Three Dimensional Circulation in Persian Gulf

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1. Introduction

Amount of spilled oil in the Persian Gulf (Jan.25, 1991) was estimated as 3-4 million barrels by King Fahd University of Petroleum and Minerals. Along the coast of the Persian Gulf, there are many habitats of mangrove, coral reef and other wild life. Spilled oil ultimately becomes tar balls which will be drifted by the Gulf circulation. Therefore it is important to understand the circulation pattern in the Gulf in order to predict the damage to marine ecosystem for long time of period. The location of oil spill was off-coast of Kuwait and estuary of Tigris-Euphrates river, where density current due to fresh and saline water was predominant. Three dimensional model including density, tidal and wind driven currents is essential in order to predict the behavior of spilled oil.

2. Numerical model

The circulation model used in this investigation is the three-dimensional model developed by Blumberg and Mellor (1983, 1987), Blumberg and Herring (1987), using a system of general orthogonal curvilinear coordinates. The governing equations are simplified according to the hydrostatic assumption and the Boussinesq density approximation.

The free surface is located at $z=\eta(x,y,t)$ and the bottom is at $z=-H(x,y)$. The continuity equation is

$$\nabla \cdot \underset{\rightarrow}{V} + \frac{\partial W}{\partial z} = 0 \qquad (1)$$

The momentum equations are

$$\frac{\partial U}{\partial t} + \underset{\rightarrow}{V} \cdot \nabla U + W \frac{\partial U}{\partial z} - fV = -\frac{1}{\rho_o}\frac{\partial P}{\partial x} + \frac{\partial}{\partial z}\left(K_M \frac{\partial U}{\partial z}\right) + F_x \qquad (2)$$

$$\frac{\partial V}{\partial t} + \underset{\rightarrow}{V} \cdot \nabla V + W \frac{\partial V}{\partial z} + fU = -\frac{1}{\rho_o}\frac{\partial P}{\partial y} + \frac{\partial}{\partial z}\left(K_M \frac{\partial V}{\partial z}\right) + F_y \qquad (3)$$

$$\rho g = -\frac{\partial P}{\partial z} \qquad (4)$$

where ρ_o the reference density, the in situ density, g the gravitational acceleration, P the pressure, K_M the vertical eddy diffusivity of turbulent momentum mixing, f the latitudinal variation of the Coriolis parameter. The pressure can be obtained by vertically integrating eq (4) from z to the free surface η.

$$P(x, y, z, t) = P_{atm} + g\rho_o\eta + g\int_z^0 \rho(x, y, z', t)\cdot dz' \qquad (5)$$

The conservation equations of temperature and salinity are written as

$$\frac{\partial \theta}{\partial t} + \underset{\rightarrow}{V} \cdot \Delta\theta + W \frac{\partial \theta}{\partial z} = \frac{\partial}{\partial z}\left(K_H \frac{\partial \theta}{\partial z}\right) + F_\theta \qquad (6)$$

$$\frac{\partial S}{\partial t} + \underset{\rightarrow}{V} \cdot \nabla S + W \frac{\partial S}{\partial z} = \frac{\partial}{\partial z}\left(K_H \frac{\partial S}{\partial z}\right) + F_s \qquad (7)$$

The equation of state is as follow,

$$\rho = \rho(\theta, S) \qquad (8)$$

At the sea surface, the boundary conditions for surface shear, surface heat flux and salinity flux are given. In particular surface heat flux is function of solar radiation, wind velocity, relative humidity, cloud cover, air temperature and surface water temperature. Inflowing boundary conditions are given as prescribed temperature and salinity and outflow boundary conditions are given as

$$\frac{\partial}{\partial t}(\theta, S) + U_n \frac{\partial}{\partial n}(\theta, S) = 0 \qquad (9)$$

At the open boundary forcing due to tidal excitation is given.

Since the ordinary x,y,z coordinate system has difficulty simulating with surface and bottom layers in regions of irregularities, it is advantageous to introduce a new set of independent variables that transform both the surface and bottom into coordinate surfaces (Phillips, 1957). If (x,y,z,t) are Cartesian coordinates, a transformation to the "σ" system, $(x^*,y^*,\sigma,t)=(x,y,(z-\eta)/D,t)$ is made where $D=H+\eta$ is the total depth and η is the sea surface elevation. A depth-conforming vertical coordinate (σ) allows for equal vertical grid points, no matter what the local depth may be. This vertical resolution is sufficient to resolve surface wind-mixed and bottom tidal-mixed boundary layers over the entire domain and at the same time provide sufficient resolution in the intermediate water column.

The model responds to surface wind stress, salinity flux and to the specification of tidal forcing and freshwater discharge.

3.Simulation Result

In order to understand the circulation pattern at the time of oil spill (January 25, 1991), the simulation was conducted 60 days starting from Jan. 1, 1991.

Grid size was 10km and vertical resolution was 10 vertical grid points (Fig.1).

