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Three-Dimensional Numerical Modeling Study of the Coastal Upwelling in the Persian Gulf

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Abstract: A numerical study is made of the dynamics of the circulation that arises from forcing by a steady, uniform longshore wind in the Persian Gulf. The three-dimensional hydrodynamic model (COHERENS) has been employed to drive upwelling in the Northern part of the Persian Gulf. Atmospheric forces as well as tidal force have been employed in this model. Total simulation times, run in a fully prognostic mode are 11 years, which is sufficient to develop a steady state seasonal cycle of circulation and water mass properties in the Persian Gulf. Findings of the model suggested that a seasonal thermocline is evident with a surface to bottom temperature difference of around 12°C in summer. Simulated results show that when the direction of upwelling-favorable wind is parallel to the coast in the Northern part of the Gulf with a speed of greater than 9 m sec^{-1}, upwelling occurs. A minimum of 4 days continual wind parallel to the coast is required to cause upwelling in this region. It is also found that the coastal sea surface temperature is a very good indicator of upwelling at the study area. The model predictions of coastal circulation and vertical temperature structure are compared with the limited available observations.

Key words: Persian Gulf, upwelling, coherens, SST, numerical modeling

INTRODUCTION

The Persian Gulf sits on top of the largest hydrocarbon reserve in the world, which makes this area extremely important for oil production. It is one of the most important strategic waterways in the world. The Persian Gulf is connected to the Gulf of Oman and the Indian Ocean through the Straits of Hormuz. The countries of United Arab Emirates, Qatar, Bahrain, Saudi Arabia, Kuwait and Iraq border, the Gulf along its Southern coastline and Iran is situated along the Gulf's Northern coastline (Fig. 1). The narrow Strait of Hormuz restricts water exchange between the Persian Gulf with the Northern Indian Ocean.

The Persian Gulf is about 990 km long and has average and maximum depths of 36 and 120 m, respectively. It is broadest (370 km) in its middle and narrowest (56 km) across the Strait of Hormuz. The Gulf is a semi-enclosed marginal sea in an arid sub-tropical region. Estimates of net evaporation rates vary between 98 mm year^{-1} to as large as 500 mm year^{-1} (Privett, 1959; Meshal and Hassan, 1986; Johns *et al*., 2003). Strong evaporation makes the Gulf an inverse estuary that is governed by outflow of saline Gulf water through the Strait and inflow of low salinity surface water from the adjacent Gulf of Oman (Swift and Bower, 2003). During summer a seasonal thermocline is evident with a surface to bottom temperature difference of around 11°C in the Persian Gulf.

Knowledge of the Gulf's circulation is of great significance for management of oil spill events, fisheries and shipping lines. On the basis of a comprehensive suite of hydrographic data acquired a year after the Gulf War in 1991, Reynolds (1993) proposed a sketch of the Gulf's general circulation (Fig. 1) that has been confirmed by most subsequent studies.

The most important episode of coastal upwelling, in terms of size, duration and economic importance, occur due to longshore wind. The phenomenon of oceanic upwelling in the coastal area is

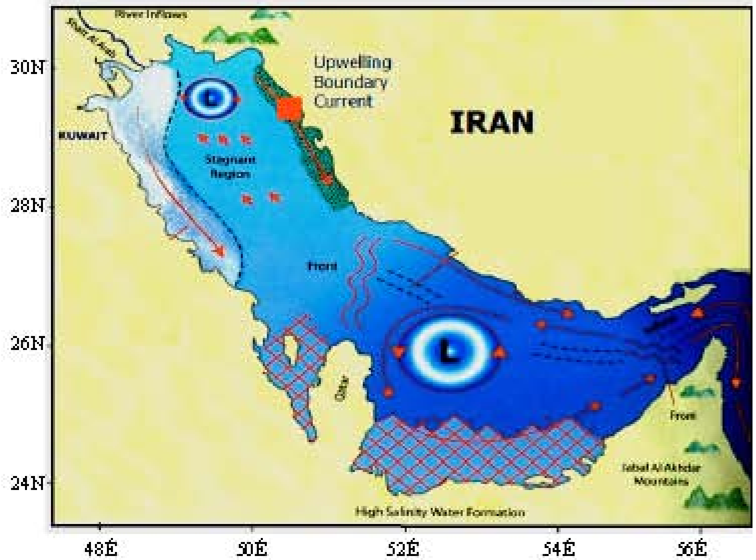

Fig. 1: Sketch of the general circulation and region of upwelling in the Persian Gulf. Modified from Reynolds (1993)

important from physical and ecological viewpoints. The occurrence of strong upwelling of cold water in a narrow coastal strip contributes to increased productivity of the sea as well as to climate modification of the adjacent land. The persistent Northwesterly wind stress, in the Northern part of the Gulf, appears to set up coastal current regimes (upwelling) along Iranian coast (Reynolds, 1993). Year-round Northwesterly winds, known as the Shamal, are believed to create a Southeast ward coastal upwelling jet along the Iranian coast between 28 29°N, but observational evidence is sparse (Fig. 1). As far as the researcher is aware, modeling studies of the Persian Gulf's coastal upwelling are lacking; that is, previous studies were either on general circulation (Sadrinasab and Kampf, 2004), or have focused exclusively on tides in the Persian Gulf (Najafi, 1997).

