A three dimensional numerical simulation for prediction of oil trajectory due to extraction activity in region between Khark Island and Busher Port in winter, Persian Gulf, Iran

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Present study consists three-dimensional numerical model of the prediction of the movement of oil slicks and diffusion oil particles in the water column. Model has previously been developed in the Assalouyeh Marine Region in the north coast of Persian Gulf, Iran and has been achieved good results. This model has been run for oil spill accident between Khark Island and Busher Port in winter (2005). Model predicts concentration distribution of oil particles and current speeds and directions for 1.7, 7 and 14 hours after spill accident in the water column in 5, 10 and 15 meters levels. Numerical results show that oil particles spread towards Khark Island and away from Busher Port in winter. Diffusion oil particles in the water column due to more turbulence are larger. Spreading follow the flow fields that are in good agreement with flow field observations and valid theories and experiment of data runs.

[Keywords: Numerical Simulation, Oil spill, Persian Gulf, Busher Port, Khark Island.]

Introduction
The oil spill accident is very harmful to the marine environment as its particles can stay in the water column for long times and pollute the deeper water environment. In the last two to three decades many researchers have studied the transport and the processes of oil spills based on the trajectory method and mass balance approaches, and various oil spill models have been developed1-4. Many of Agency Government have prepared the maps of the oil unexpected spill. Important component of these maps are the application of numerical models of oil slick movement and particle concentration distribution of oil in the Water column.

In 1988, A model of residual currents and pollutant transport was developed in the Persian Gulf.5 A pollutant transport model was presented for the Persian Gulf, with particular relevance to the portion of the Gulf adjacent to the coast of Saudi Arabia. Model was developed specifically for oil spill simulations, but it can be adapted to other pollutants. Residual currents in this part of the Gulf were dominated by wind-forcing, and part of the model consists of a computation of the mean wind-driven currents for each month. This was achieved by first solving the shallow-water equations (using a finite difference algorithm) for the depth-averaged velocities, and then solving the momentum equations for the vertical velocity profiles. Pollutant transport part of the model included surface spreading of the slick, evaporation and dispersion into the water column, convection, and both horizontal and vertical dispersion of the pollutant plume. Model was applied to the simulation of a 5000-barrel surface spill in the Marjan offshore oil field.

In 1988, Elsamra and et al.6 studied horizontal and vertical distribution of oil pollution in the Persian Gulf and the Gulf of Oman. Sea-area of the Persian Gulf and the Gulf of Oman was divided into three zones according to the sources and transport mechanism of oil pollutants. Zone of tanker routes showed gradual change of oil concentrations from around 27 ppb in the Gulf of Oman to concentrations around 22 ppb in the Persian Gulf. Zone of coastal waters showed lower values of oil concentrations. Mechanisms of oil pollutant transport in the two gulfs was discussed. The effect of offshore oilfields as a
fixed-point source of oil pollution in the area was discussed in horizontal and vertical scales. A subsurface layer (5-10 m) of high oil concentration (= 26ppb) was detected at stations near to offshore oil-fields and extended to cover a larger area. Sea-area of the Gulf region, subtropical and almost landlocked, is the largest offshore oil development area in the world. Potential pollution sources in the region are many, including offshore oil production, transport and recently, the Gulf War. This paper presents the oil concentration in the different depths of the water body extending about 820 km and including the open and coastal waters in front of the State of Qatar and UAE in the Persian Gulf and those in front of Sultanate of Oman in the Gulf of Oman.

In 1989, A comprehensive stochastic model was formulated to simulate the fate and transport of oil spills\(^7\). Model consisted of a set of algorithms describing the processes of advection, turbulent diffusion, surface spreading, vertical mechanical dispersion, emulsification, and evaporation. Each algorithm was developed separately and was linked to related processes and to environmental and other parameters. Model required as input the velocity field of the transporting medium. This could be obtained from a three-dimensional hydrodynamic model for tidal and wind-driven currents for the region of interest. Oil spill fate and transport model was used to simulate a surface oil spill in the Abu Ali region on the western side of the Persian Gulf. Simulation resulted indicate that the model could predict the fate and transport of oil slicks with reasonable accuracy.

