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Numerical simulations of oceanographic characteristics of the Persian Gulf and Sea of Oman using ROMS model

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In this paper, oceanographic characteristics of Oman Sea has been simulated using oceanographic model ROMS. The study area was limited from Arvand Roud in the north of Persian Gulf to RAAS AL HAD in the south east of Oman Sea. Oceanographic parameters on the study area were simulated by the ROMS model for 7 years period and the results were analyzed in comparison to satellite data in the study area in different seasons. Propagation pattern of Indian Ocean Surface Water (IOSW) in to the Persian Gulf and Oman Sea was considered for examination using the ROMS model. The model outputs for surface currents and temperature show the similar pattern as compared to remote sensing data and previous work.

[**Keywords**: Numerical simulation, Persian Gulf, Sea of Oman, ROMS model]

Introduction

Study of atmosphere-ocean interaction is an important issue in oceanography. One of the common methods is simulation using numerical oceanic models which have been widely used for various oceanographic studies.

Bower et al[1] studied the Persian Gulf and Red Sea outflows and their effects on the thermocline and other physical oceanographic parameters using historical bathymetric information and a model for plume simulation. They show that product waters from both outflows are transformed away from the sill region in narrow boundary currents, at least during part of the year. In rest of the year, they move in the form of separated pieces.

Ezam et al[2] studied the Persian Gulf outflow structure and its spreading pathways during 1992 using Princeton Ocean Model (POM). As the input of the model, meteorological data including wind speed and net shortwave radiations were obtained from the International Comprehensive Ocean Atmosphere Data Set (ICOADS) and National Center for Environmental Prediction (NCEP), and Sea Surface Temperature data were achieved from Advance Very High Resolution Radiometer (AVHRR). The results show a good acceptance with the measurements in the Persian Gulf and Sea of Oman.

Hassanzadeh et al[3] studied the effective factors on the variability of salinity in the Persian Gulf including wind and thermohaline forcing using the oceanic numerical model COHERENS (Coupled Hydrodynamical Ecological Model for Regional and Shelf Seas). Based on the model outputs, the variability of salinity has a very complex pattern. Thermohaline forcing has a more effective role than the wind on the salinity pattern. Thermohaline fluxes affect the salinity from the surface to bottom of the sea. During September to November, this effect increases because of dominating evaporative salinity flux over the Indian ocean surface water inflow.

Kampf and Sadri Nasab[4] used the numerical oceanic model COHERENS to investigate the water mas properties and circulation of the Persian Gulf. The results show that there is a significant cycle in the Persian Gulf during the spring and summer, and it converts to the Mesoscale eddies during autumn and winter.

L'Hégaret et al[5] described seasonal variability and intense mesoscale features due to The Arabian Sea and Sea of Oman circulation and water masses, subject to monsoon forcing, that used atmospheric and oceanic data including reanalysis products from ECMWF, marine cruise observations and international program for ocean monitoring, climatological data bank, remote sensing data for sea surface height, and also numerical simulation of Indian ocean.

Pous et al[6] investigated on circulation of the Persian Gulf and effect of Arvand Roud plume using a coupled shallow water and numerical ocean model. The optimum configuration was used for the models. The results show that: 1) The Shamal wind produces a cyclonic gyre in the south and an anticyclonic gyre in the north of Persian Gulf. Near the Iranian and Arabian Coast, there are southeasterly currents due to combination of wind stress and pressure gradient related to the sea surface slope, and upside down in deeper area of the Persian Gulf; 2) the cyclonic gyer in the eastern part of the Persian Gulf is more powerful than western part.

Pous et al[7] studied the inter seasonal and inter annual variability of circulation in the Persian Gulf and strait of Hormuz using a 2D numerical model (MARS2D), to make the boundary values, and a 3D numerical model (MARS3D). The results of the model were compared to measured data and also the sensitivity analysis of the model based on the vertical mixing parameterization.

Prasad et al[8] studied the variability of Persian Gulf outflow in the North of Indian Ocean using observation in 1990-1992. It was indicated this phenomenon is produced by decreasing sea water temperature and reducing sunshine duration in cold season. It was found that seasonal changes in this phenomenon simultaneously occur with monsoons effects on the circulation of Arabian Sea.

Reynolds[9] analyzed the observation data that achieved during ROPME marine cruise, during February to June 1992, recorded by Mt. Mitchell research vessel. Based on the recorded data at seven separate legs, the physical oceanographic parameters of the Persian Gulf were investigated and compared to the model results and previous observations.

Seo et al[10] investigated on the ocean-atmosphere interaction and its effect on western Indian Ocean using the SCOAR (Scripps Coupled Ocean-Atmosphere Regional model) that couples the Oceanic and Atmospheric models using a flux SST coupler.

Shetye et al[11] investigated on the circulation and water masses of the Arabian sea and Indian Ocean using previous studies and measurements. The pattern of physical oceanographic parameters at the surface layer and also in depth were described and used to show the seasonal and annual variability of the parameters.

Thoppil and Hogan[12] investigated circulation and Mesoscale eddies in the Persian Gulf using high resolution (1km) Hybrid Coordinate Ocean Model (HYCOM). The main factors affecting the Iranian Coastal Current (ICC) and Iranian Costal Eddies (ICE) were discussed and their seasonal and annual variability were demonstrated.

Vic et al[13] investigated the eddy-topography interaction and its effect on the Persian Gulf outflow using the Regional Ocean Model System (ROMS) using two scenarios, with and without topography at the bottom.

In the other study, Vic et al[14] investigated Mesoscale dynamics in the Arabian Sea and focused on the Great Whirl life cycle using ROMS model. The results of the model confirmed the relation between basin-scale down welling Rossby waves and generation of Great Whirl.

Yao and Jones[15] studied on general circulation in Persian Gulf and Sea of Oman using numerical ocean model that used Hybrid coordinate in vertical direction.