The principle objective of this study is to present a three-dimensional numerical modeling of coastal upwelling in the Northern part of the Persian Gulf, where Reynolds (1993) mentioned it.

MATERIALS AND METHODS

This study employs the three-dimensional hydrodynamic model COHERENS (Coupled Hydrodynamic-Ecosystem Model for Regional Seas) (Luyten *et al*., 1999) based on sigma coordinates. This model uses 10 sigma levels on an ETOPO2 (two minute worldwide Bathymetry/Topography) bathymetry, being interpolated and slightly smoothed onto a 4-minute grid. Maximum water depth is set to 150 m, which only modifies the topography of the Gulf of Oman and has no impact on the resultant circulation in the Persian Gulf. Cartesian lateral grid spacing is 6.6 km (north-south) and 7.4 km (Eastwest). The model is forced by climatologic monthly mean atmospheric forcing (wind speed, air temperature, humidity, cloud cover and precipitation) derived from 54 years of National Oceanic and Atmospheric Administration data. A reduced river discharge of 10 km^3 $year^{-1}$ as an estimate of flow rates after dam construction is used by the model. Monthly mean vertical profiles of temperature and salinity, extracted from previous hydrographic data (Alessi *et al*., 1999) are prescribed at the Eastern open-ocean boundary. Tidal boundary forcing is included using the four major constituents: M_2, S_2, O_1 and K_1. The tidal part of the model has been calibrated against previous tidal studies (Najafi, 1997).

Simulations cover a total period of 11 years including an initial spin-up period of 10 years. The model is run in a fully prognostic mode with 80 sec time step for all variables. Then model has been calibrated with available data and run for additional year to simulate upwelling. As the change of coastal water temperature is an indication of coastal upwelling and also with the knowledge that, thermocline occurs during summer, different wind speeds and durations were applied parallel to the coastline in the Northern part of the Gulf during summer (July).

RESULTS AND DISCUSSION

As mentioned formerly, this is the first study on upwelling in the Persian Gulf, hence, there is no field data to compare the findings of the model with them, but findings of simulated seasonal and spatial variations in temperature and salinity in the Persian Gulf are in general agreement with field data (Alessi *et al*., 1999). Figure 2 shows comparison of the TS-diagrams computed by the model results with by Alessi *et al*. (1999) which has been taken from historical data in the Northern part of the Gulf during summer. Also circulation patterns, of the model compare well with earlier investigations (Kaempf and Sadrinasab, 2006). However, a discussion of this would go beyond the scope of this study.

Figure 3 shows the annual surface and bottom temperature difference in the Northern part of the Gulf for the last year of the simulation. As can be seen from Fig. 3 the maximum temperature difference is 12 degrees in summer (July) which is in agreement with.

As the change of coastal sea surface temperature is the best indicator of coastal upwelling, summer time is chosen to blow upwelling-favorable wind over the domain to simulate the upwelling in the Northern part of the Gulf. To do this, several models have been run with different wind speeds