In 1992, Chandy John\(^8\) studied Circulation and mixing processes and their effect on pollutant distribution in the western Persian Gulf. Current measurements at four offshore locations in the western Persian Gulf from 1986 to 1989 showed periods of stagnation or low currents, and steady Shamal-(northwest storms) driven currents which had significance to the mixing and transport of pollutants in this area. A major effect of Shamal on the net circulation was observed in June 1986 at the Station CM3 surface where the net drift increased from 50 km during the first two weeks to about 100km during the next two weeks. Drift direction during this period was 45 ° clockwise from Shamal wind direction. At CM4, the net drift was even reversed from southward to northward when Shamal winds changed to 'Kaus' winds (southeast storms) in August 1987. Progressive vector diagrams showed that the residual current in the region controls the pollutant transport of the surface water at CM1 generally towards the south and southwest and the bottom water towards the southeast. In contrast to CM1, the net drift at CM2 showed smaller southeastward drift. However, the near-bottom flows at all stations were towards the southeast and southwest, except near-bottom at Station CM3, where eastward and northeastward residual advective transports observed during the whole observation period. This unique northeastward near-bottom current has a special significance to the overall residual circulation of the Persian Gulf. The strongest tidal current transport occurs at Station CM1, which is near the location of an amphidromic point for M2 harmonic tidal constituent. Movement of pollutants offshore over a tidal cycle would be generally toward the southeast during flood and toward the northwest during ebb tide. Large tidal mixing was observed in the region and the associated turbulent diffusion causes pollutants to be rapidly dispersed and thereby shows almost uniform distribution in the vertical. Complex tidal mixing and transport exist at Station CM1 where predominantly diurnal tidal elevations exist with mixed, mainly semi-diurnal tidal currents and vice versa (predominantly semi-diurnal tidal elevations exist with mixed mainly diurnal tidal currents) at CM3. An earlier study by John et al. 1 indicated that the formation of high-salinity water in the Gulf of Salwah may be one of the most important sources of the salinity-related density gradient proposed by Hunter to drive circulation in the Persian Gulf. However, this study shows that the net displacement of water towards the southeast was also due to the predominant northerly and northwesterly winds.

In 1992, the model for oil slick predictions was built around a deterministic hydrodynamic model\(^9\). Wind-driven water Currents was computed using depth-averaged shallow-water Equations. Oil slicks were directly averted by those currents with a lagrangian approach. A simulation was made for the Persian Gulf during the period 25 January-1 February 1991, Movements of the slicks were reasonably well simulated according to the observations related by the media. This work on the Persian Gulf made with atmospheric analyse data was extended everywhere in real time in order to produce oil
In 1993, an oil spill response model, configured for operation on a personal computer, was applied to predict the transport and fate of oil from the Mina Al Ahmadi spill in the northern Persian Gulf\textsuperscript{12}. Model predicts the drift, spread, evaporation, dispersion, emulsification, and shoreline interaction of the spilled oil. Wind data necessary as input to the model was generated by Monte Carlo procedures from an analysis of historical data or provided by wind forecasts. Current data was provided by a hydrodynamic model of the Gulf Predictions of tidal (M2, $S2$, $K1$ and $O1$) and wind-induced (eight major wind directions) circulation were included as input to the spill model. Spill model was validated against the 1983 Norwuz platform spill and the 1980 Hasbah spill. Model was applied in forecast and hindcast modes to predict the transport and fate of the spill. Predictions of tidal (M2, $S2$, $K1$ and $O1$) and wind-induced (eight major wind directions) circulation were included as input to the spill model. Spill model was applied in forecast and hindcast modes to predict the transport and fate of the Mina Al Ahmadi (Sea Island). Thermal spill, which started on 19 January 1991 Model predictions were compared to the observations of slick size and arrival times at key locations along the Saudi Arabian coast. Model correctly predicted the spill path and size but overestimated the rate of transport in the forecast mode. Hindcasts were in better agreement with the observations.

In 1994, Roger Proctor and et al.\textsuperscript{11} studied modelling tides and surface drift in the Persian Gulf--application to the Gulf oil spill. A tide and surge forecasting model capable of predicting conditions for up to 5 days ahead has been developed to provide environmental data on tides, currents and particle trajectories in the Persian Gulf. A two-dimensional depth-integrated model on a 5' x 5' grid of the entire Gulf, driven by a 10 constituent tidal forcing at the mouth near the Strait of Hormuz and by meteorological forecasts from the United Kingdom Meteorological Office global numerical weather prediction model was used to provide hourly distributions of the depth-averaged tidal and wind-driven currents. Following the discharge of oil from Mina AL Ahmadi into the Gulf in January 1991 an oil spill model was interfaced to the tide and surge model, providing forecasts of the movement and spread of the oil slick. Oil spill model used a three-dimensional particle tracking algorithm to model the dispersion of the oil so that surface and sub-surface concentrations could be determined. The effects of surface evaporation and decay of the oil were included in the model.