In this research, the physical oceanography situation of Persian Gulf and Oman Sea was simulated using oceanic model ROMS and its results were compared with available measured data.

Sea of Oman, at the south east of I.R. of Iran, is the tail of Indian Ocean. It is limited to Iranian Makran coasts from the north and to Arabian Sea and Oman from the south and Tropic of Cancer passes from the south of Sea of Oman. Its width from Raas Al Had, north eastern of Oman, to Port Govater at the end of south eastern of Iran (in the boundary of Iran and Pakistan) is about 320 km and it length is about 560 km. It links to Persian Gulf and consists of one of the important shipping routes for supplying world's energy, through strategic Strait of Hormuz, at the north of Mosandam Peninsula. Iranian ports in the Sea of Oman include Jask, Chabahar and Konarak and in the southern part (at the coasts of the Oman) include Sur, Muscat, Mutrah, Khaburah, and Sohar (Fig. 1). Climate of the region, considering geographical position is affected, at one hand by the Monsoon of Indian Ocean, and in on other hand by subtropical high pressure in that severe heating is one of the most important climatic phenomena.

In terms of meteorological events of the region, monsoonal severe winds, dust storm, strong showers, large humidity and morning fog are significant phenomena. It has a hot and long-time summer and short-time winter. Most of the precipitation of the region happens during winter. The region has two

Fig. 1 — Schematic view of the study area

separable seasons include winter with moderate and cool temperature in December, January and February and hot summer for the rest of the year.

Sea of Oman is affected by two typesof winds: one is westerly wind or Shamal, and another is Monsoon wind from South South West (SSW). Arabian Peninsula protects western part of Sea of Oman from monsoon wind. So, wind field is changed from the dominant direction West North West (WNW) at Jask to dominant direction West (W) at the boundary of Hormuzgan and Sistan and Baluchestan provinces. By passing from the protected part of Sea of Oman to the wind effected part, the dominancy of westerly wind is decreased.

Sea of Oman is a transition from estuary to deep ocean circulation. Circulation of the Sea of Oman includes following features:

- An outlet in deep part from Strait of Hormuz penetrated up to 200 m and dispersed through the width of the basin.
- It make anti clockwise eddies that produce cold water upwelling features along the Iranian coastal regions.

In the Sea of Oman there is a circulation with two eddies. A circulation in clockwise direction in west of the Sea affects the surface water in Oman Coastal regions and strait of Hormuz. An anti clockwise circulation is at the central part of Oman Sea. Combination of these eddies make a cold water filament. (Fig. 2)

The cold water region may be seen in sea surface temperature in satellite images. Figure 3 shows pattern of general circulation in Arabian sea.

Material and Methods

To simulate the circulation in the Persian Gulf and Sea of Oman, the Regional Oceanic Model System (ROMS) was used. ROMS is a free surface model with terrain following coordinate in that basic oceanic equations are solved numerically. The model has a reasonable accuracy and physical efficiency that has the ability of application in deep and coastal oceanic regions and has different vertical turbulence schemes, with multi levels, and nested complex grids (Fig. 4). In vertical direction, basic equations are discretized based on topography using terrain following coordinate. In default mode, central second order finite difference on the staggered vertical grid is used. In horizontal direction, basic equations are given based on orthogonal curvilinear coordinate, proper for boundary on Arakawa-C grid and also have a central second order finite difference option. General

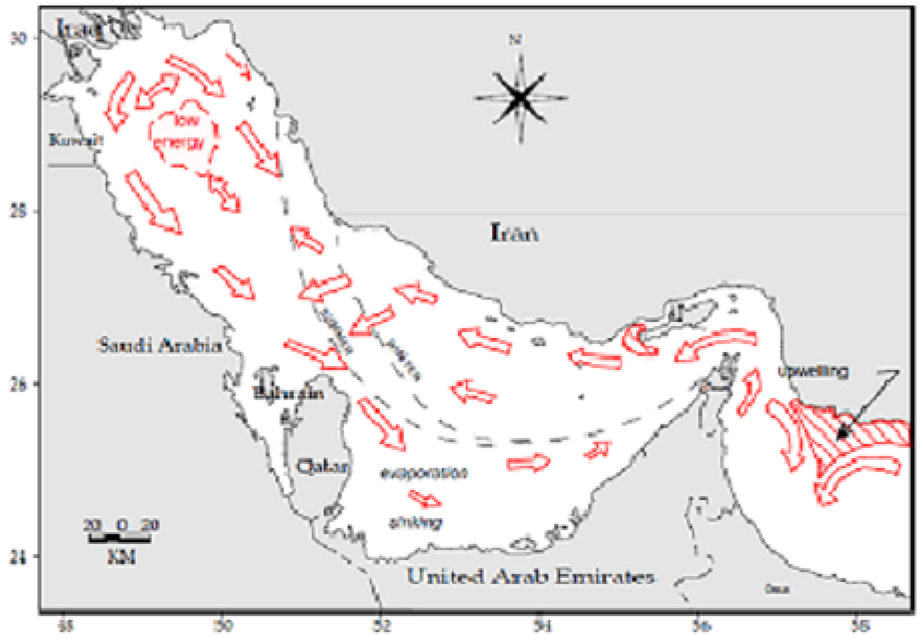

Fig. 2 — Circulation of Persian Gulf and Sea of Oman[9]