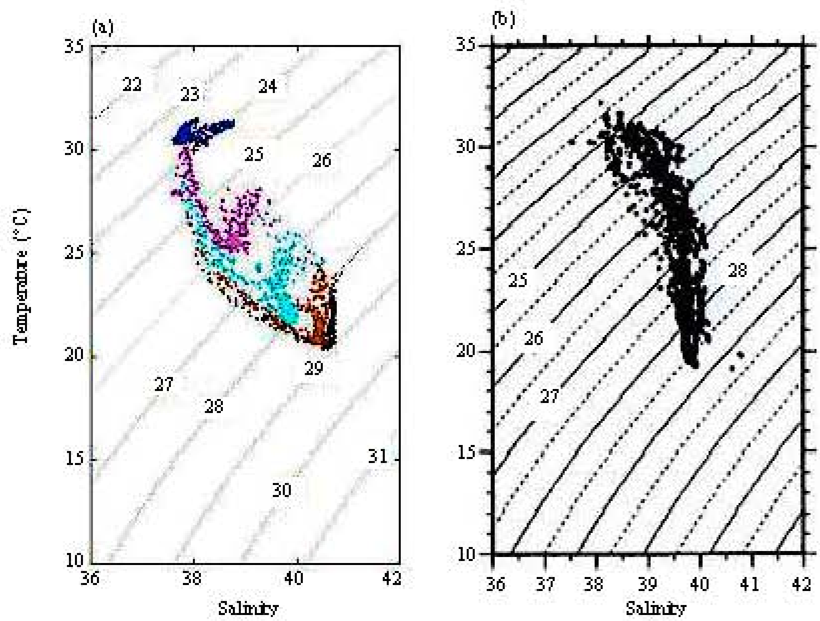

Fig. 2: Calculated TS-diagram by the model (a) in the Northern part of the Gulf and TS-diagram from historical data by Alessi *et al*. (1999) and (b) during summer

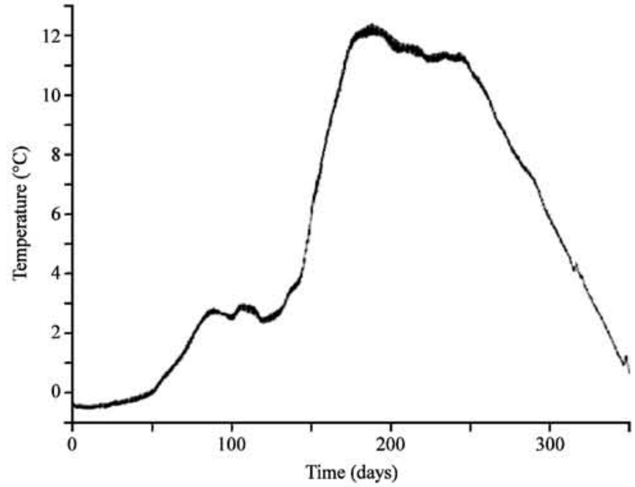

Fig. 3: Computed annual surface and bottom temperature difference in the Northern part of the Gulf by the model

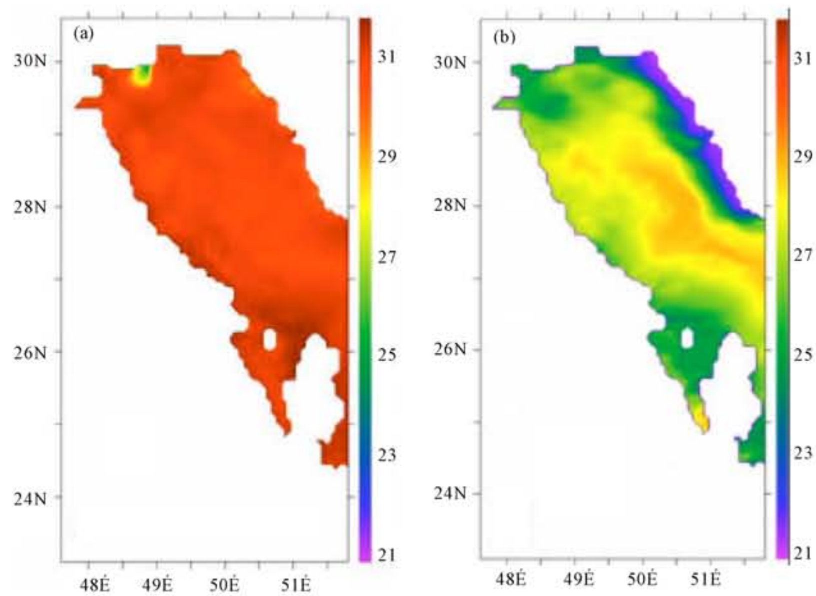

Fig. 4: Sea surface temperature in the region of study (a) in normal condition and (b) with resonant wind

and durations parallel to the coastline in mid July. A first experiment was preformed with wind speed of 4 m sec^{-1} and duration of 7 days, but no indication of upwelling was observed. In the next attempts, speed of the wind was increased by 1 m sec^{-1} intervals. After 4 days of consecutive wind with a speed of 9 m sec^{-1}, a longshore baroclinic jet was observed which in turn led to active upwelling.