In 2006, coupled solution of oil slick and depth averaged tidal currents was developed on three-dimensional geometry of Persian Gulf\textsuperscript{12}. In this model, simulation of oil spill due to tidal currents in Persian Gulf was performed by coupled solution of the hydrodynamics equations and an equation for convection and diffusion of the oil. Hydrodynamic equations utilized in this work consist of depth average equations of continuity and motion in two dimensional horizontal planes. The effect of evaporation was considered in the continuity equation and the effects of bed slope and friction, as well as the Coriolis effects are considered in two equations of motion. Overlapping cell vertex finite volume method was applied for solving the governing equations on triangular unstructured meshes. Using unstructured meshes provided great flexibility for modeling the flow in arbitrary and complex geometries, such as Persian Gulf flow domain. Results of the hydrodynamic model for tidal currents in Persian Gulf domain was examined by imposing tidal fluctuations to the main flow boundary during a limited period of time. Finally, the developed model was used to simulate an accidental oil spill from a point in Persian Gulf. In 2007, the numerical simulation of oil spillage trajectory was developed in the Persian Gulf\textsuperscript{13}. The study employed a 3-D rectilinear hydrodynamic model combined with oil spill model. Typical representative environmental conditions of the Persian Gulf were first setup into a hydrodynamic circulation model using data from various sources. Performance of the hydrodynamic model was then tested against measurements of tidal fluctuation and sea currents at selected locations. Spill analysis model was setup using the flow field produced from the hydrodynamic simulation and its performance was further validated against documented events of Al-Ahmadi historical oil spill crisis in the Gulf. The comparison of the actual and simulated oil spill drift was found reasonably acceptable allowing for further application in risk assessment studies in UAE Coastal water and in the entire Persian Gulf as well.

In the present study, a three-dimensional numerical model is used to simulate the movement of oil slick from spill accident in region between Khark Island and Busher Port in the north coasts of Persian Gulf in winter. Model is based on the Navier-Stokes and the mass transport equations to predict the oil particles in the water column and also at different depths.
Materials and Methods

Region is zonally at 26°45′N and meridionally at 48°53′E (Fig. 1). Zone is located on the northern coastline of the Persian Gulf. It is bounded by Mahshahr port, Deylam port, Busher port and Assalouyeh on the north and by the Khark island on the south. The model use Spreading, Evaporation, Dissolution, Vertical dispersion equations governing the behaviour of the spill and current. Momentum and continuity and oil particle transport equations and Oil particle transport equation was used in model. Oil slick on the sea is also subject to the action of waves, especially breaking waves and upper layer turbulence. Total mass of dispersed droplets smaller than \( d_{\text{max}} \) is given:

\[
M_{\text{tot}}(d_e) = C(o) \cdot D_{ba}^{0.57} \cdot S_{\text{cov}} \cdot d_{\text{max}}^{1.7}
\]  

(1)

where \( C(o) = \left[ \mu \cdot (T_{\text{oil}}) \right]^{-1} \) and

\[
D_{ba} = 0.0034 \cdot \rho_w \cdot g \cdot H_{\text{rms}}^2
\]

and

\[
d_{\text{max}} = \left( \frac{12 \sigma}{g(\rho_w - \rho_o)} \right)^{1/2}
\]

and also

\[
d_{\text{min}} = \frac{0.12 \cdot \sigma^{3/5} \cdot \omega_f^{2/5}}{\rho_w^{3/5} \cdot g^{4/5}}
\]

Maximal possible (due to the oil availability) concentration of the oil droplets is given:

\[
C_{\text{max}} = \frac{h_o \cdot \rho_o}{z_m}
\]  

(2)

Entrainment rate as a function of the oil type, breaking-wave energy and temperature using an empirical relation given as:

\[
Q(d) = K_{en} \cdot D_{ba}^{0.57} \cdot S_{\text{cov}} \cdot F_w \cdot d^{0.7} \cdot \Delta d
\]  

(3)

where \( F_{\text{wc}} = 0.032(U_{\text{wind}} - U_i)/T_w \)

The process of emulsification is affected by the wind speed, the thickness of oil slick, environment temperature, etc. Generally, the time evolution of the water content of the surface oil is computed according to the approach proposed:

\[
Y_w = (1 - e^{-K_B \cdot (1 + U_{\text{wind}})^{1.7}}) / K_B
\]  

(4)

The density of the emulsified oil is estimated from the balance of oil and water. It is computed according to:

\[
\rho = \frac{\rho_o d_{\text{max}}^{1.7}}{1 + \phi}
\]
\[ \rho_c = (1 - Y_w) \rho_o + Y_w \rho_w \]  

(5)

Emulsification and evaporation tend to increase the viscosity of oil\(^1\):\(^7\):

\[ \mu = \mu_o \exp \left( \frac{2.5Y_w}{1 - 0.65Y_w} \right) \]  

(6)

where \[ \mu_o = \rho_o \nu_{oil} \]

Salinity and heat budget equations are not used in the model as the water column is assumed homogeneous. Momentum equations in the \( x, y \) and \( z \) directions without hydrostatic approximation are used. Prevailing wind is assumed to be northwest. In the first stage, the shape of oil slick is assumed to be elliptical and homogeneous. Oil is assumed to be a single component and the density of the oil and water mixture is variable.

