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Investigation of the Heat Fluxes Effect on Oil Pollution Diffusion in the Persian Gulf

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Abstract. An Eulerian model is set up for Persian Gulf based on Coupled Hydrodynamical Ecological model for Regional Shelf Sea (COHERENS). The study area is the Persian Gulf, and the studied period is one year. Two experiments are designed to examine the impact of heat fluxes on the transport and diffusion of oil pollutions released within the surface layer. The aim of this study is to use a three dimensional hydrodynamic multi-purpose model coupled with contaminant modules, in order to simulate the diffusion of oil pollutions and found the effect of heat fluxes components on increase and/or decrease of pollution concentration, and its distribution. Analyze the results of numerical simulation indicate that, heat fluxes is important factor for pollutants diffusion in the north of the Gulf and also for decreasing pollutant concentration. Heat fluxes change more the tracer distribution of pollutant and have a similar contribution on pollutant concentration decrease rate; they cause to move pollution towards coast of Bahrain, Qatar and partly Saudi Arabian from initial position of release after one year. The results of this numerical simulation can be used in providing appropriate solutions to prevent oil from spreading further in the region.

Keywords: Oil pollution, Heat fluxes, COHERENS, Persian gulf, Numerical simulation

1. Introduction

Persian Gulf is located in the southwest Asia, an extension of the Indian Ocean located between Iran and the Arabian Peninsula, between 24° to $30^{\circ}30'$ N latitude and 47° to $56^{\circ}25'$ E longitude, with a maximum depth of 90 m and an average depth of 36 m (fig. 1). According to the report of Persian Gulf Studies Center in 2008; Persian Gulf with an area of 237473 km squares (measured by Hydrographic Office of Iranian Geographic Organization, 2007) is the third largest gulf of the world after Mexico and Hudson Gulfs. The Strait of Hormuz is a narrow waterway between the gulf of Oman and the Persian gulf and has 54 km wide in the narrowest place of its. Most of the produced oil is transported by means of oil tankers with an annual estimate of 35,000 tankers crossing the Strait of Hormuz [1]. Through its waters, in giant ocean-going tankers, passes much of the oil from Bahrain, Iran, Iraq, Kuwait, Qatar, Saudi Arabia and the United Arab Emirates. Bordered by Iran, Oman's Musandam Peninsula and the United Arab Emirates, this stretch of water is of obvious military significance, The Persian Gulf and its coastal areas are the world's largest single source of crude oil and related industries dominate the region.

An oil spill is a release of a liquid hydrocarbon into the environment, and is a form of pollution. Because of the importance of oil transportation in the Persian Gulf, possibility of pollutant diffusion in this region exists from various ways. An oil spill accident can cause serious problems to the ocean environment through its contamination. Therefore, a real-time prediction of oil spill transport is very essential for clean-up operations and to estimate the effect of physical processes such as wind, tide and heat fluxes on pollutant transport. The use of numerical modeling in oil spill incidents is a well-established technique that has proven to provide cost-effective and reasonable estimates of oil surface drift [2]. As for the other pollutants, oil is subject to advection and diffusion, as it is often less dense than water, much of the oil travels in a surface slick, which is affected by wind, waves and the surface current in the water [3]. In this study the movement of oil pollution and the influence of heat fluxes on it were simulated by a three-dimensional hydrodynamic model, COHERENS. That sure, the result, after analyzed, will noteworthy help us to protect the marine environment and do preventive actions in this field. In recent years, few researches have studied the pollutant diffusion in the Persian

Gulf using different approaches. Elhakeem and Elshorbaghy (2007) used a 3-D hydrodynamic model (mike3-hd) combined with oil spill model (mike3-sa), to simulate and validate oil spill in the Persian Gulf with considering the impact of external forces such as climate change, tidal forces, currents and other hydrographic conditions [2], And other research, but, what is more, even less attention has been paid to the role of heat fluxes on how to distribute pollution in different area of Gulf. So, the aim of the present study is to set up an Eulerian model based on COHERENS to simulate the impact of heat fluxes on the oil pollution diffusion in the Persian Gulf in full one year.

