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Impact of mesoscale eddies on climate and environmental changes in the Persian Gulf

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Abstract

This study investigates the role of mesoscale eddies significance in marine and climatic environmental researches. Therefore, mesoscale eddies in the Persian Gulf (PG) were identified and tracked based on the SSH-based method using the Arc GIS software. The Sea Surface Height (SSH) field data were extracted from the AVISO Reference Series from 2010 to 2014. The areas with the highest activity of eddies are located in the northern and central regions of the PG. The strongest eddies are observed in summer. Therefore, major environmental impacts of eddies were observed in the north of the PG in parallel with the Iranian coasts. Considering the Eddy Kinetic Energy (EKE) and the eddy diffusion coefficient, cyclonic eddies had more climatic and environmental effects, and the tracers such as pollutants can be dispersed quite rapidly in the north of the PG along the Iranian coast. Eddies (cyclonic) also appear to have the effect of cooling and .decreasing temperature typically by 1 °Celsius in the atmosphere of the nearby regions

Keywords: Mesoscale eddies; Persian Gulf; Sea surface height; Eddy kinetic energy.

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1. Introduction

Mesoscale eddies are very significant in terms of not only ocean currents dynamics but also climatology, air–sea interaction, and biochemistry. Exploration, exploitation, and extraction of oil and gas resources in the seas, navigation, protection of the marine environment as well as the construction of offshore structures and other engineering projects including the stability of estuaries, shipping and fishing channels, etc. require determination of sea surface height and sea surface currents. Eddies play a vital and effective role in local climate change and environmental conditions of seas by mixing and dispersing tracers including heat, salinity, nutrients, biochemical, pollutants, etc. As aquatic animals can live under proper climatic conditions such as certain salinity of sea water and specific temperatures, therefore, eddies play a major role in the discussion of their migration. In other words, examination of the eddies is important in fishing industry. The Persian Gulf (PG) is exposed to oil contamination and the spread of related pollutants due to the presence of oil and gas fields.

The PG has mostly a cyclonic general circulation and is surrounded by currents of Iranian coasts in the north, northwestward currents from the Strait of Hormuz, and one southeastward current in the south of the PG. The most prominent feature of this circulation is the conversion of the main current energy, near Iranian coasts, into a series of mostly cyclonic eddies (Thoppil and Hogan, 2010a; Thoppil and Hogan, 2010b). Oceanic mesoscale eddies can be divided into two types of warm- and cold-core eddies. The noticeable feature of warm (cold) core eddies is that they have a higher (lower) temperature and a lower (higher) sea-level in their center. Primary factors for the formation of eddies are the force exerted by wind stress, baroclinic instability, and wind gradient balance (Gopalan *et al.,* 2000).

Mesoscale eddies play a key role in creating atmospheric vorticity like tropical storms and greatly affect their intensity. For example, cold-core eddies weaken tropical storms; while warm-core eddies enhance the intensity of tropical storms. It is a well-acknowledged fact that marine and coastal environments are affected by such oceanic eddies. Continuous environmental characteristics of eddies determine the climate of the ocean and its surrounding atmosphere. The expansion of a cyclonic eddy causes the water to rise at the center (upwelling), which leads to upwelling of the cold and nutrient-rich subsurface water to the surface of the water column. Therefore, a cyclonic eddy is considered as a cold-core and high biomass eddy that can reduce the atmospheric temperature of the region (Kumar *et al.,* 2002). To study the environmental effects of eddies, the eddy horizontal diffusion coefficient and eddy kinetic energy (EKE) can also be used. Identification of such eddies, using height gradient patterns and sea surface temperature, is difficult because the surface variations are too small. The best approach for dealing with these mesoscale eddies is to use altimeters derived from height anomalies and sea surface temperature. In this approach, the high and low signal of height and air surface temperature are used as an indicator for warm- and cold-core eddies, respectively (Gopalan *et al.,* 2000). Recognition of the variations in these mesoscale eddies in temporal and spatial dimensions have been increasingly attended to in recent decades. Frenger *et al.* (2013) have analyzed the effects of eddies on atmospheric parameters such as air temperature, winds, clouds, and precipitation. Dandapat and Chakraborty (2016) investigated the three-dimensional properties of mesoscale eddies in the southern part of the Bay of Bengal using satellite altimetry and Argo floats for the period of 1993-2014. Busireddy *et al.* (2018) have indicated that the thermohaline structures associated with warm-core eddies and its reaction with the surrounding atmosphere in the northern part of the Bay of Bengal can vary. The effects of warm-core eddies on surface climatic variables have also been determined. Significant changes were observed in anomalies of the surface air temperature and sea surface temperature, values of air-sea specific humidity, and enthalpy fluxes during the warm-core eddy period (Busireddy *et al.,* 2018). Density differences in water masses and large-scale major currents and surface wind stresses cause sloping isopycnal lines and create baroclinic instability in the PG. The presence of these instabilities leads to the formation of eddies around the main current. The required conditions for the formation of mesoscale eddies, especially on the Iranian coast are provided given the formation of thermocline (Mehrfar *et al.,* 2019), the water flow of Arvandrud, and the northern and central regions of the PG (Thoppil and Hogan, 2010a). Thoppil and Hogan (2010a) also found that number of eddies in the PG is highest in the summer. The inflow of fresher water from the middle of the Strait of Hormuz into the PG causes large scale turbulence structures in the density field perpendicular towards the coastal area of Iran. This change in the density field can lead to the process of baroclinic instability (Rahnemania, *et al.,* 2019). Furthermore, as one of the mechanisms governing eddy formation is baroclinic instability, there can be significant changes in the general circulation of water and the formation of eddy in the PG (Mehrfar *et al.* 2020). Eddies generated in the PG are mostly cyclonic (Raeisi *et al.,* 2020). Identifying the time and location of the formation of eddies and tracking eddies can be addressed as an important and effective factor in dispersion of pollutants. Satellites can approximately measure some processes at or near the surface. Furthermore, this is the first study that has identified and tracked eddies of the region over the period of 2010-2014 using the SSH-based method and Archiving Validation and Interpretation of Satellite Oceanography data (AVISO) Reference Series Data. This method measures the characteristics of eddies including their lifespan, EKE, and horizontal diffusion coefficient with a higher accuracy. In this method of identifying and tracking eddies, it is assumed that eddies have a Gaussian symmetric structure, and the geostrophic approximation is applicable around eddies. The eddy formation region was also examined. Then the eddy horizontal diffusion coefficient and EKE were calculated, and the temporal and spatial analysis of the occurrence of eddies with the highest coefficient was performed to study the environmental impacts of eddies. In addition, for the most powerful eddies, the sea surface temperature was compared with the air temperature at a height of 2 meters, and the effect of eddies on the atmosphere of the region was studied. The present study could play an important role in not only identifying eddies of the PG but also specifying the impact of their interaction on the environment of the region.