Elevation of the sea surface and water velocity everywhere is zero, except along the open boundary of the computational domain. Vertical velocity is zero at side boundaries and bed and in the open boundaries they are given by the tidal informations. An idealized seawater basin consists of 555 \( \times \) 180 km\(^2\) area grided with the grid size \( \Delta x = \Delta y = 3000 \text{ m} \) of in horizontal and 20 layers in vertical, and the time step for integration is typically 5s. Spill parameters are shown in (Table 1).

At coastal boundary, the normal component of velocity is zero. At open boundaries, the sea surface elevation is set equal to tide table data. The entire coastal boundary consists of a shoreline with no river inflows. There is no inflow or outflow in coastal boundary, as it is impermeable. There is also no-slip condition at the coastal boundaries and at the sea bed.

A regular rectangular mesh (555 \( \times \) 180 km\(^2\)) with grid size \( \Delta x = \Delta y = 3000 \text{ m} \) and with 11346 grid in computational domain (26°45’N, 48°53’E) is used and it is located between Jvadelaym Port in west and Assalouyeh in East, (Fig. 1). Model uses topographically following \( \sigma \)-coordinate in vertical. For this domain we use 20 layers of 0.05 \( \sigma \) each. \( \sigma \) is given by:

\[ \sigma = H \frac{z - h}{H - h} \]  

(7)

where \( H \) is the height of the model top, \( h \) is the height of the local topography and \( z \) is the vertical coordinate from the bed. Total volume of the spilled oil is 629.33 barrels. An accidental spill at 10 in the morning, on 25\(^{th}\) Feb., 2005 near 21 km from shore (shipsloading area) was assumed to happen. Mean temperature and maximum wind speed were 35.515 \( ^\circ \text{C} \) and 5.96 m/s respectively in winter(on 7\(^{th}\) Feb., 2005). Figure 2 shows the seabed topography of Region. The water depth ranges from 1 m to 75 m. The model uses Boussinesq approximation as Lipps equations without the use of hydrostatic pressure equation\(^18\). Algorithm for advection equation is the multidimensional positive definite advection transport algorithm (MPDATA)\(^19\),\(^20\). MPDATA is based on the upstream scheme, an iterative method based on the antidiffusive velocities is applied to correct the excessive numerical diffusion in such scheme. Such procedure may be repeated by any optional number of times. For two iterations, the MPDATA is a second-order-accurate in time and space for any advective velocity field. The properties of this scheme are: stability, consistency and conservation of positive definitives\(^19\),\(^20\).
Wind in winter are predominantly from northwest, along the axis of the Persian Gulf basin. Current speeds at depth of 5 from the water surface in Busher Port is shown in (Table 2) and observations wave in (Table 3).

![Fig 2. The seabed topography of region between Mahsher Port and assalouyeh.](image)
Results and Discussion
Winds in winter are predominantly from northwest, along the axis of the Persian Gulf basin. In winter time the prevailing northwesterly wind is strong and leads to surface currents offshore. Figure 3A shows south and south–eastern currents in the west and east of the region and along the coast; also no cyclonic circulation was observed after 1.7 hrs predictions for the 7th Feb. 2005 ( winter) at a depth of about 5 m below the surface. North–westerly wind which is typical of winter time, produces south–eastern currents, and also currents along the coast. The predictions of concentration from the scenario for oil spill, which is released 21 km from the shore in region between Khark Island and Busher Port, are shown in (Fig. 3B). Current direction is south and south–eastern so the movement oil slick is the same as. Figure 4A shows south and southeast weak currents at the depth of 5 m from the surface in region between Khark Island and Busher Port after 7 hrs. Figure 4B shows the distribution of particles after 7 hrs. Turbulence as a result of wave breaking breaks up the oil slick further into smaller patches, although the model results show an overall concentration after 7 hours in these figure. Corresponding pattern and concentration of the oil spill at a depth of about 5 m below the surface and the flow field causes not to break the slick(spill) into parts. Size of the spill at this depth is smaller and it appears to be intact (in one piece) from maximum 0.0018 kg/m³ after 1.7 hrs to maximum 0.0022 Kg/m³ after 7 hrs. At this depth it appears to mix less.

Figure 5A shows south and southeast currents and return current toward the northwest at the depth of 5 m from the surface in region between Khark Island and Busher Port after 14 hrs. Figure 5B shows the concentration of the oil spill is more after 14 hrs(max. 0.00011 Kg/m³)and more spreading due to less turbulent mixing. In fact the horizontal extent of the spill at 5 m depth appears to be larger than that for the spill after 7 hrs at 5 m depth.