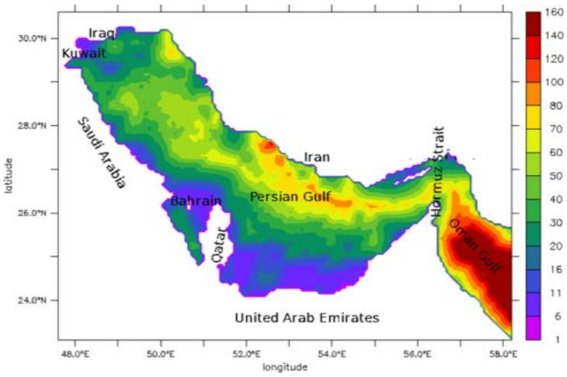

Fig. 1: Bathymetry (meter) and map of the Persian Gulf [4].

2. Numerical Model

COHERENS is a 3-D hydrodynamic multi-purpose model for shelf and costal seas that coupled to contaminant, biological and resuspension models. The program was developed over the period 1990-1998 by a multinational European group. It has primarily been used to simulate conditions in the North Sea and stratified coastal areas [5]. The user has the choice of several updated advection schemes for momentum and scalars. The model is based on the Boussinesq approximation and vertical hydrostatic equilibrium. We can solve these equations in both Cartesian $\left(x_1, x_2, x_3\right)$ and spherical $\left(\lambda, \phi, x_3\right)$ coordinates, but in vertical direction x_3 convert to sigma.

2.1. Mathematical Model

The hydrodynamic section of model composed of the horizontal momentum equations that use Boussinesq approximation and vertical hydrostatic equilibrium, the primitive equations of continuity, thermal and salinity equations in the sigma coordinate. The program also, solves a series of transport equations as follows for a given number of contaminant distributions [5]:

$$\begin{aligned} &\frac{1}{J}\frac{\partial}{\partial t}\left(JC_i\right)+\frac{1}{J}\frac{\partial}{\partial x_1}\left(JuC_i\right)+\frac{1}{J}\frac{\partial}{\partial x_2}\left(JvC_i\right)+\frac{1}{J}\frac{\partial}{\partial x_3}\left(JwC_i\right)= \\ &\frac{1}{J}\frac{\partial}{\partial x_3}\left(\frac{\lambda_T}{J}\frac{\partial C_i}{\partial x_3}\right)+\frac{1}{J}\frac{\partial}{\partial x_1}\left(J\lambda_H\frac{\partial C_i}{\partial x_1}\right)+\frac{1}{J}\frac{\partial}{\partial x_2}\left(J\lambda_H\frac{\partial C_i}{\partial x_2}\right) \end{aligned} \tag{1}$$

where $J=\frac{\partial X_3}{\partial x_3}$ represents the ratio of a unit length in the physical to a unit length in the transformed space; u, v, w are the components of velocity in the x, y and z directions; λ_T, ν_T denote the diffusion coefficients and vertical eddy viscosity, respectively; λ_H is the horizontal diffusion coefficient for salinity and temperature, and $C_i \left(i=1, Nc\right)$, and initial distribution are specified by the user, and this equation has these boundary conditions:

$$\frac{\lambda_T}{J}\frac{\partial C_i}{\partial x_3}=0 \ \text{ at } \ x_3=0, L. \tag{2}$$

$$\lambda_H\frac{\partial C_i}{\partial x_1}=0, uC_i=0 \quad \text{or} \quad \lambda_H\frac{\partial C_i}{\partial x_2}=0, vC_i=0 \tag{3}$$

That (2) means a zero-flux condition at the sea bottom and surface, and (3) means no fluxes are allowed across land boundaries.

2.2. Model Setting and Configuration

The numerical model calculates in Cartesian coordinates, with the vertical axis representing sigma coordinates, the horizontal axis representing Arakawa C grid [6]. The model uses the total variation diminishing (TVD) scheme for the advection item of momentum and scalar. We use this scheme to avoid numerical dissipation caused by the upwind scheme and false direct transport brought about by the lax-wandroff scheme and to improve the calculation accuracy. The model is initialized in December (because of seawater is well mixed in winter), using uniform temperature and salinity fields with values of $19^{\circ}C$ and $38psu$ .The model was run with an external mode time step of 60 s and an internal mode time step of 5 min, which satisfies the CFL condition. The calculation is based on the ‘‘ $k-\varepsilon$ ” turbulence closure scheme, which is used after considering the turbulent kinetic energy k and dissipation rate ε to obtain the vertical eddy viscosity coefficients ν_T for momentum and λ_T for vertical eddy diffusion coefficient for temperature and salinity. The turbulence energy k is obtained by solving a transport equation and the dissipation rate ε is computed from:

$$\varepsilon = \varepsilon_{\circ} k^{\frac{3}{2}} / l \tag{4}$$

Where $\varepsilon_{\circ}$ is a constant coefficient and l is the mixing length, that obtained algebraically using ‘‘quasi-parabolic” law. The horizontal diffusion coefficient is determined using the proportional relationship with the horizontal grid spacing and the magnitude of the velocity deformation tensor. The model domain includes Persian Gulf with one open boundary in the gulf of Oman, covering the area of 47 ° - 58 ° E; 24 ° - 31 ° N, Five sigma layers are used in the vertical direction. As the input data, the meteorological parameters (wind components at 10 meter above ground, air temperature relative humidity, cloud cover and precipitation) are needed. All these data were derived from the National Oceanic and Atmospheric Administration (NOAA). The model Includes realistic topography; it is forced by the surface wind stress, heat fluxes and tide, that tidal harmonic constants of the four tidal components (K1, O1, M2, and S2) are specified [2]. The model was run for 5 years to reaching the steady state, and then set the initial concentration for corresponding grid pollutions for the release location shown in fig.2. This is located at longitude of $50^{\circ}02'E$ and latitude of $28^{\circ}96'N$; near the Nowruz oil field, that in this region, the potential of oil spill is higher than other parts of gulf because of existence much oil field. The type of oil that spills, is crude oil of Iran, which product in National Iranian Oil Company, and has the density between 0.8 to 0.9 kg/l at $20^{\circ}C$ and the viscosity less than 12 CST, with accidental spill of 950 tons of it that has about 6 km radius and defined concentration in the model setting. Then run the model with this hypothetical contaminant for one year to predict the distribution of oil pollutions in various months after release.

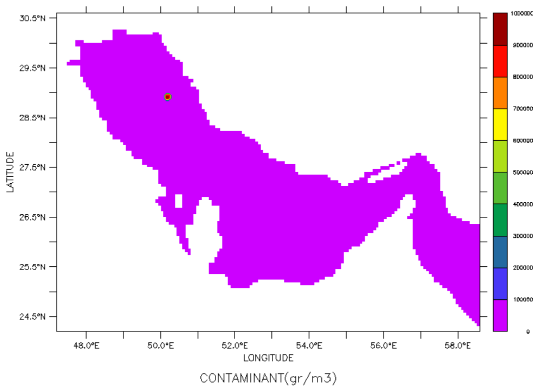

Fig. 2: Initial surface distribution of the oil pollution concentration $\left(gr/m^3\right)$ at first day of December in $50^{\circ}02'E, 28^{\circ}96'N$

3. Heat Fluxes

Changes in energy stored in the upper ocean result from an imbalance between input and output of heat through the sea surface. This transfer of heat across or through a surface is called a heat flux. Heat fluxes applied in model are: Sensible Heat Flux (Q_{se}) , Net Infrared Radiation (Q_{lw}) , Latent Heat Flux (Q_{la}) and the flux of solar energy into the sea (Q_S) , that non-solar flux has three components as follow [7]:

$$Q_{nsol} = Q_{la} + Q_{se} + Q_{lw} \tag{5}$$

4. Results

As mentioned, two experiments done in this study, in the first, all forces (wind, heat fluxes and tide) were there (Run1). In the second, the non-solar heat fluxes components are not considered (Run2) that difference between first run and second indicates the influence of heat fluxes. The diffusion path of oil pollution released from the initial position was calculated by analyze the results of numerical simulation. Fig.3 shows the pollution distribution in the north of the Persian Gulf in one year after release, Forced by wind, heat fluxes and tide, the oil pollution run northeast, travel along Iranian coast, and then with an anticlockwise circulation goes to the northwest of the Gulf and at last travel along Saudi Arabian coast with a trend to the south of the gulf, That these results have good agreement with Reynolds and Hunter results [8], [9].

The model outputs also show that anticlockwise circulation regime in the Persian Gulf becomes dynamical instability and eddy currents in early winter (Dec-Feb) and for this, the Indian Ocean Surface Waters (IOSW) inflow cannot reach to northwest part of the Gulf and complete the circulation pattern and oriented toward west near the bushehr coast. Model outputs in spring, show that part of ISOW inflow started moving toward northwest of the Persian Gulf with beginning the March and then in April and May this inflow reaches to north and northwest of the gulf. In the summer (Jun-Aug) parts of ISOW reaches to the northwestern end of the Gulf and complete the anticlockwise circulation because of low power of the SHAMAL wind stress in summer. In mid-fall (Oct) the flow rate has reduced and ISOW comes to northwest of the gulf slower and as shown in fig.3 stagnant and recirculating flow in the central part of the northern Persian Gulf can be seen. Which all these results have good agreement with Reynolds [8], Hunter [9], Kampf and Sadrinasab [10] results.