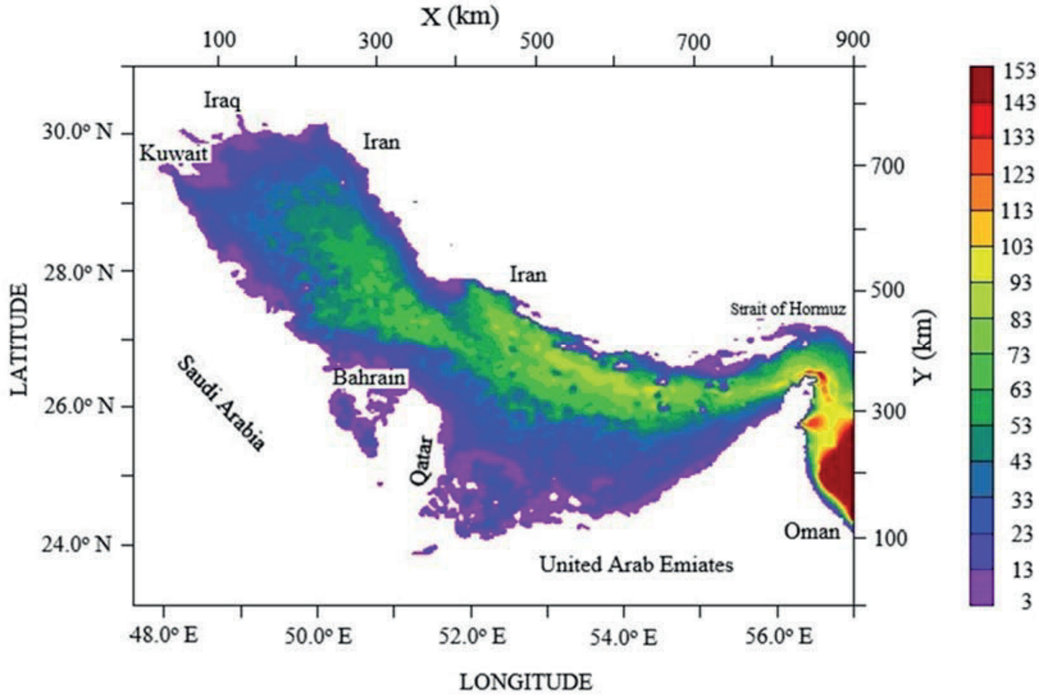


Figure 1. Coastline geometry and bottom topography of the Persian Gulf (m), based on ETOPO-2 data

2. Materials and methods

2.1. Study area

The PG is a semi-closed shallow basin with an average depth of about 35 m, is connected to the Sea of Oman through the Strait of Hormuz (Yao and Johns, 2010; Noori *et al.,* 2017), is located within the longitude from 48°E to 56°E and latitude from 24°N to 30°N (Figure 1) (Ezam *et al.,* 2010), and is extended to the Arvandrud delta from the north and to a vast desert along the coasts of Qatar, Kuwait, Saudi Arabia, Bahrain, and the United Arab Emirates (UAE) from the south (Pous *et al.,* 2015). This semi-closed basin is of strategic importance and is the route of many oil tankers carrying oil from this region to other parts of the world (Noori *et al.,* 2019).

2.2. Identification and tracking of eddies using SSH-based method

Eddies were identified using the SSH-based method. For this purpose, the SSH field of the AVISO Reference Series data was used. In this method, it was assumed that the geostrophic approximation is applicable around eddies, and the field lines are almost corresponding to the SSH-closed contours