Figure 6A shows the same south and southeast currents and return current toward the northwest at the depth of 10 m from the surface in region between Khark Island and Busher Port after 1.7 hrs.

Fig. 3- At the depth of 5 meters from the water surface 1.7 hours after the accident of spill (winter), A) Velocity vectors of current (m/s), the value shown in the legend represents maximum speed 0.025 m/s; B) Concentration distribution of Oil particles (kg/m³) between Khark Island and Busher Port.

Fig. 4- At the depth of 5 meters from the water surface 7 hours after the accident of spill (winter), A) Velocity vectors of current (m/s), the value shown in the legend represents maximum speed 0.11579m/s; B) Concentration distribution of Oil particles (kg/m³) between Khark Island and Busher Port.

Figure 6B shows the corresponding pattern and concentration of the oil spill at a depth of about 10 m below the surface.
Size of the spill at this depth is smaller and is one piece due to less turbulent mixing and also more stability and buoyancy force. Slick spreads in size much less than that for the spill at 5 m depth. Figure 7A shows south and southeast currents and return current toward the northwest at the depth of 10 m from the surface in region between Khark Island and Busher Port after 7 hrs. Figure 7B shows the concentration of the oil spill is more after 7 hrs (max. 4.5×10⁻⁶ Kg/m³) and again more spreading due to less turbulent mixing. In fact the extent of the spill at 10 m depth appears to be larger than that for the spill after 1.7 hrs at 10 m depth.

Figure 8A shows south and southeast currents and return current toward the northwest at the depth of 10 m from the surface in region between Khark Island and Busher Port after 14 hrs.

Figure 5- At the depth of 5 meters from the water surface 14 hours after the accident of spill (winter), A) Velocity vectors of current (m/s), the value shown in the legend represents maximum speed 0.03675 m/s; B) Concentration distribution of Oil particles (kg/m³) between Khark Island and Busher Port.

Fig. 6- At the depth of 10 meters from the water surface 1.7 hours after the accident of spill (winter), A) Velocity vectors of current (m/s), the value shown in the legend represents maximum speed 0.00024 m/s; B) Concentration distribution of Oil particles (kg/m³) between Khark Island and Busher Port.

Fig. 7- At the depth of 10 meters from the water surface 7 hours after the accident of spill (winter), A) Velocity vectors of current (m/s), the value shown in the legend represents maximum speed 0.02253 m/s; B) Concentration distribution of Oil particles (kg/m³) between Khark Island and Busher Port.

Figure 8B shows particle concentration distribution of oil in the water column after 14 hrs.
Figure 8 - At the depth of 10 meters from the water surface 14 hours after the accident of spill (winter). A) Velocity vectors of current (m/s), the value shown in the legend represents maximum speed 0.03674 m/s; B) Concentration distribution of Oil particles (kg/m³) between Khark Island and Busher Port.

Figure 9A shows northwest currents at the depth of 15 m from the surface in region between Khark Island and Busher Port after 1.7 hrs and also no cyclonic circulation was observed after 1.7 hrs predictions. The flow at this depth is reverse to that at the depth of 5 m from the surface (Fig. 3A), this maybe due to continuity and restrictions of flow. Tidal forcing appears to produce strong currents at this depth, while surface currents are influenced by wind forcing. Figure 9B shows particle concentration distribution of oil in the water column after 1.7 hrs. The slick spreads in size larger than that for the spill after 14 hrs at 10 m depth.

Figure 10A shows northwest currents at the depth of 15 m from the surface in region between Khark Island and Busher Port after 7 hrs and also no cyclonic circulation was observed after 7 hrs predictions. Figure 10B shows particle concentration distribution of oil in the water column after 7 hrs. Slick spreads in size larger than that for the spill after 1.7 hrs at 15 m depth.

Fig. 9- At the depth of 15 meters from the water surface 1.7 hours after the accident of spill (winter), A) Velocity vectors of current (m/s), the value shown in the legend represents maximum speed 0.02327 m/s; B) Concentration distribution of Oil particles (kg/m³) between Khark Island and Busher Port.

Fig. 10- At the depth of 15 meters from the water surface 7 hours after the accident of spill (winter), A) Velocity vectors of current (m/s), the value shown in the legend represents maximum speed 0.11199 m/s; B) Concentration distribution of Oil particles (kg/m³) between Khark Island and Busher Port.
Figure 11A shows south and southeast currents and return current toward the northwest at the depth of 15 m from the surface in region between Khark Island and Busher Port after 14 hrs. Figure 11B shows particle concentration distribution of oil in the water column after 14 hrs. Slick spreads in size larger than that for the spill after 7 hrs at 15 m depth.