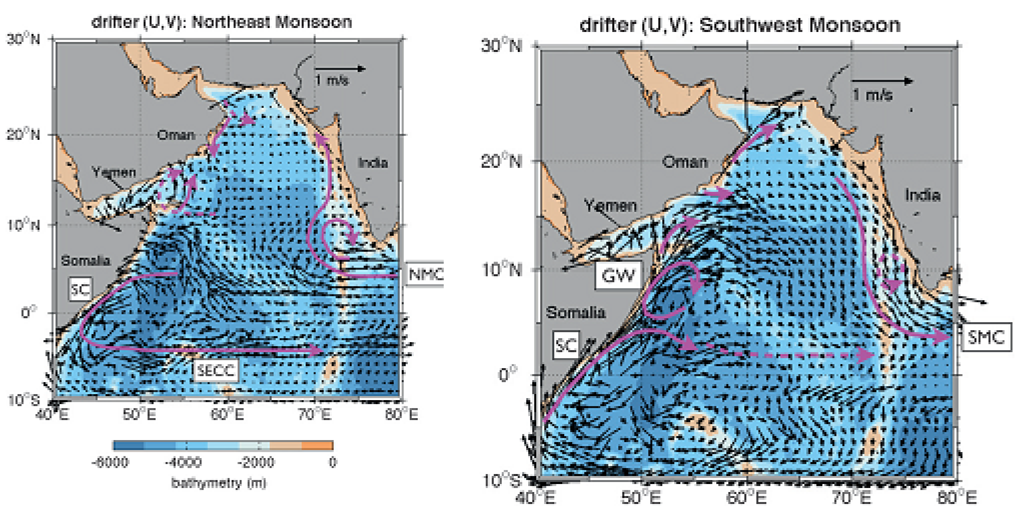

Fig. 3 — pattern of general circulation in Arabian Sea and Sea of Oman[16]

formulation of curvilinear coordinate includes Cartesian and spherical. Vertical boundary condition for the surface level that is estimated based on the atmospheric forcing are:

$$K_m \frac{\partial u}{\partial z} = \tau_s^x(x, y, t) \quad \dots (1)$$

$$K_m \frac{\partial v}{\partial z} = \tau_s^y(x, y, t) \quad \dots (2)$$

$$K_T \frac{\partial T}{\partial z} = \frac{Q_T}{\rho_0 c_P} + \frac{1}{\rho_0 c_P}\frac{dQ_T}{dT}\left(T - T_{ref}\right) \quad \dots (3)$$

$$K_S \frac{\partial S}{\partial z} = (E - P)S \quad \dots (4)$$

$$w = \frac{\partial \zeta}{\partial t} \quad \dots (5)$$

The first two equations are related to wind induced surface stress in x and y direction, third equation is related to temperature changes trough latent and sensible heat, fourth equation is related to salinity changes based on precipitation and evaporation, and the fifth equation is related to changes of vertical component of velocity based on sea level fluctuation.

Temperature and salinity or any tracers in constant Z, geopotential or isopicnal levels are calculated by the model. Parameterization of vertical mixing in the model may be selected by user based on local or non-local closure schemes. Local closure schemes are based on turbulence energy equation and parameterization of generalized length scale such as level-2.5 scheme of Mellor and Yamada. Non-local closure scheme is based on k profile and boundary layer formulation that is given by Large et al and K profile scheme is designed for ocean surface and bottom boundary layers simultaneously. Generalized length scale is a two-equation turbulence model that has a wide range of vertical turbulence closures as energy-energy/length scale product model (K-Kl), energy-dissipation rate model (K-e), and energy-vorticity fluctuation model (K-w).

In this study, the bathymetric data were obtained from the ETOPO1 data set, initial, boundary, and climatology data were obtained from WOA data set and atmospheric forcing were from ECMWF data set with 0.25° resolution that has been used in some studies such as L'Hégaret et al[5]. The schemes which have been used for running the model are given in Table 1.

The model was run for seven years for the study area and the simulation results were analyzed based on the previous studies and satellite images.

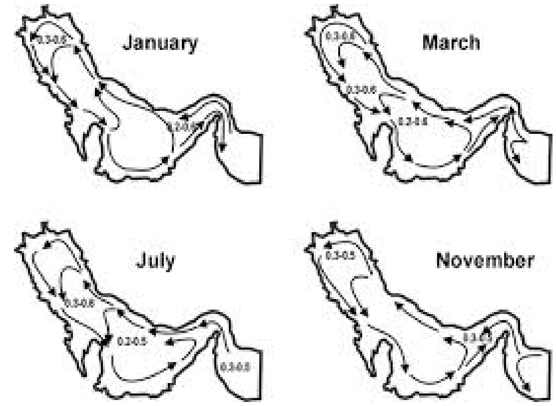

Fig. 4 — Pattern of general circulation in the Persain Gulf and Sea of Oman in four season[17]

Table 1 — The schemes for the ROMS model

Model components	Used parameters and methods
Boundary conditions	closed boundary in north, south and west, Gradient in east
Momentum equations	UV_ADV ,UV_VIS2,UV_LOGDROG
equation of state	TS_MPDATA
model setup	SOLVE3D , SPLINES
analytical setup	ANA_FSOBC, ANA_M3OBC, ANA_STFLUX, ANA_SSFLUX ، ANA_BPSLUX, ANA_BTFLUX ، ANA_SRFLUX
Vertical mixing of temperature, salinity and current	GLS_MIXING
Closure options for generalized length scale	KANTHA_KLAYSON,N2S2_ HORAVG

Results

Based on the results of simulations, pattern of sea surface temperature, salinity and current were analyzed. To verify the simulated parameters, satellite images were used.

Pattern of temperature fields

Zonal and meridian cross sections of Persian Gulf, Sea of Oman and Strait of Hormuz are shown in Figures 5 to 9. Figure 10 shows sea surface temperature pattern in February that indicates the warm water of Indian Ocean is moving from the northern part of Sea of Oman and through the Strait of Hormuz to the Persian Gulf. It can be seen that it produces a front in south east of the Persian Gulf. Two eddies can be seen in this region that move west of the Persian Gulf. Variation of temperature field in Sea of Oman is small and is close to that of the north Indian Ocean. Sea surface temperature in the Sea of Oman is about 24℃, and for the north of Persian Gulf it is about 18 ℃.