The average geostrophic velocity around each SSH contour is also calculated using the following equations (Chelton *et al.,* 2011):

$$u = -\frac{g}{f} h_y \quad (1a)$$

$$v = \frac{g}{f} h_x \quad (1b)$$

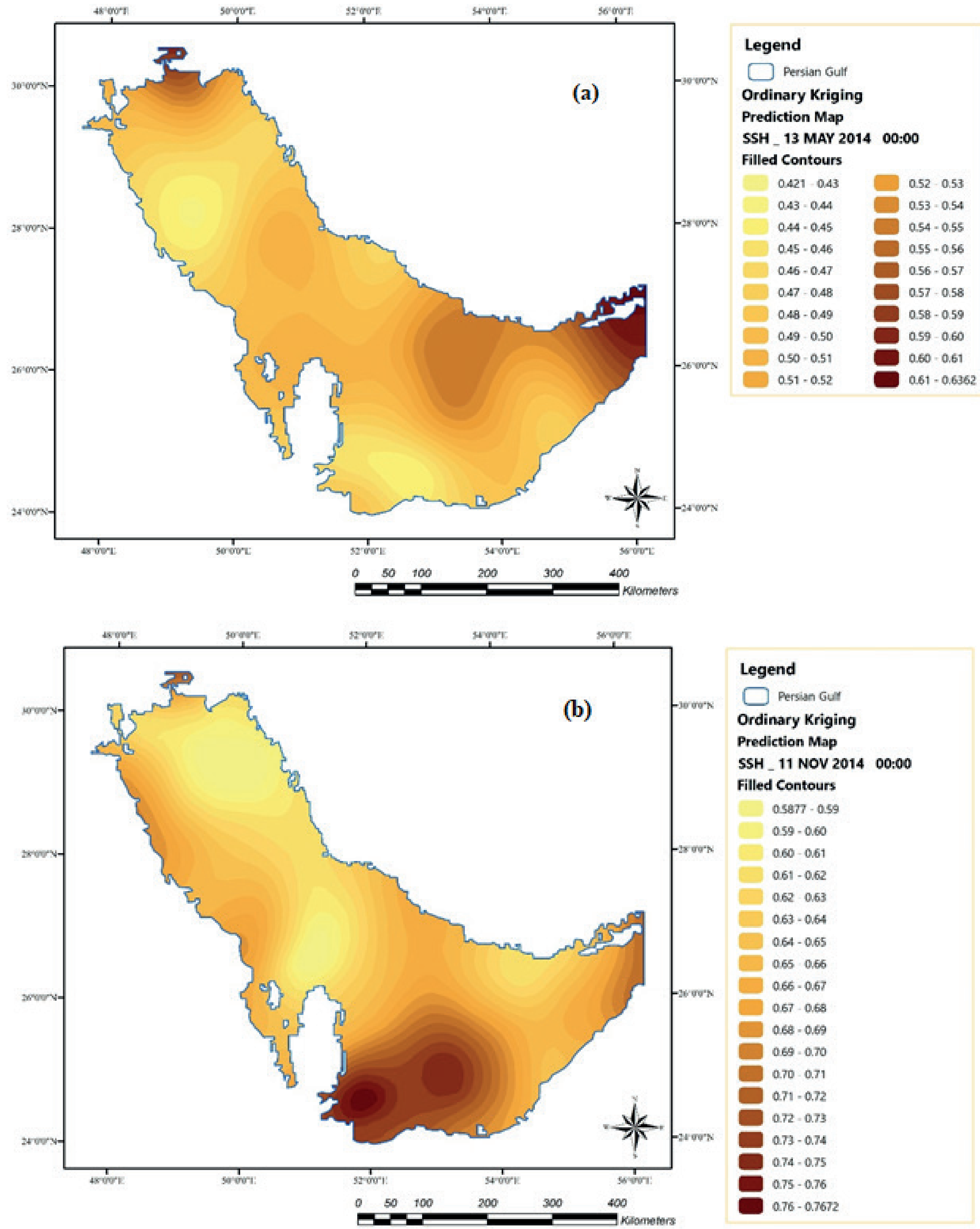


Figure 2. Map of iso-hypes lines in the PG over different seasons on (a) May 13, 2014 (spring), (b) November 11, 2014 (autumn)

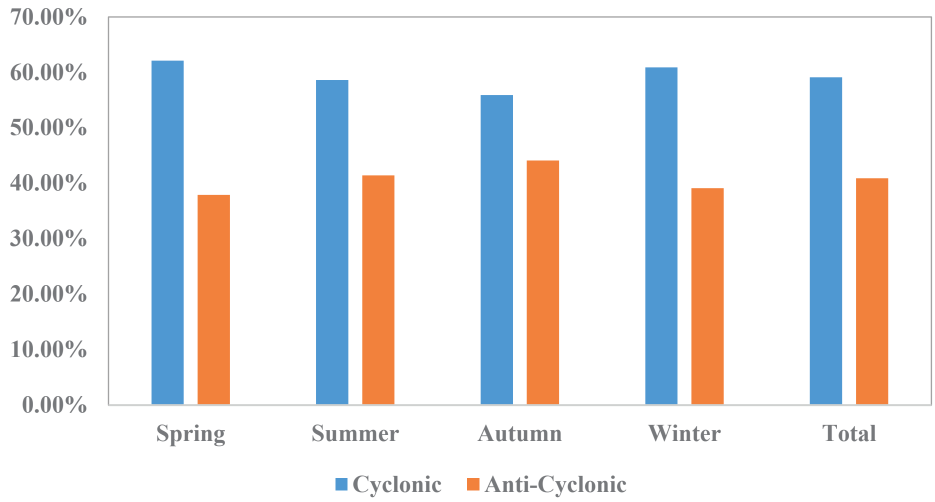


Figure 3. Bar graph of the percentage of the seasonal mean of eddies extracted using SSH-based method with consideration of the eddy polarity (2010-2014)

The eddy horizontal diffusion coefficient ($k^{x.y}$) was calculated using the following equation (Chelton *et al.,* 2011):

$$k^{x.y} \sim L_d \bar{u} \quad (2)$$

which, $k^{x.y}$ is the eddy horizontal diffusion coefficient m^2/s .where, $\bar{u}$ is the mean characteristics velocity of eddy, and L_d is the length scale of this semi-two dimensional turbulence phenomenon. One of the important parameters in this method is the effective radius (L_{eff}), which is equal to the radius of a circle with an area equal to the area of the eddy.

