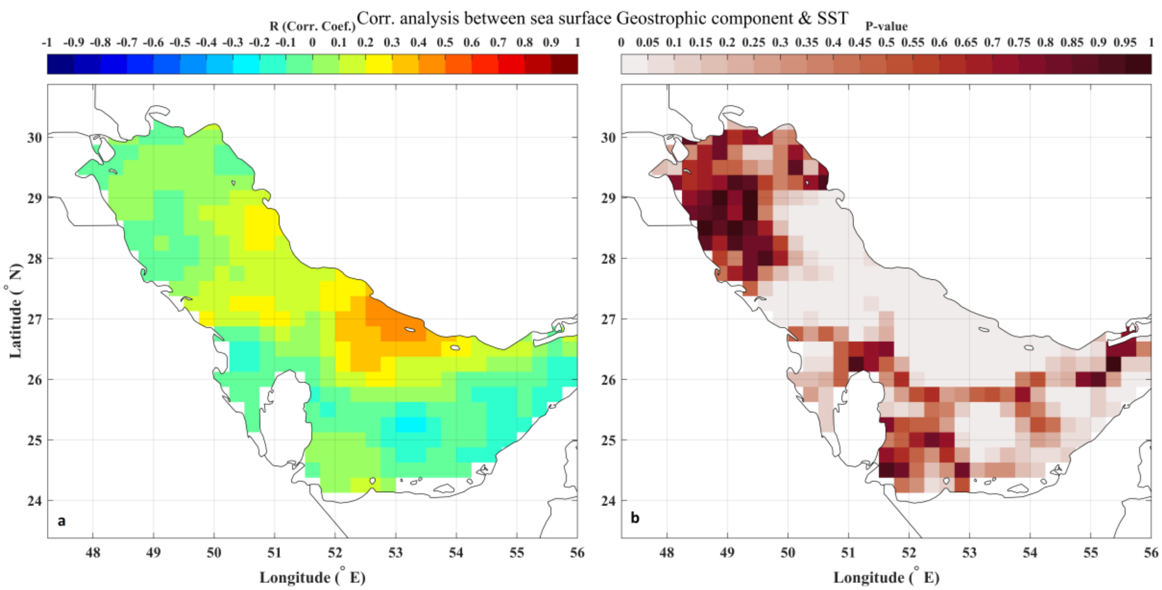

Fig. 6 **a** The spatial correlation coefficient and **b** *p*-value map between geostrophic current and SST (2000-2020)

According to Fig. 6, a significant positive correlation (about 0.5) with a *p*-value lower than 0.05, between geostrophic current and SST is found in the northern coastal region of the Persian Gulf (about 52.5˚ E – 53.5˚), reflecting that the geostrophic current plays a crucial role in modulating SST and geostrophic anticyclonic eddy formation in this sector (Yuan and Castelao, 2017) where has the strongest relationship between the components of current (geostrophic and Ekman currents) and SST so there is a possibility of upwelling and mesoscale eddy creation at the same time. Upwelling and mesoscale eddy are the considerable cyclic phenomena that can affect the climatological characteristics of the Persian Gulf, especially where their intensities reach their peak. As a result, it will be very useful and necessary to study the interaction of these two phenomena and their effects on the physical characteristics of the Persian Gulf.

The positive correlation in the northern coastal region weakens over the central parts and extends towards the southern sectors, and becomes negative (about -0.3) with a *p*-value lower than 0.05, in some southern and southeastern parts of the Persian Gulf as well as near the Strait of Hormuz which indicates that the interaction of geostrophic current and SST can cause the formation of cyclonic eddies in these areas (Yuan and Castelao, 2017). While in other places with a *p*-value greater than 0.05, there is no possibility of any significant relationship between these two quantities that lead to the formation of eddy geostrophic.

In the northwestern region, some southern, southeastern, and eastern parts of the Persian, there is an insignificant correlation between geostrophic current and SST (*p*-value more than 0.05), indicating that geostrophic current is not the major driving factor to enhance SST in these sectors. Other factors such as Shamal events (Al Senafi and Anis, 2015) and upwelling patterns (Kämpf and Chapman, 2016) also contribute to changes in SST.

As shown in the spatial *p*-value map in Figure 5, the areas that have an acceptable *p*-value to ensure the results of correlation analysis are the sector where eddies are likely to form (Thoppil and Hogan, 2010; Farzaneh et al., 2018).

Conclusions

This research investigates Ekman and geostrophic currents variability over the Persian Gulf and analyses the relationship between the spatial variations of SST and components of current by evaluating the long-term time series. The significant results can be summarized as follows:

- During the two winter months (January and February), the Ekman Current is almost uniformly distributed throughout the Persian Gulf and it has more intensity than the summer months due to the Winter Shamal events, and the maximum value of this current component is seen in the center of the Persian Gulf in all months.

- The direction of the Ekman surface currents is toward the sea in the northern region of the Persian Gulf so the Ekman current gives rise to the formation of coastal upwelling currents and consequently, cold waters come up from the depths, near the coastal areas in this region.

- The maximum value of the geostrophic component is seen in the northwestern part of the Persian Gulf (near the mouths of rivers) as well as the easternmost region of the Persian Gulf (Strait of Hormuz) in all months due to the difference in surface density in these areas because of the entry of freshwater through river discharge and less salty water inflow through the Strait of Hormuz to the Persian Gulf.

- The existence of eddies is obvious in the region of the Persian Gulf indicating the existence of clockwise and anti-clockwise circulations as geostrophic currents which have a vital role in creating the main currents in the Persian Gulf.

- The maximum value of total current is seen in the northwestern Persian Gulf in all months where the geostrophic component is increased due to differences in surface density because of the entry of freshwater through river discharge and the Strait of Hormuz to the Persian Gulf. Therefore, the geostrophic component plays an important role in the formation of the total current in this region.

- The maximum of the mean total current occurs in June and the direction of the total currents is more affected by the direction of the geostrophic component, which predisposes the surface of the Persian Gulf to the formation of eddies.

- A significant intensification in SST is evident from June to September, however, the value of SSTs reaches the maximum value in August and the eastern sectors of the domain observe the maximum SST during all months.

- A negative correlation between Ekman current and SST is found over the Persian Gulf from 2000 to 2020. The highest negative correlation coefficient with a *p*-value lower than 0.05 between Ekman current and SST is located about 52˚ E - 53˚ E where the most intense coastal upwelling can occur in the northern Persian Gulf.

- A significant positive correlation (about 0.5) between geostrophic current and SST is found in the northern coastal regions of the Persian Gulf (about 52.5˚ E – 53.5˚) reflecting that geostrophic current plays a crucial role in modulating SST and geostrophic anticyclonic eddy formation in this sector.

- Certain parts of the northern Persian Gulf have the strongest relationship between the components of current and SST so there is a possibility of upwelling and mesoscale eddy formation at the same time. As a result, it will be very useful and necessary to study the interaction of these two phenomena and their effects on the physical characteristics of the Persian Gulf.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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