In winter time as the cold northwesterly winds are strong more turbulent mixing and convection is expected and the water column is almost uniform in $T$, $S$ and density (Fig. 12A, B for Leg 1 and Leg 6, Reynolds22). Convective condition, as flowing cold air cools the surface water could also be expected that may increase the spread of the spill at deeper layers. In summer the thermocline is well developed (Fig. 12A, B). It also is observed $T$ and $S$ in the Persian Gulf waters of Hormozgan Province- (2001-2) (Fig. 13).

Thermocline develops very markedly in summer time, so vertical profiles of $T$, $S$ and density also show strong variations in the water column, in this area (Fig. 12A, B).

In winter time as the cold northwesterly winds are strong more turbulent mixing and convection is expected and the water column is almost uniform in $T$, $S$ and density (Fig. 12A, B for Leg 1 and Leg 6, Reynolds22). Convective condition, as flowing cold air cools the surface water could also be expected that may increase the spread of the spill at deeper layers. In summer the thermocline is well developed (Fig. 12A, B). It also is observed $T$ and $S$ in the Persian Gulf waters of Hormozgan Province- (2001-2) (Fig. 13),
dissolved. The evaporation is in winter due to the temperature and windy condition and also dissolution which may be the result of more turbulence (stronger winds) in winter. Again two stages of the rates of evaporation and dissolution are observed corresponding to two stages of area growth of the spill. The same is not true, for dissolution which may be the result of more turbulence (stronger winds) in winter.

Figure 16A shows oil density of the oil slick versus time. The density of oil is increased up to about 10 hours and also oil viscosity (Fig. 16B).

Figure 17A shows mass droplets of the oil versus time is increased up to about 10 hours and also (Fig. 17B) show concentration of oil particles.

Figure 18 shows adsorption of water by oil due to emulsification process in surface. versus time is increased up to about 10.

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**Figures 15A and 15 B also show the percentage of the slick which is respectively evaporated and**
Figure 19 shows entrainment rate of oil particles per unit surface area versus time. The buoyancy force depends on the density and size of the oil droplets so that larger, more buoyant, ones tend to remain in the surface layer whereas the smaller droplets are mixed downwards. Vertical speed of larger droplets are more and tend toward surface.

Table 4 shows the values oil particles condensate and speed current in region between Khark Island and Busher Port on the north coastals of Persian Gulf after spill accident in winter from model results. Table 5. shows computation of currents speed (m/s) from model and Mt. Mitchell\textsuperscript{23}. Table 6 shows some comparison between the some current speeds at different depth predicted by the model and observation at Taheri port(Fig. 2) in winter. Figure 20 shows comparison of numerical model results and observations(test) Concentration distribution of oil particles ($\mu$g/g) in winter.
A 3-D flow and oil trajectory and fate models have been made to predict the movement of an oil slick and the concentration distribution of oil particles in the water column and also the advection, evaporation and dissolution on the water surface. The flow model uses the MPDATA scheme for the advection terms and is usually more efficient than other schemes in terms of numerical diffusion. Predicted flow fields for winter time seem to follow the wind forcing at the surface and tidal forcing in deeper parts. North–westerly wind which is typical of winter time produces south–eastern currents, and also currents along the coast. It can be observed that the oil slick thickness decreases rapidly during the initial 10 hours. This means that the first stage of spreading occurs in a short time and mainly gravity driven. Evaporation leads to a very significant mass loss of the oil and it has a profound effect on density, viscosity and other of properties of oil. The rates of dissolution are 0.02–0.1% of the rates of evaporation. This is mainly due to very low solubility of oil components in water. Decrease of buoyancy force and also stratification do not lead to accumulation of particles near the water surface. Particles mix in the water column due to instability of water column in winter. Further work is required to improve the model by inclusions of heat and salinity budgets for the water columns. This is particularly important for summer as thermocline is well developed in most parts of the Persian Gulf (Fig. 12a and 12b and e.g. Reynolds). Inclusion of surface water breaking which can lead to entrainment of oil droplet into deeper water may also be as important.

**Table 4.** The values oil particles concentration and current speed in region between Khark Island and Busher Port on the north coastals of Persian Gulf after spill accident in winter from model results