The following equation was used to calculate the EKE:

$$\text{EKE} = \frac{1}{2}(u^2 + v^2) \quad (3)$$

Once the eddy is detected at time k, its geometric center and the outermost closed contour can also be detected. The mentioned process is repeated at time k+1 by searching for the nearest eddy (Chelton *et al.,* 2011). The data used in this study were SSH fields adapted from AVISO Reference Series Data between 2010 and 2014. These data had an accuracy of 0.25 degrees. Moreover, tracking of eddies was performed with a time step of one week. The pertinent maps were plotted using ArcGIS software.

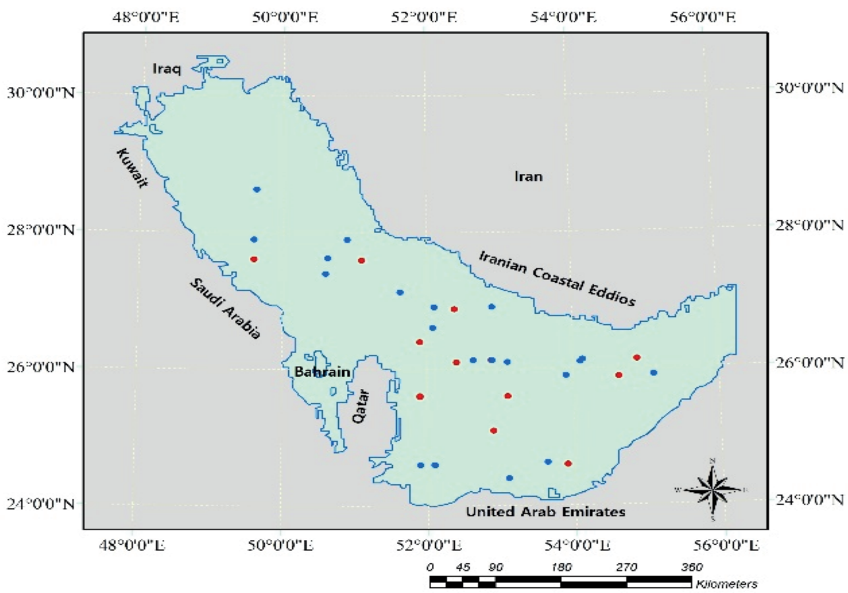
3. Results and Discussion

This section aims at addressing the climatic and environmental impacts of mesoscale eddies in the PG. Figure 2 demonstrates the map of height contours in the PG for two months of 2014 (one sample day from spring and autumn). On average, 78 eddies were observed in year, 60% of the observed eddies were cyclonic (Raeisi *et al.,* 2020), and in general the number of eddies in warm seasons was higher than that of the cold seasons.

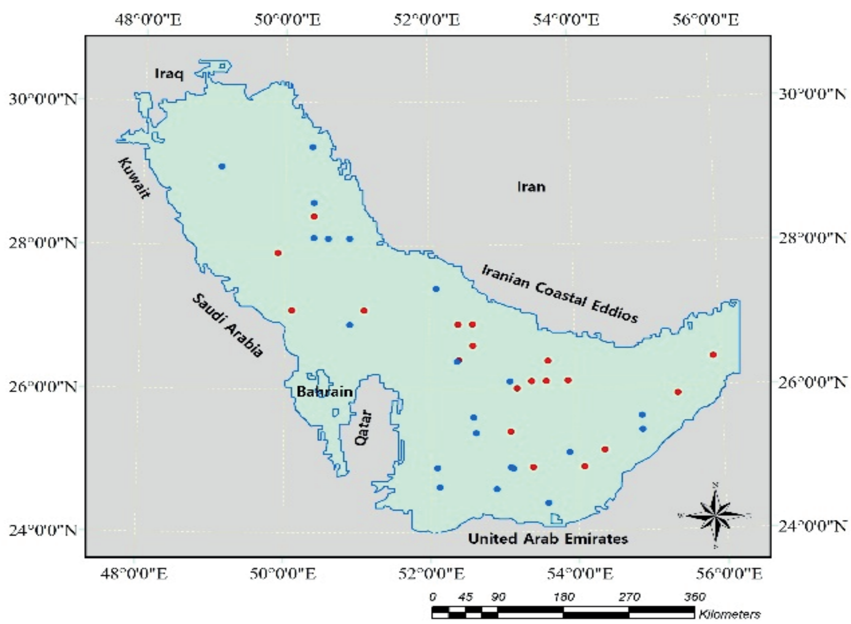
3.1. Mesoscale Eddies

The number of anti-cyclonic eddies reached the highest percentage in autumn and experienced the lowest percentage in spring (Figure 3). Figure 4 shows the location of eddy origin in summer and winter seasons of 2014. Cyclonic and anti-cyclonic eddies are marked with blue and red circles, representatively. As it was already noted, turbulent eddies require energy to survive and grow. If the energy source is large enough to cause instability, eddies will also be active enough.