Figure 11 shows the meridian cross section of the western part of Sea of Oman near the Strait of Hormuz. The mixing layer is about 50 to 100 m in the region. The vertical decreasing of temperature started from 200m depth (about 22 °C) and continued to depth of about 700 m (10 °C). Sea surface temperature is about 22 to 24℃ and it reaches 6℃ in the deepest part (1400 m). It can be seen that isothermal layers from surface to bottom in the cross section are almost parallel and it may be the result of strong stability in the region.

Figure 12 shows sea surface temperature variations in May. In this example, warm water penetration from Sea of Oman to the colder water of Persian Gulf can be seen. The difference between temperature of northern and southern part in this month is more than that of February. In addition, difference of

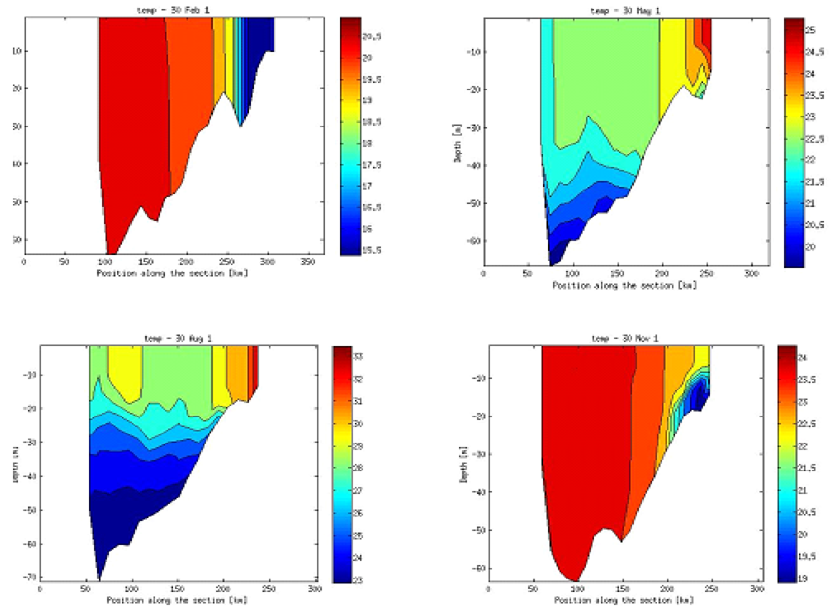

Fig. 5 — Meridian cross section of temperature in Persian Gulf for 4 months (4 seasons)

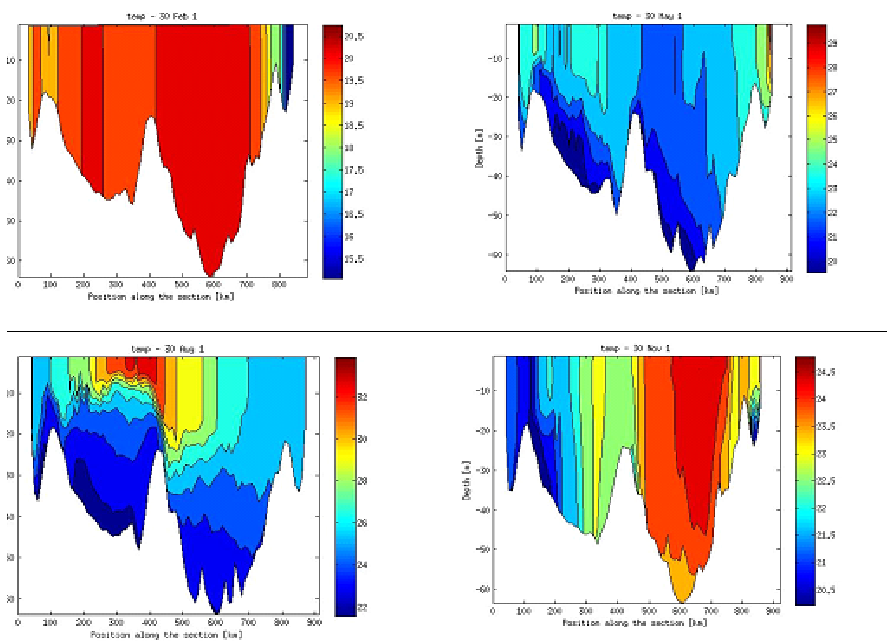

Fig. 6 — zonal cross section of temperature in Persian Gulf for 4 months (4 seasons)

temperature in different parts of Sea of Oman is smaller than that of the Persian Gulf. Temperature limits in this month is between 18 to 24 °C.

Patterns of the sea surface temperature in Persian Gulf and Sea of Oman during June are shown in Figure 13. Penetration of warm water from Sea of Oman into the Persian Gulf is extended and as it is seen, the current passes through Hormuz Strait (from the vicinity of Iran's boundary) towards the inner parts of the Persian Gulf. Generation of eddy at the entrance of Hormuz Straight towards the central parts of the Persian Gulf and its outflow into the North of Indian Oceannear coastal region of Oman is seen in the figure.