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Time (hour)</th>
<th>Minimum of the oil particles concentration (Kg/m³)</th>
<th>Maximum of the oil particles concentration (Kg/m³)</th>
<th>Mean of the oil particles concentration (Kg/m³)</th>
<th>Minimum current speed (m/s)</th>
<th>Maximum current speed (m/s)</th>
<th>Mean current speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Five meters from the water surface</td>
<td>1.7</td>
<td>0.0001</td>
<td>0.0018</td>
<td>9.5×10⁻⁵</td>
<td>1.8×10⁻⁶</td>
<td>0.025</td>
<td>0.0125</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.0002</td>
<td>0.0022</td>
<td>1.2×10⁻⁵</td>
<td>3.6×10⁻⁵</td>
<td>0.11579</td>
<td>0.06</td>
</tr>
<tr>
<td>Ten meters from the water surface</td>
<td>1.7</td>
<td>1×10⁻⁷</td>
<td>1.8×10⁻⁷</td>
<td>1.45×10⁻⁷</td>
<td>6.3×10⁻⁶</td>
<td>0.00024</td>
<td>1.2×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1×10⁻⁶</td>
<td>4.5×10⁻⁶</td>
<td>2.75×10⁻⁶</td>
<td>1.14×10⁻⁶</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Fifteen meters from the water surface</td>
<td>14</td>
<td>4×10⁻⁷</td>
<td>1×10⁻⁶</td>
<td>0.7×10⁻⁶</td>
<td>7.7×10⁻⁶</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td>2×10⁻⁶</td>
<td>0.00013</td>
<td>7.5×10⁻⁵</td>
<td>2.24×10⁻⁵</td>
<td>0.023</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.0001</td>
<td>0.0019</td>
<td>1×10⁻³</td>
<td>1.11×10⁻⁶</td>
<td>0.112</td>
<td>0.055</td>
</tr>
<tr>
<td>Fifteen meters from the water surface</td>
<td>14</td>
<td>1×10⁻⁵</td>
<td>0.00011</td>
<td>6×10⁻⁵</td>
<td>7.633×10⁻⁶</td>
<td>0.03675</td>
<td>0.0185</td>
</tr>
</tbody>
</table>
Such a model can also be incorporated into an environmental monitoring package to give real-time forecasts, after full evaluations. In this model we did not consider the vertical variations of physical parameters in the water. This may influence the vertical intrusion of the slick towards deeper water. This may introduce some error in predicted concentration, especially further away offshore. Two stages of thickness variation with time is observed, the early stage is short and is more influenced by buoyancy which leads to faster spreading (up to about 10 hours), then the second stage which is mainly wind driven and slower. Table 6 shows some comparison between the some current speeds at different depth predicted by the model and observation at Taheri port (Fig. 2) in winter. There is a good agreement between the two. However after about 15 hours, the current speeds show large increase in the observation, that are not show in predicted values. This may be due to external effects that are not considered by the model. This indicates that may be one has to extend the area of computation that is limited by the computing power for the present study.

### Table 5. Computation of speed currents(m/s) from model and Mt. Mitchell

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Model</th>
<th>Mt. Mitchell data</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Max. 0.1613</td>
<td>0.2262</td>
</tr>
<tr>
<td></td>
<td>Mean 0.0472</td>
<td>0.0549</td>
</tr>
<tr>
<td>20-24</td>
<td>Max. 0.2338</td>
<td>0.1627</td>
</tr>
<tr>
<td></td>
<td>Mean 0.0736</td>
<td>0.0397</td>
</tr>
</tbody>
</table>

### Table 6. Comparison of numerical model results and observations mean current speed(m/s) in Taheri Port in winter (27°40′N, 52°20′E).

<table>
<thead>
<tr>
<th>Depth (From the water surface, m)</th>
<th>Numerical model</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.0273</td>
<td>0.0277</td>
</tr>
<tr>
<td>10</td>
<td>0.02905</td>
<td>0.0291</td>
</tr>
<tr>
<td>15</td>
<td>0.056</td>
<td>0.069</td>
</tr>
<tr>
<td>15 (After 7 hours)</td>
<td>0.063</td>
<td>0.076</td>
</tr>
<tr>
<td>15 (After 14 hours)</td>
<td>0.053</td>
<td>0.069</td>
</tr>
</tbody>
</table>

Such a model can also be incorporated into an environmental monitoring package to give real-time forecasts, after full evaluations. In this model we did not consider the vertical variations of physical parameters in the water. This may influence the vertical intrusion of the slick towards deeper water. This may introduce some error in predicted concentration, especially further away offshore. Two stages of thickness variation with time is observed, the early stage is short and is more influenced by buoyancy which leads to faster spreading (up to about 10 hours), then the second stage which is mainly wind driven and slower. Table 6 shows some comparison between the some current speeds at different depth predicted by the model and observation at Taheri port (Fig. 2) in winter. There is a good agreement between the two. However after about 15 hours, the current speeds show large increase in the observation, that are not show in predicted values. This may be due to external effects that are not considered by the model. This indicates that may be one has to extend the area of computation that is limited by the computing power for the present study.