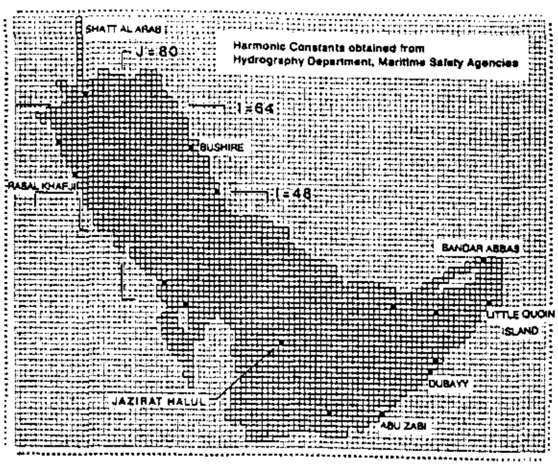

Fig.1 Model segmentation of Persian Gulf and stations where harmonic constants are available.

Initial distributions of temperature and salinity were obtained from Sailing Direction, Pub.170. Tidal forcing was given at Holmes strait and harmonic constants used in this analysis were obtained at Bandar Abbas and Little Quoin Island. Fresh water discharge from Tigris-Euphrates river was estimated by Public Works Research Institute from World Water Balance and Water Resource of the Earth (UNESCO, 1978) (Fig.2). Wind velocity was $6\text{m}\cdot\text{s}^{-1}$ of NW direction between Feb.1-Feb.10 and $6\text{m}\cdot\text{s}^{-1}$ of SE direction between Feb.11-Feb.20, based on data measured at Khafji for 25 years (Fig.3) and meteorological data obtained at MEPA, Saudi Arabia (1991).

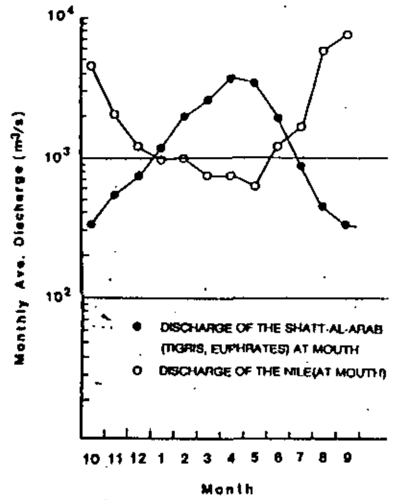

Fig.2 Estimated values of monthly averaged freshwater discharge from Shatt Al Arab at mouth (by Public Works Research Institute).

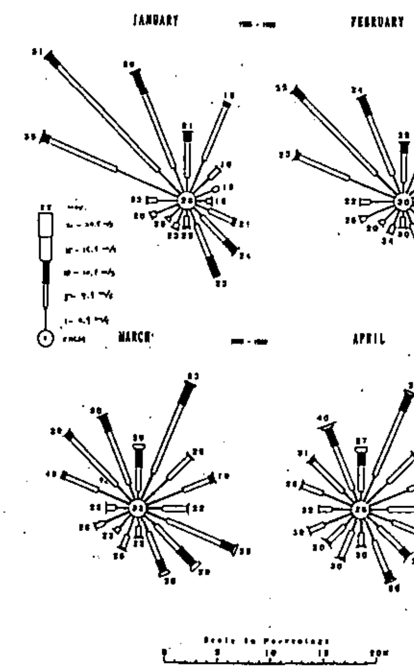

Fig.3 Long-term averaged (1965-1988) wind velocity and direction obtained at Khafji.

Predicted surface elevation changes showed excellent agreement with observed data at tidal stations along the coast of Gulf (for example, Fig.4). When NW wind of $6m\cdot s^{-1}$ was imposed, strong surface current was simulated from estuary of Tigris-Euphrates river toward the coast of Kuwait (Fig.5).

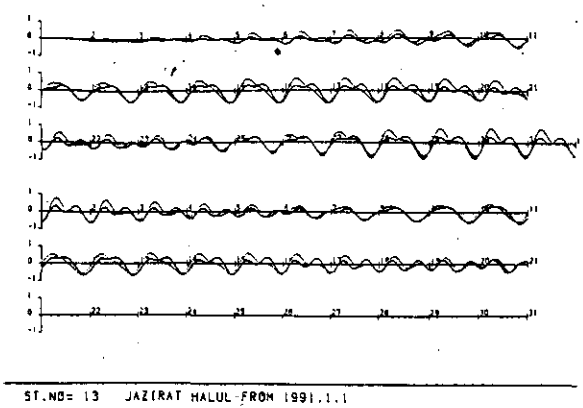

Fig.4 Comparisons of tidal elevation between observed and predicted values from 1991, 1.1.-1991, 2.20.

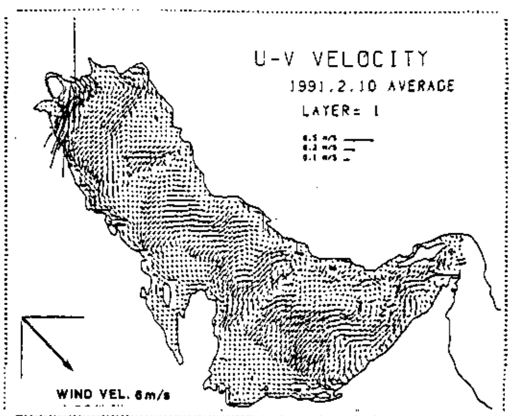

Fig.5 Distribution of horizontal residual currents at surface layer in 1991, 2.10.