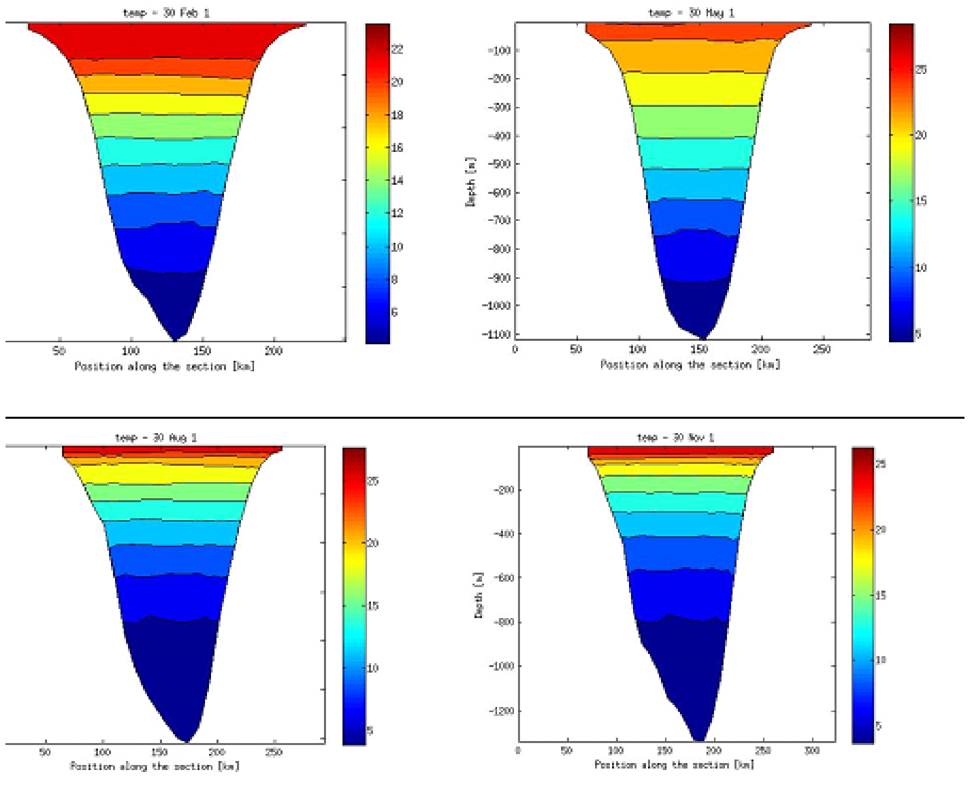

Fig. 7 — Meridian cross section of temperature in Sea of Oman for 4 months (4seasons)

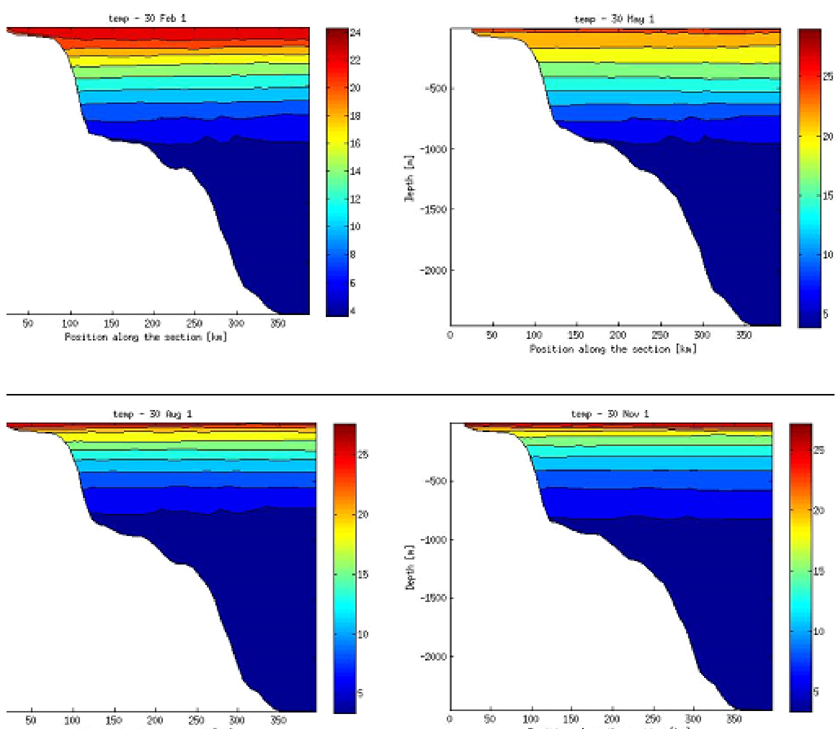

Fig. 8 — zonal cross section of temperature in Sea of Oman in 4 months (4 seasons)