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### Conclusion

In winter, changes of density increase the turbulence and reduces instability of buoyancy force. In winter wind intense is more and wind stress cause waves and also turbulent energy will be more. More particles accumulate on the surface, which is less turbulence. One of important property of water in oil dissolution is its salt content which affects oil solubility in water and vapor pressure of oil in evaporation process and density in sedimentation process. The vertical velocity of large particles are more and often they return towards surface and also affect the entrainment rate of large particle is more. Oil entrainment rate of oil particles is dominated by particles size, intrusion depth of oil particles, oil type, breaking-wave energy and temperature. The
oil particles mix in water column due to dispersion and dissolution. Density and viscosity and thickness of oil slick are increased in emulsification process and also evaporation and oil spreading became slow. Adsorption of water by oil due to emulsification process increase oil density. Surface density gradient is dominated by surface temperature distribution and water currents due to temperature difference cause thermal transformation. Vertical density gradients are dominated by halocline and water currents due to salinity difference cause mass transformation. In winter there is thermal transformation in water surface and mass transformation in water column. So oil particles are in depth than in water surface. In winter, changes of density increase the turbulence and reduce instability due to buoyancy force. In winter, wind is more intense and wind stress cause waves and also turbulent energy will be more. More particles accumulate on the surface, which is less turbulence. Increase of prevailing winds velocity that is stronger in winter, currents entering the Persian Gulf from the Strait of Hormuz and turbulent mixing and also decrease of stability and stratification in water column all cause particles to move away from shore and increase the influence of oil particles in depths. The influence of oil particles in water column is due to less stability of water and decrease of Buoyancy force (decrease of Richardson number) and increase of turbulent mixing (increase of Reynolds number) and decrease of water viscosity and increase of surface water density. Buoyancy force is dominated by density, droplets size and the vertical velocity. The evaporation process is as a function of area and thickness of the oil slick, vapor pressure, mass transfer coefficient. The evaporation increases salinity and decreases buoyancy force. The dissolution process is as a function of area of the oil slick, mass transfer coefficient and solubility.

Acknowledgement
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References


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## Nomenclature Defining Symbols

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C(o)$</td>
<td>A proportionality constant dependent on the oil viscosity ($\mu$) at oil temperature $T_{oil}(k)$</td>
<td>$Q(d)$</td>
<td>Entrainment rate of oil particles with particle sizes in the interval $\Delta d$ around $d$ ($kg/m^2s$)</td>
</tr>
<tr>
<td>$d$</td>
<td>Particle size (m)</td>
<td>$T_w$</td>
<td>Breaking wave period (s)</td>
</tr>
<tr>
<td>$d_{min}$</td>
<td>Minimum particle</td>
<td>$U_i$</td>
<td>Threshold wind speed for wave breaking ($\approx 5m/s$)</td>
</tr>
<tr>
<td>$d_{max}$</td>
<td>Maximum droplet size</td>
<td>$U_{wind}$</td>
<td>Wind speed</td>
</tr>
<tr>
<td>$D_{ba}$</td>
<td>Average energy dissipation per unit surface area in a overturning wave</td>
<td>$Y_W$</td>
<td>Water content of the emulsion</td>
</tr>
<tr>
<td>$F_{wc}$</td>
<td>Fraction of sea surface hit by breaking waves per unit time</td>
<td>$Y^{F}_W$</td>
<td>Stable water content of the emulsion whose is 0.8</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity</td>
<td>$z_m$</td>
<td>Thickness of the mixing layer</td>
</tr>
<tr>
<td>$h_o$</td>
<td>Initial oil slick thickness within the unit surface area $A$</td>
<td>$S_{cov}$</td>
<td>Fraction of surface area covered by oil ($0 \leq S_{cov} \leq 1$)</td>
</tr>
<tr>
<td>$H_{rms}^2$</td>
<td>Rms wave height (m)</td>
<td>$\Delta d$</td>
<td>Particle size interval (m)</td>
</tr>
<tr>
<td>$k_{en}$</td>
<td>An empirical constant dependent on the oil type and weathered state</td>
<td>$\nu_{oil}$</td>
<td>Kinematic viscosity of oil</td>
</tr>
<tr>
<td>$K_A$</td>
<td>A curve fitting constant whose value varies with wind speed, with $4.5\times10^{-6}$ being the most widely used</td>
<td>$\rho_c$</td>
<td>Density of the emulsion</td>
</tr>
<tr>
<td>$K_B$</td>
<td>$K_B = 1/ Y^{F}_W = 1.25$</td>
<td>$\rho_w$</td>
<td>Water density</td>
</tr>
<tr>
<td>$M_{oil}(d_e)$</td>
<td>Total mass of dispersed droplets smaller than $d_{max}$ ($kg/m^2$)</td>
<td>$\rho_{oil}$</td>
<td>Kinematic viscosity of oil</td>
</tr>
<tr>
<td>$\omega_f$</td>
<td>Wave frequency</td>
<td>$\rho_o$</td>
<td>Density of the remaining oil</td>
</tr>
<tr>
<td>$\sigma$</td>
<td></td>
<td></td>
<td>Interfacial tension</td>
</tr>
</tbody>
</table>