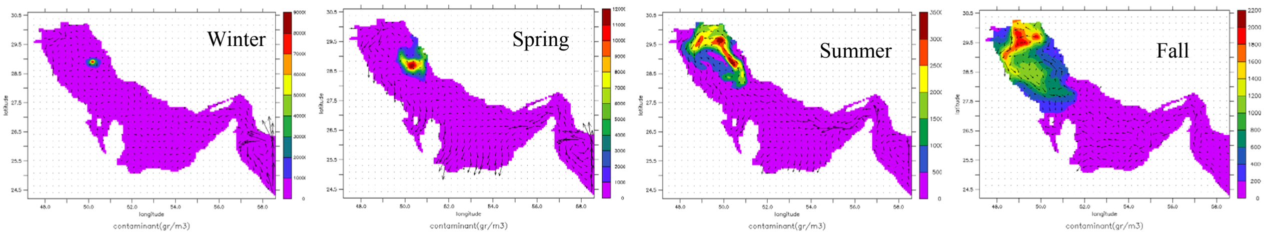

Fig. 3: Contaminant distribution and circulation pattern at the surface in seasons after release (Dec-Nov) in Run1

4.1. The Effect of Heat Fluxes on Oil Pollution Diffusion

The difference between run1 and run2 (run1 minus run2) shows the influence of heat fluxes on oil pollution distribution, fig. 4 shows the oil pollution distribution due to the heat fluxes in seasons after release, the contaminant difference represents with increasing pollution concentration, (Δ $CONCN > 0$), positive value or decreasing, (Δ $CONCN < 0$), negative value; that show the effect of heat fluxes on how to distribute of oil pollution. As shown in fig.4 the heat fluxes cause to diffuse oil spill from initial position (near the Nowruz oil field) to the coast of Saudi Arabia, Bahrain, and Qatar. In winter heat fluxes cause to increase concentration along Iranian coast, in spring and summer heat fluxes cause to increase concentration in center of the Gulf and some part of Arabian coast, and at last in the fall they cause to increase pollution concentration near the coast of Saudi Arabia, Bahrain and Qatar.

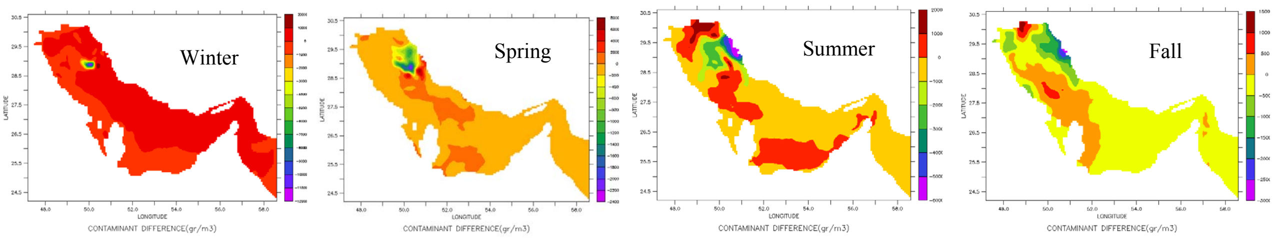

Fig. 4: Contaminant concentration difference (g/m3) field (Run 1 minus Run 2), at surface layer (Dec-Nov)

As seen in fig.5 (a), comparison between the two times series has shown. with remove of heat fluxes from the forces exerted on the model, concentration decrease is more slowly and with a gentler slope, which this indicate the effect of heat fluxes on concentration decrease, this result also is shown with follow table (table 1), that indicate the maximum concentration values and the geographical coordinates of event in the model in Run1 (run with all forces) and

Run2 (run without heat fluxes), which indicate in the absence of heat fluxes, maximum pollutants concentration values in the different months are larger and slower reduction occurs than when the heat fluxes applied in model.