According to Reynolds's (1993) observations, there are two components of very saline currents: one in the north and the other in the



(a) Summer



(b) Winter

Figure 4. The origin of eddies from 2009 to 2014 for (a) summer and (b) winter; Blue and red circles indicate cyclonic and anticyclonic eddies, respectively

south of the PG along the coasts of the UAE. In May and June, the surface water flux of the Indian Ocean has the maximum penetration toward the north of the PG and increases several kilometers. Consistent with the penetration of low salinity water flux, especially in the coastal part of Iran, where the penetration of low salinity water is less, the velocity of currents also increases. The velocity of currents is low from January to March and then increases from May. In winter, the northern branch current cannot penetrate more than 27°N under the stress of northwesterly wind (Mehrfar *et al.,* 2019). When the wind decreases in summer and spring and the seasonal thermocline develops (Mehrfar *et al.,* 2019), the current becomes stronger in the coastal area of Iran (Torabi Azad and Mehrfar, 2017), and can reach almost to the northern end of the PG, and bring a low salinity up to 28°N (Mehrfar *et al.,* 2019). The increase of the velocity of coastal currents in summer is the main source of the activity of most eddies in this season. One of the sources of energy to create the instability is the potential energy stored in sloped isopycnal lines that is released by the baroclinic instability.

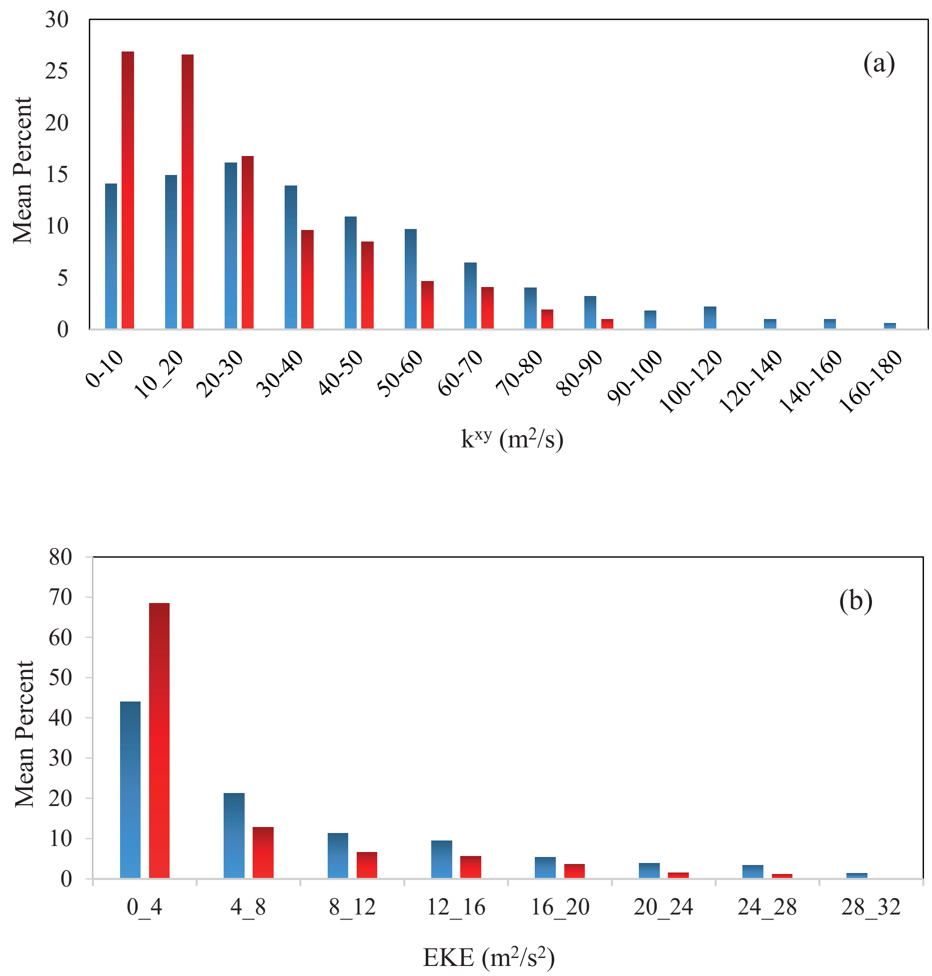


Figure 5. (a) Eddy horizontal diffusion coefficient Histogram (Raeisi *et al.,* 2020), (b) EKE Histogram (The red and blue histograms are assigned to the anti-cyclonic and cyclonic eddies, respectively)

The development of large scale instability (baroclinic) occurs along the current boundary of the entering current. Formation of the mesoscale eddies is vividly observable. The length scale of these eddies (mainly cyclonic) are of order of Rossby radius of deformation.

Figure 4 presents eddies' formation regions in summer and winter. It is evident that the origin of eddies is observed predominantly in the eastern and central regions and slightly in the northwestern regions of the PG in summer; however, more dispersion of these regions is observed in winter, and eddies are observed near the Arabian coasts and southeastern coasts of the PG.

The origin of eddies increases in the eastern and inlet region of the PG during summer due to the strengthening of the inlet currents to the PG. Moreover, the origin of eddies increases in the southeast and near the Arabian coasts during winter due to the strengthening of the outlet flows of the PG as well as their interaction with the topography of seabed. The highest number of eddy origins in the whole year is observed in the middle region of the PG, where the outlet and inlet currents to the PG interact, and the baroclinic instabilities occur. In the northwest of the PG, the origin of eddies is observed due to baroclinic instabilities caused by the interaction of the PG flows and Arvand inlet flows.