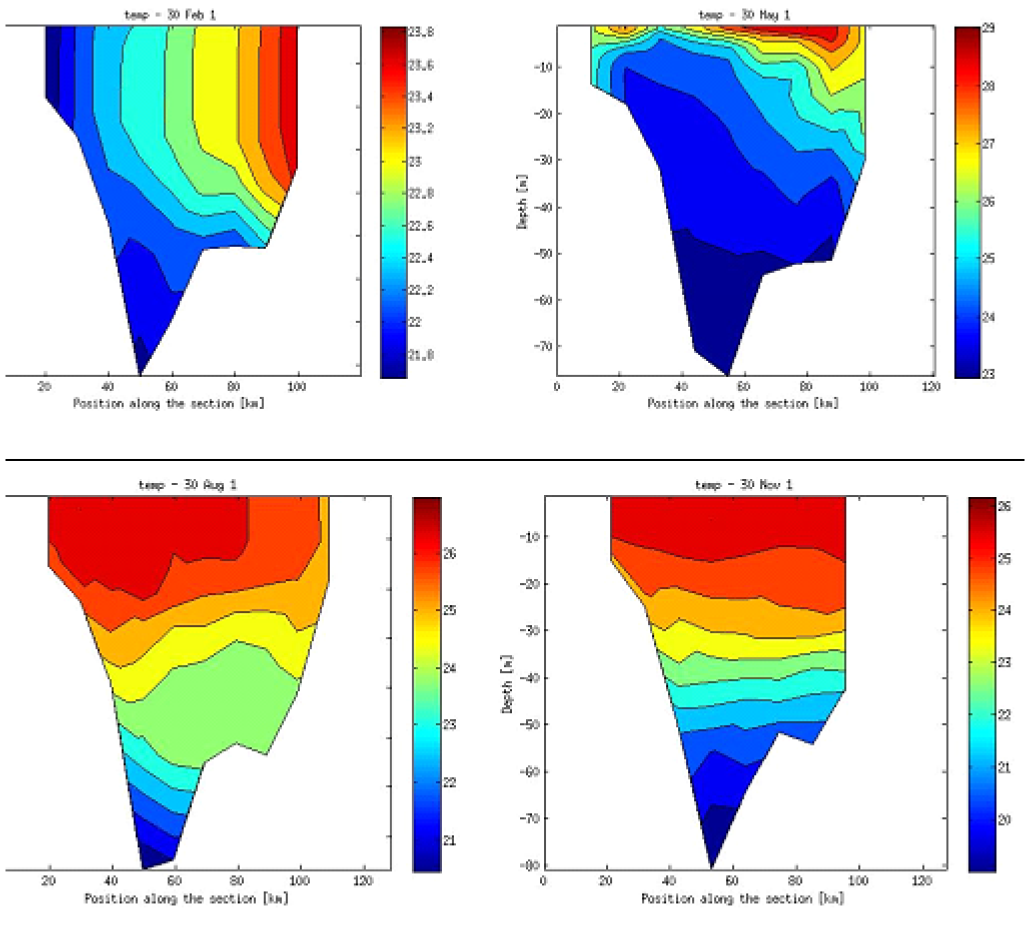

Fig. 9 — meridian cross section of temperature in Strait of Hormuz in 4 months (4 seasons)

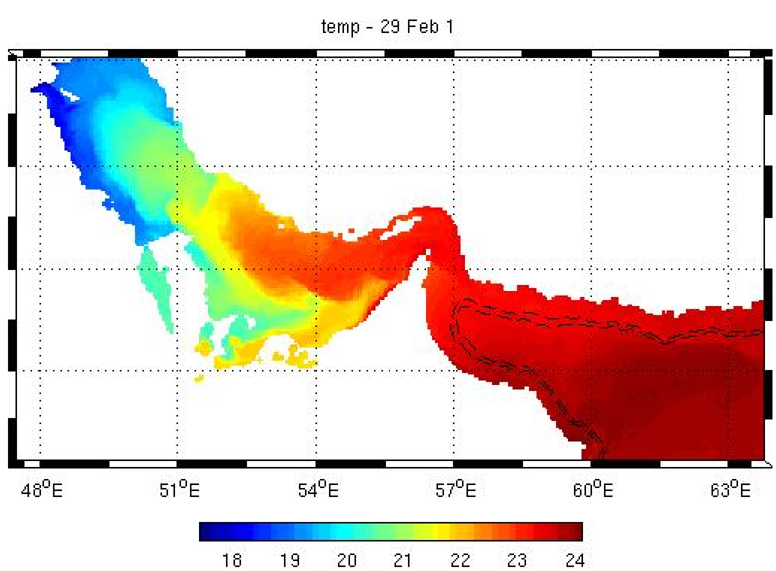

Fig. 10 — Sea surface temperature in Sea of Oman and Persian Gulf in February

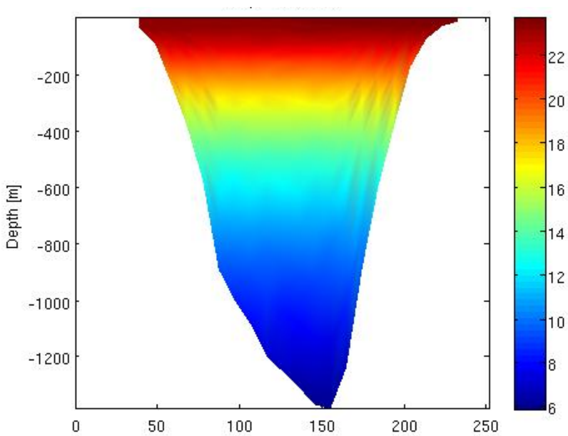

Fig. 11 — Meridian cross section of Sea of Oman near the Strait of Hormuz.

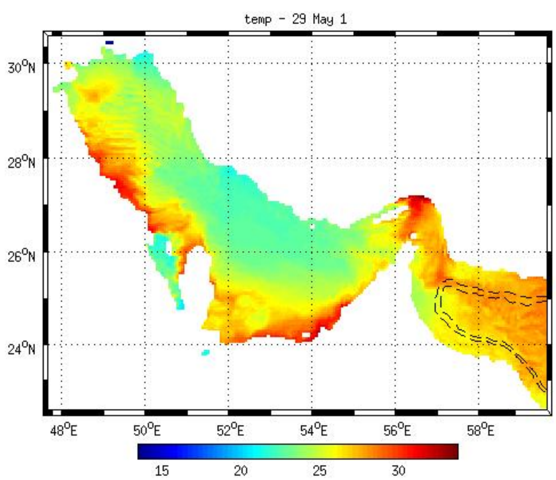

Fig. 12 — Pattern of sea surface temperature of Persian Gulf and Sea of Oman in may