During July, in normal condition, sea surface temperature is nearly 32°C everywhere in the domain except at the river mouth where it is slightly lower (Fig. 4a, b). But in the condition when

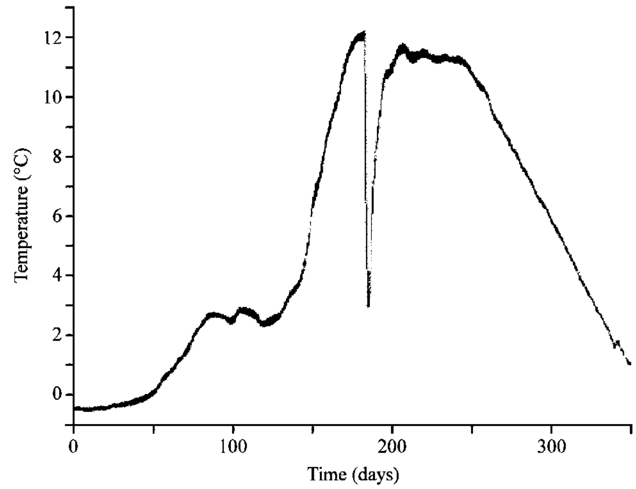

Fig. 5: Time series of SST at the location of upwelling

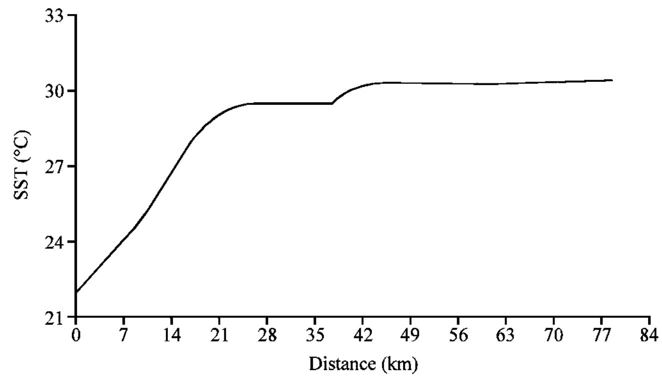

Fig. 6: Variation of SST with offshore distance at the location of upwelling

upwelling-favorable wind exceeds 9 m sec^{-1} and blows parallel to the Northern part of the coast, after a period of 4 days, a dynamic balance is established between the wind-induced frictional force at the water surface and the Coriolis force. Due to this balance, a mass transport of water takes place in the surface layer, which is directed to the right of the blowing wind and also due to a decrease in water level along the coastline, mass conservation requirement causes vertical motions of upwelling.

Figure 4b show, the coastal upwelling development which substantially reduces coastal surface temperatures from 32°C to about 21°C in the region of study.

Figure 5 shows the time series of sea surface temperature by the model at the place marked red square in Fig. 1. As shown in Fig. 5, a sudden drop of sea surface temperature occurs in the model due to establishment of upwelling in the study area.

Figure 6 represents variations of sea surface temperature with offshore distance at the mentioned location where upwelling occurred in the model. This figure clearly exhibits the width of the upwelling strip which is about 21 km at the same location. This is in close agreement with Reynolds (1993).

Figure 7 shows time series of the vertical profile of sea surface temperature by the model along the coast at the location where upwelling occurs in the model. As can be seen in Fig. 7, before

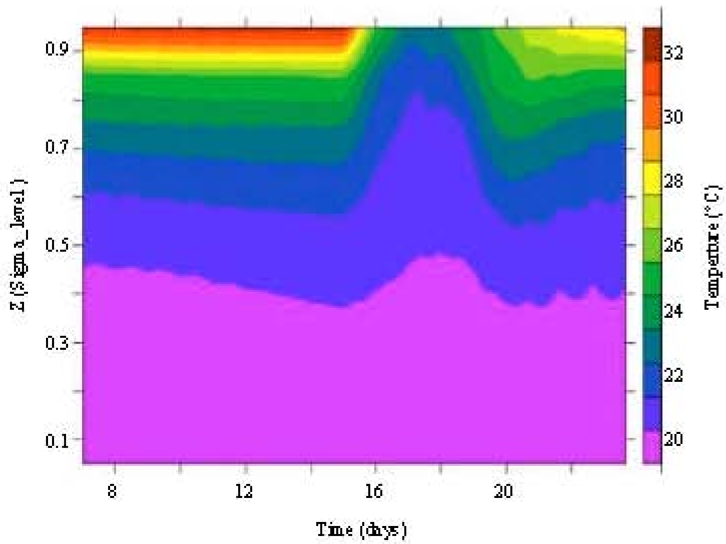

Fig. 7: Vertical profile of SST at the location of upwelling

blowing of upwelling-favorable wind, thermocline is evident in the region of study, but after upwelling-favorable wind, cold water from beneath moves towards surface and diminishes the coastal sea surface temperature approximately by 11°C.

CONCLUSION

A seasonal thermocline is evident with a surface to bottom temperature difference of around 12°C in summer. In the Northern part of the Gulf when the wind direction is parallel to the coast with a speed of greater than 9 m sec^{-1}, upwelling can occur. Also, findings of the model suggested that 4 days continual wind parallel to the Northern coast is required to establish upwelling in this region. It is also found that the coastal sea surface temperature is a very good monitor of coastal upwelling at the study area.

ACKNOWLEDGMENT

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