3.2. The environmental effects of eddies

In order to study the environmental impacts of eddies in the PG, this section addressed the eddy horizontal diffusion coefficient and

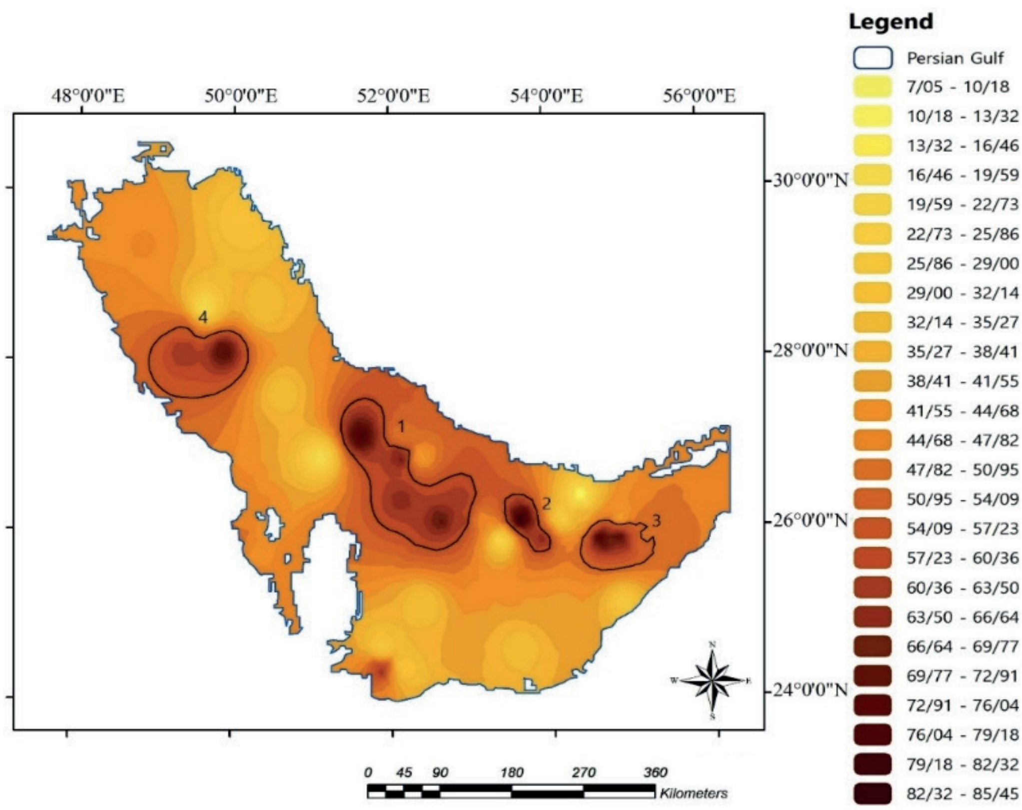


Figure 6. Distribution of eddy horizontal diffusion coefficient in the PG summer (Areas with the highest value are marked with numbers 1 to 4) (Raeisi *et al.,* 2020)

EKE. Figure 5a evaluates the eddy horizontal diffusion coefficient in all seasons and over a 5-year period (Raeisi *et al.,* 2020). The major percentage of eddies in cold seasons of the year (autumn and winter) had low coefficients, while eddies in warm seasons (spring and summer) experienced high coefficients, as well. About 10% of eddies in warm seasons had the eddy diffusion coefficient of higher than 90 m^2/s, while the eddy diffusion coefficient of cold seasons is less than 50 m^2/s. With the increase in the amount of kinetic energy of eddies (per unit mass), the percentage of observations decreased sharply. More than half of eddies (54%) had a kinetic energy of less than 4 m^2/s^2, and about 18.5% had a kinetic energy more than 16 m^2/s^2 (Figure 5b). Approximately, 70% of anti-cyclonic eddies and 45% of cyclonic eddies had a kinetic energy of less than 30 m^2/s^2. More than 20% of cyclonic eddies and 7% of anti-cyclonic eddies had a kinetic energy of more than 60 m^2/s^2 (Figure 5b). The Figures 5a and 5b indicate cyclonic eddies were stronger and had more environmental effects. The mentioned finding shows the importance of the effect of eddies in warm seasons on the dispersion of tracer such as pollutants. As shown, the powerful eddies of these seasons were cyclonic. Generally, the presence of the most energetic eddies can be observed in the region in summer, over which the activity of eddies increases.

Due to the movement of several oil tankers in the PG, the pollutants in the region are mainly oil and oil products, and if the areas with pollutant accumulations are identified, it will be a great help to their cleanup. For this reason, the spatial eddy horizontal diffusion coefficient was investigated over a 5-year period, and its internalized map was plotted in Figure 6. Figure 6 indicates the areas with the highest eddy horizontal diffusion coefficient in summer (related to the warm half of the year) (Raeisi *et al.,* 2020). The mentioned areas are located in the northern and northwestern part of the PG. Areas 1, 2 and 3 were located in the northern and central regions of the PG, and areas 4 were located in the northwest of the PG. Given that the mean of diffusion coefficient for areas 1, 2, and 3 were higher than that of area 4, they are likely to have a greater impact on the dispersion of pollutants.

The currents of Iranian coasts gradually become stronger and penetrate to the north of the PG in summer due to the increase in the inlet current into the PG from the Sea of Oman. Therefore, dispersion of pollutants is observed along the coasts of Iran in the north of the PG. The mentioned observation is consistent with the results of other studies including the model of Haj Rasouliha *et al*. (2013).