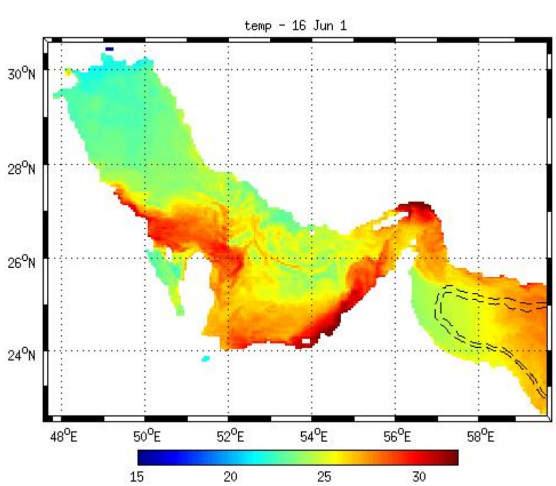

Fig. 13 — Sea surface temperature in Persian Gulf and Sea of Oman at June

-Pattern of salinity fields

Patterns of the sea surface salinity in Persian Gulf and Sea of Oman are shown in Figure 14. Maximum salinity was 40 PSU in Persian Gulf and minimum salinity in Sea of Oman was 35 PSU. In the figure low levels of surface salinity originating from Oman Sea into the Persian Gulf is seen near the Iranian coastal region. High salinity waters from the Persian Gulf towards the Sea of Oman is seen in southern part of the Strait of Hormuz and disappears after Strait of Hormuz that shows the sinking of the Persian Gulf outflow water into the lower layers in the strait and Oman Sea. The simulations of sea surface salinity in four months (four seasons) are shown in Figure 15. The temporal variation of salinity in four seasons is very small and it may be considered that the pattern of the sea surface salinity in the Persian Gulf and Sea of Oman has a negligible change.

-Pattern of surface currents

In Figure 16, patterns of surface currents are seen in Sea of Oman and Persian Gulf. The dominant current pattern in Sea of Oman shows a large eddy in the area linking the Sea of Oman to Indian Ocean and also a westward current in the northern part and an eastward current in the southern part of this sea. Also the dominant pattern of currents in Persian Gulf is an anticlockwise circulation with some meso-scale eddies in the central part of the Persian Gulf.

In Figure 17 patterns of surface currents in Sea of Oman and Persian Gulf are shown in May. Comparing with Figure 16, it is seen that current speed in eastern part of Sea of Oman in February is

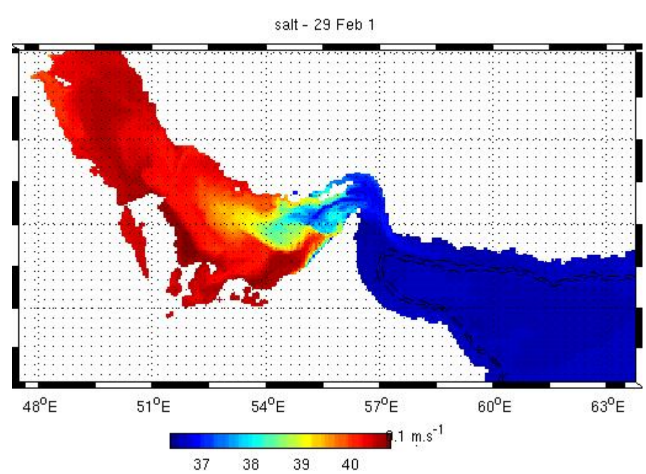

Fig. 14 — Pattern of sea surface salinity in Persian Gulf and Sea of Oman in February

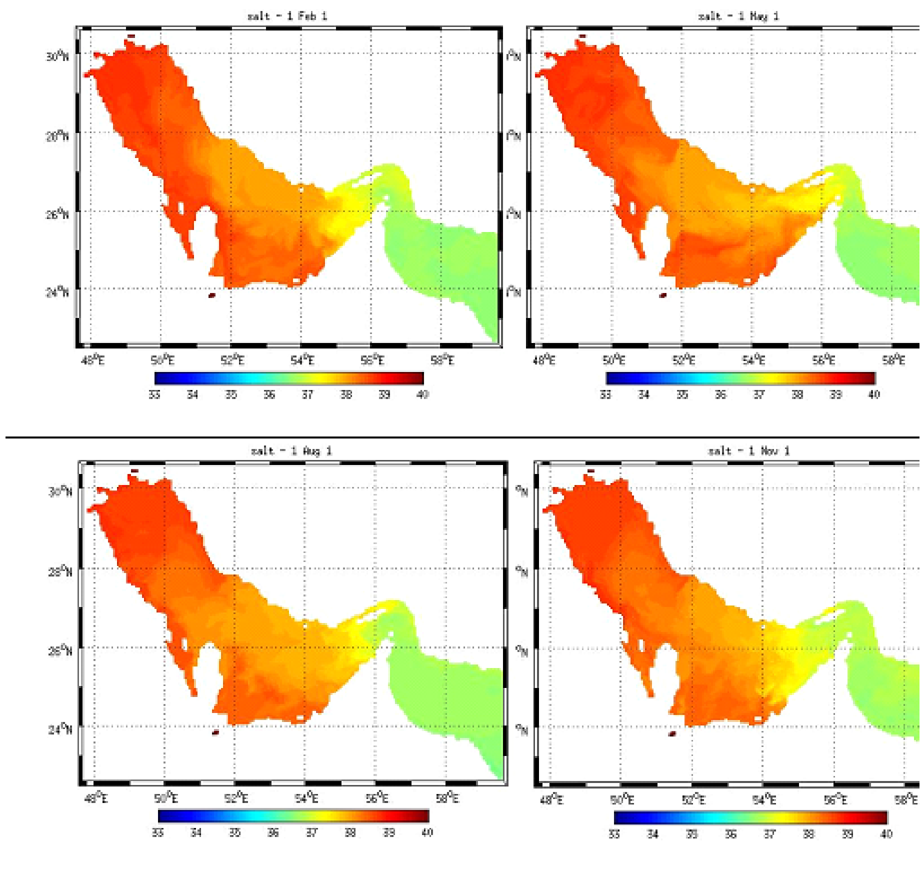

Fig. 15 — Pattern of sea surface salinity in Persian Gulf and Sea of Oman in 4 months (4 seasons)