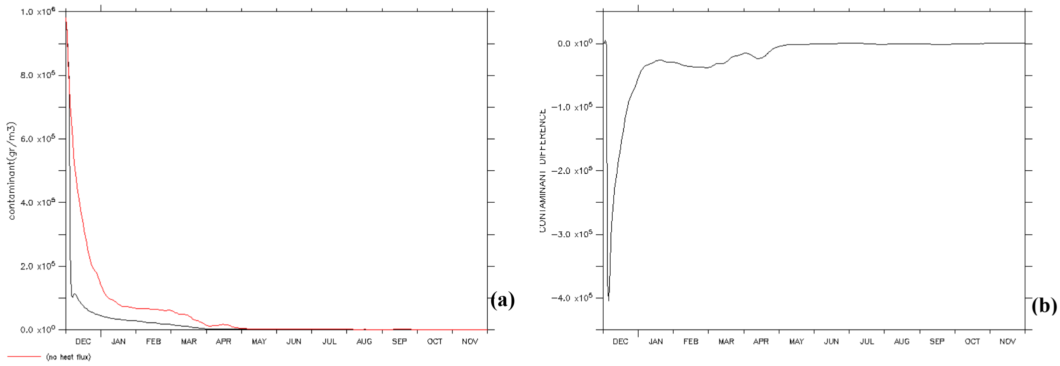

Fig. 5: (a)-Time series of contaminant concentration in main run (-) and run without heat fluxes (-) in initial position of release, and (b) time series of effect of heat fluxes on contaminant concentration at surface layer $(\Delta CONCN)$ in initial position, $50^\circ 02' E, 28^\circ 96' N$

Table 1: Maximum value of concentration and geographical coordinate of event in tow run

month	geographical coordinate of occurrence	Max concentration in Run1 (gr/m^3)	Max concentration in Run2 (gr/m^3)
Dec	$x = 50^\circ 22' E, y = 28^\circ 70' N$	198959	449721
Jan	$x = 50^\circ 20' E, y = 28^\circ 79' N$	39996	159897
Feb	$x = 50^\circ 12' E, y = 28^\circ 80' N$	29854	99725
Mar	$x = 50^\circ 25' E, y = 28^\circ 76' N$	25978	59885
Apr	$x = 50^\circ 45' E, y = 28^\circ 70' N$	17910	34899
May	$x = 50^\circ 18' E, y = 29^\circ 39' N$	7958	15956
Jun	$x = 50^\circ 69' E, y = 29^\circ 45' N$	6978	8946
Jul	$x = 50^\circ 85' E, y = 29^\circ 20' N$	3975	5941
Aug	$x = 50^\circ 73' E, y = 29^\circ 62' N$	1964	4483
Sep	$x = 50^\circ 68' E, y = 29^\circ 30' N$	1785	3993
Oct	$x = 50^\circ 60' E, y = 29^\circ 23' N$	1582	2965
Nov	$x = 49^\circ 48' E, y = 29^\circ 62' N$	1565	2392

Fig.5 (b) also show the time series of contaminant concentration differences in Run 1 and Run 2 at one year after release (Dec-Nov), which indicates the effect of heat fluxes on how to decrease or increase of concentration in initial position of release and different months. Positive value of $(\Delta CONCN)$ shows the increase in concentration and the negative value shows decrease of concentration due to the heat fluxes. It has one minimum that indicate sever concentration decrease in early December, because of more strength of SHAMAL wind and increasing the vapor rate in this month as found in Chao results[11], and within mid-May heat fluxes have no significant effect on decrease or increase of pollutions concentration in initial position of release.

5. Conclusion

Real-time prediction of heat fluxes-induced transport of an oil pollution floating on the sea surface was obtained**.** The prediction was based on the result of model simulations in the Persian Gulf region, one technique was proposed for understanding the influence of heat fluxes on oil pollution diffusion, which was the difference between two runs of the model. In the first run (Run 1) all effective physical processes, such as; wind, heat fluxes, tidal forces and other on oil pollutions diffusion were considered and then run the model, but in the second one (Run 2) the effect of heat fluxes was removed, but other parameters are used the same as previous run. The model output indicated that the heat fluxes are major factor in the mode of pollution diffusion so that in absence of heat fluxes pollutants paths have a significant change. Also the heat fluxes have effective role in rate of decreasing concentration in compare with other forces. The point should be noticed is that the numerical simulation with a 3-d hydrodynamic model such as coherens is very useful to investigate the influence of the physical processes on the transport and diffusion of oil pollutions. However, the result of simulation will need to be more verified against observations in the future but now, because of lack of such observations in the Persian Gulf, we could not verified result with them more, and suggest working on it in the future.

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