3.3. The climatic effects of eddies

Eddies can affect their adjoining atmosphere throughout their lifespan. Maps of sea surface height that well demonstrate the presence of eddies were compared with the map of air temperature at the height of 2 meter to examine the effect of eddies on atmosphere and indicated the mentioned effect with a one-day delay. For instance, three cyclonic eddies (A, B, and C) on June 30, 2014 have been indicated in Figure 7a. Figure 7b, the map of air temperature at the height of 2m on July 1, 2014 presents the temperature impact of the three eddies on the atmosphere.

Eddies effect on the corresponding areas A, B, and C. As shown in Figures 7a and 7b, these areas are within the geographical range of eddy activity. Eddies usually have some effects

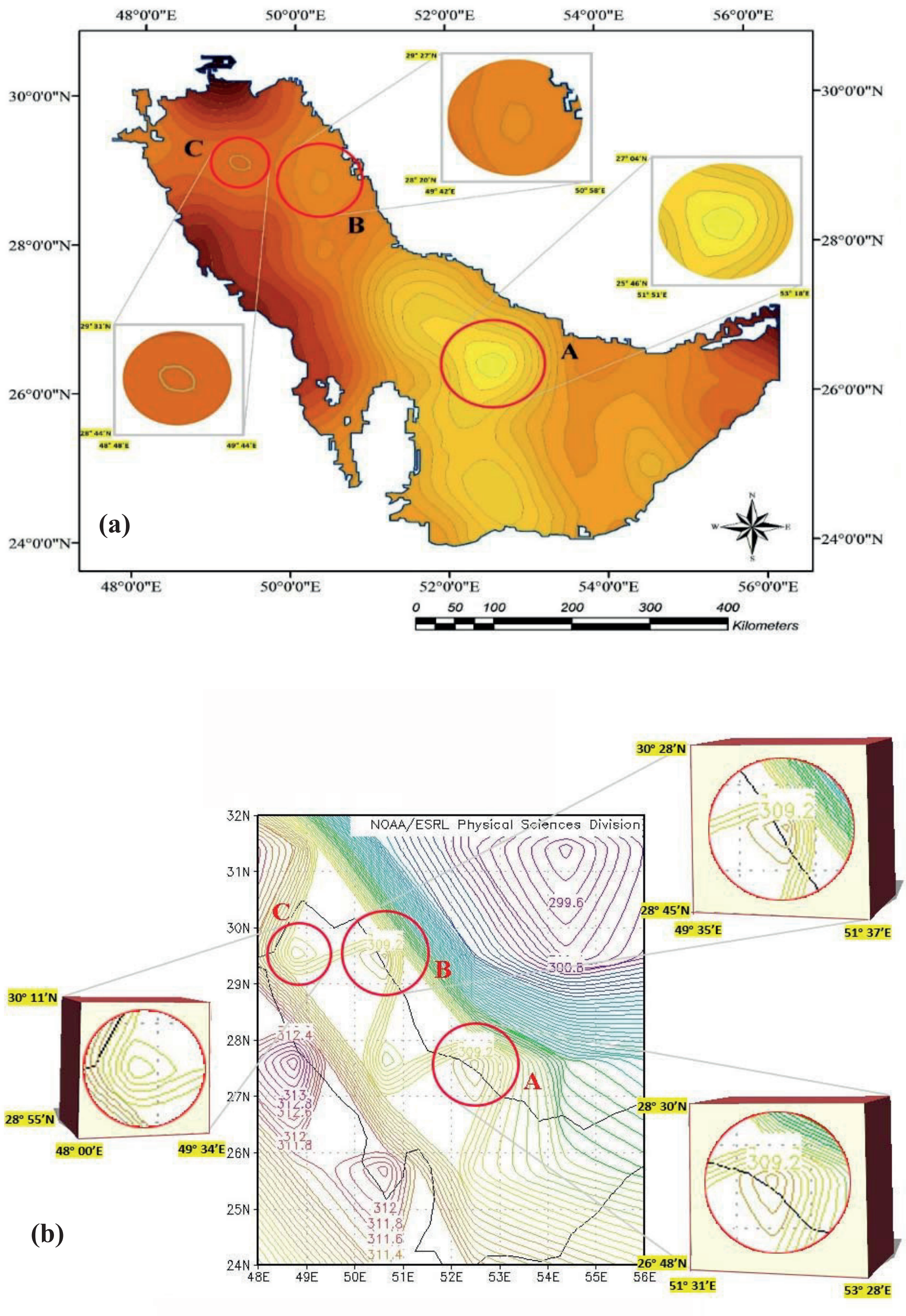


Figure 7. (a) Sea surface height contour lines (Map of eddies), June 30, 2014, (b) Isotherms of air at the height of 2 meter above sea surface (Kelvin), July 1, 2014

on the temperature of the region during their lifespan. Eddy A, for instance, is demonstrated in Figures 7a and 8a with a lifespan of two weeks. The effect of eddies on atmosphere of the region has been indicated in Figures 7b and 8b on the map of air temperature at the height of 2m with a one-day delay. The effect of eddies has caused the temperature gradient in the dimensions around those of the eddy. Eddies affect their surrounding air over the