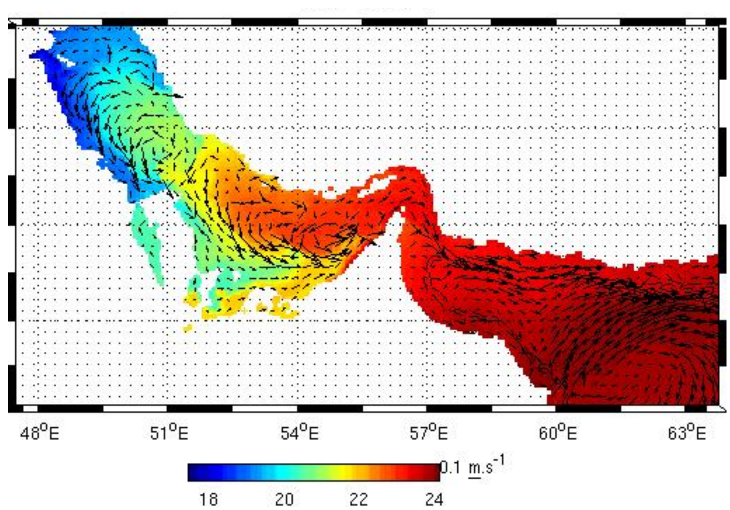

Fig. 16 — Pattern of surface current in February

more than the one in May. However the eastern pattern of surface current in February and May is almost unchanged. Two main eddies in the central and eastern part of Sea of Oman is obvious in these two figures. A similar surface current pattern is seen in Persian Gulf and it is similar to the pattern shown by Reynolds[9] (Fig. 2). Two main eddies are observed in the northern and central part of Persian Gulf in both of the figures and the current speed in May is lower than that in February.

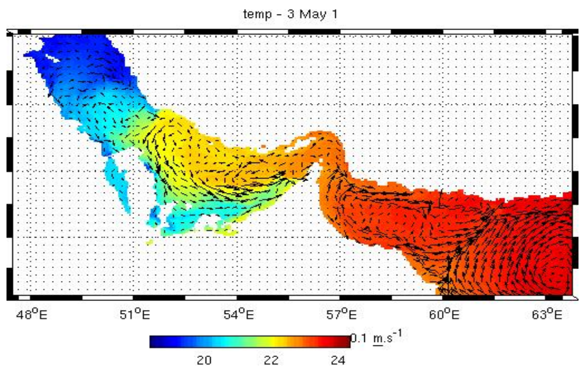

Fig. 17 — Pattern of surface current in Persian Gulf and Sea of Oman in May

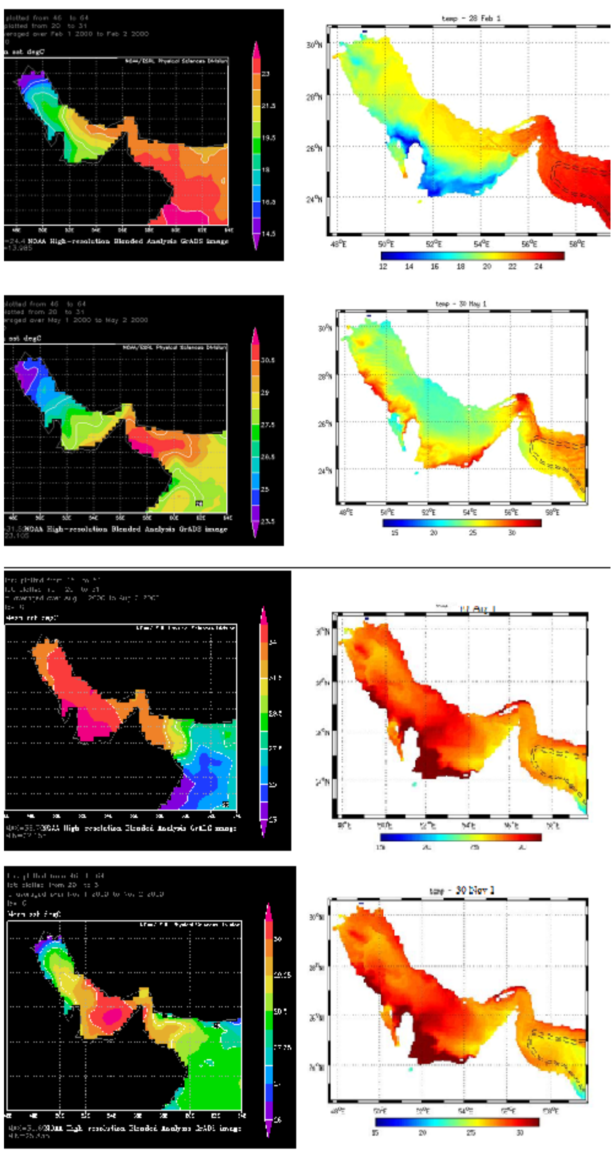

Fig. 18 — Sea surface temperature in Persian Gulf and Sea of Oman for 4 months (4 seasons) with corresponding satellite images

Discussion

To verify the results of the model, SST reanalysis data of NOAA for the year 2000 for the first days of the months were compared with the simulations of ROMS ocean model (Fig. 18). As it is seen, limits of temperature and pattern of isotherm lines in most of the month in satellite images and model simulations are in good accordance (with differences about 1-2 °C) and temperature differences during August and September in Persian Gulf and November and December in Sea of Oman can be seen.

Conclusion

Examination on temperature, salinity and current pattern revealed the qualitative result that exposed the lacking information of this study domain. The Patterns of temperature in Persian Gulf and Sea of Oman show movement of Indian Ocean waters to Persian Gulf trough the northern coasts of Sea of Oman and Strait of Hormuz. Model output exposed the formation of eddy in the Persian Gulf and Sea of Oman. Also consideration of temperature profiles in Sea of Oman show upwelling near the northern coasts of Sea of Oman. Patterns of salinity in the model simulations of for Persian Gulf and Sea of Oman show flow of saline water from the sub surface water of the Persian Gulf and through the Strait of Hormuz into lower depths of the Oman Sea. Pattern of surface current simulations in these basins are in accordance with previous study in this region. Higher resolution modeling are required to investigate more details of the currents, temperature and salinity fields in these basins.

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