This current was clearly observed from US Airforce airplane when the author joined the first observational flight after Gulf war organized by US coast guard and NOAA from Dharan to Kuwait and Iraq. On the otherhand bottom current was simulated from the coast of Kuwait toward Iraq and Iran (Fig.6). When SE wind of $6m\cdot s^{-1}$ was imposed between Feb.11-Feb.20, strong inshore currents were created along the coast of Saudi Arabia and this current drifted spilled oil into the shoreline of Saudi Arabia, especially in Abu Ali Island (Fig.7). In order to understand the mass flux exchange between Persian Gulf and Indian Sea the computation domain was enlarged to include some part of Indian Sea and same simulation was conducted for 60 days starting from Jan. 1, 1991. Since the volume of Persian Gulf is large comparing with inflows from river and Indian Sea, the computation did not reach to quasi-steady state, yet. However, even the system is in transient condition, the averaged evaporative mass flux and net flux between Persian Gulf and Indian Sea were estimated. Cross sectional flux distribution near Hormz strait (Indian Sea side) showed that inflow from Indian Sea into Persian Gulf existed in the surface layer and outflow into Indian Sea from Persian Gulf existed in the lower layer (Fig.8). During the simulation period, inflow from Tigris-Euphrates river was about $1.7x10^8$ m^3/day, however, the evaporative mass flux was about $10x10^8$ m^3/day, which was 6 times larger than river inflow. Net loss between evaporative mass and river inflow should be supplemented by inflow from Indian Sea.

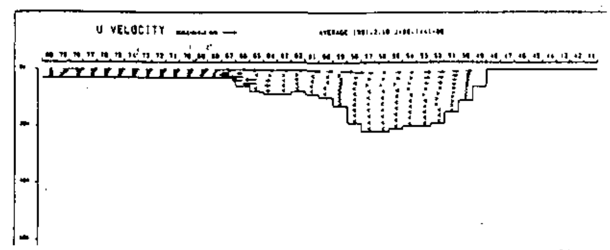

Fig.6 Vertical distribution of residual U currents at J=88 in 1991, 2.10.

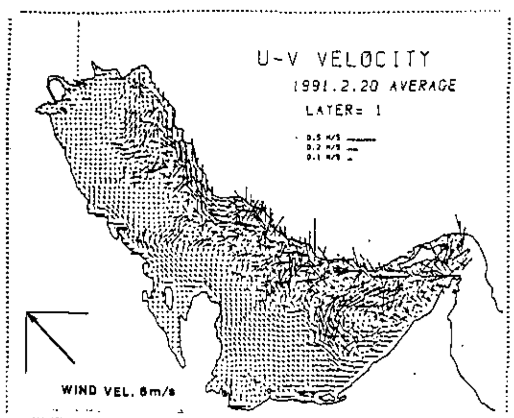

Fig.7 Distribution of horizontal residual currents at surface layer in 1991, 2.10.

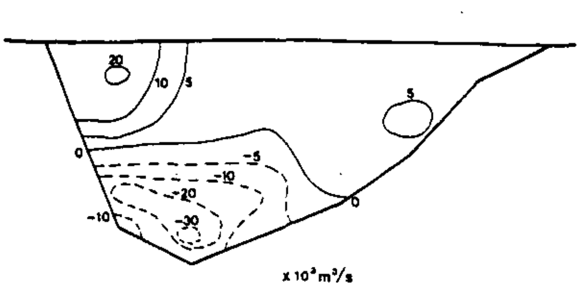

Fig.8 Mass flux distribution between Persian Gulf and Indian Sea at cross section near Holmz strait.

However at 60th day, the net flux across the cross section was about -9.8×10^8 m^3/day, which indicated outflow from Persian Gulf was larger(Fig.9). Probably this result was obtained due to the error in initial salinity distribution. The simulation of longer time period should improve the net flux across the cross section.

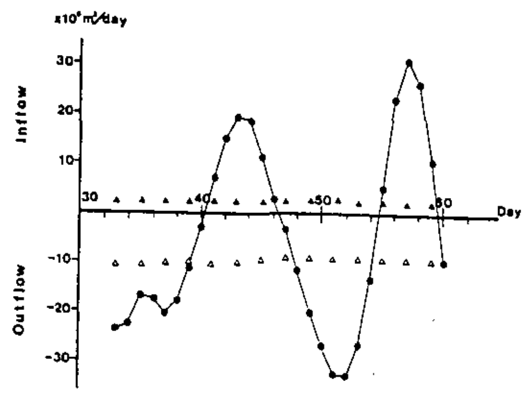

Fig.9 Mass balance in Persian Gulf.
△ : Mass loss due to evaporation
: Mass inflow from Tigris-Euphrates river
● : Mass exchange between Persian Gulf and Indian Sea

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