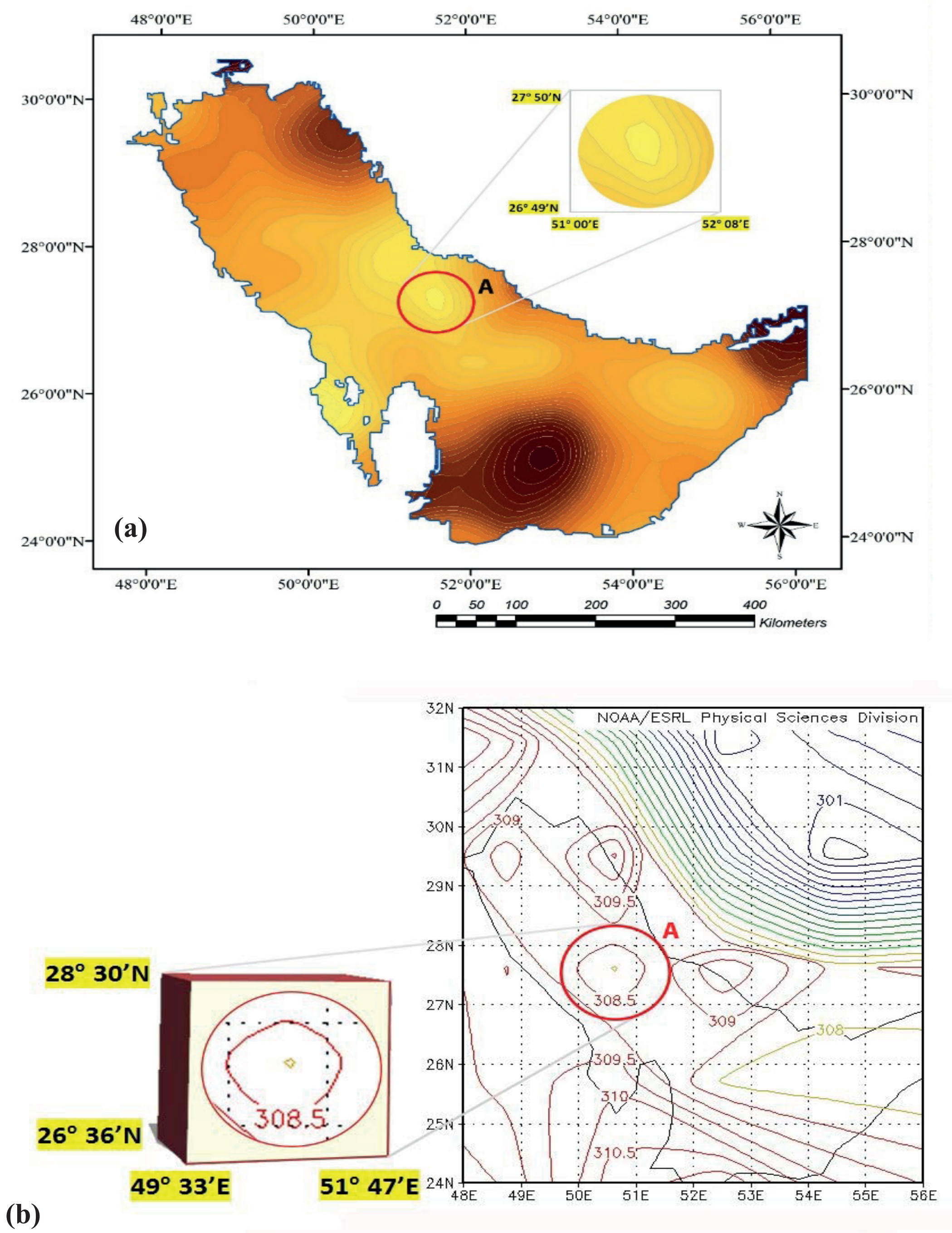


Figure 8. (a) Sea surface height contour lines (Map of eddies), July 7, 2014, (b) Air Isotherms at the height of 2 meter (Kelvin), July 8, 2014

period of their activity and cool the surrounding air. Moreover, in terms of location, this effect is maximum in the north and northwest coasts of the PG where eddies have the highest activities.

Conclusion

The origin of highest number of eddies over the year is in the central region of the PG. In winter, the dispersion of eddy origin regions is observed to extend along the Arabian coasts. An increase in the origin of eddies is observed in the eastern regions in summer due to the strengthening of inlet flows and in the southeastern regions in winter due to the strengthening of outlet flows in the PG.

The largest activity area of eddies is in the eastern regions of the PG and towards the coasts of Iran as well as the northwest of the PG. Therefore, the mentioned regions can be considered as the areas that are susceptible to eddies' environmental effects. Surface currents toward south flow from the center of the PG towards the Bahrain coastal shelf, Qatar, and the shallow coasts of the UAE. These currents are stronger during spring and summer and are weaker in winter. The intensity of the currents increases in July, which is the most active time for eddies and is the most important time in terms of eddies environmental impacts. From the statistical point of view, it is shown that the highest number of eddies is in summer, as reported by others. The eastern areas are the interaction site of inlet and outlet coastal currents in the PG, and the northwestern area of the PG is the interaction site of the Arvand and the PG currents. The mentioned interactions can cause baroclinic instability and hence, eddy formations.

Considering the eddy horizontal diffusion coefficient and EKE distribution, it is concluded that cyclonic eddies have stronger environmental and atmospheric effects than those of anti-cyclonic ones. It can also be concluded that these eddies have the effect of cooling and decreasing of temperature of the nearby atmosphere. Moreover, in areas where eddies are more active, the cooling effect appears greater. The mentioned cooling effect (typically about 1 °C) is observed with a one-day delay. This effect has caused the temperature gradient in the atmosphere of the region with horizontal scale of about that of the eddy, which is typically about 100 km. Such horizontal temperature gradients can lead to local atmospheric circulations that are also important in air pollution dispersion in the area, particularly in summer when synoptic winds are weak.

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