2006-1897: RECENT HYDRODYNAMIC AND RECIRCULATION FINDINGS OF THE ARABIAN GULF

Walid Elshorbagy, United Arab Emirates University

Mir Azam, Chuden_Cti

Kouichi Taguchi, Chuden-Cti

Tetsuya Ichikawa, Chuden_Cti

tomohiko terasawa, Chuden_Cti

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Recent Hydrodynamic and Recirculation Findings of the Arabian (Persian) Gulf

The Arabian (Persian) Gulf is a strategic water carrier that overlooks major oil-reach gulf countries and transports most of the world traded oil. Understanding its water dynamics is therefore a necessary component for any environmental studies, coastal development projects, and oil pollution prediction models to be undertaken in the region. The current paper reports major findings of recent field observations and hydrodynamic modeling effort conducted in the Arabian Gulf. The field observations were obtained during a hydrographic survey conducted to measure the salinity and temperature in the southern shelf of the Gulf in summer and winter seasons. Salinity and temperature fields were developed to complement the physical data established from earlier studies. Hydrodynamic simulation of the Arabian Gulf was made using a three dimension rectilinear grid system with parallel layers and considering typical seasonal wind fields developed via combining Hellerman historical data with the new data recorded in the southern shelf. Model calibration was carried out via comparing the simulated results with observed levels and currents. The mean flow pattern was then studied by investigating the major factors contributing to the residual current. While the tide was found contributing little to the residual flow, the wind was found to generate strong currents along the coasts of Saudi Arabia and UAE.

Introduction

The Arabian (Persian) Gulf is an arm of the Arabian Sea located in the North-Temperate tropical margin and bordered by eight countries; Iran, Iraq, Kuwait, Saudi Arabia (S.A), Bahrain, Qatar, United Arab Emirates (UAE), and Oman (Figure 1). As these countries host more than 67% of the world oil reserve, the Arabian Gulf is considered one of the most strategic semi-closed seas in the world. The oil-related activities besides other development and anthropogenic activities represent a permanent and hazardous source of accidental oil spills and eventually major marine pollution problems. Carrying out oil spill forecasts, ecological modeling, and other relevant environmental studies n the Arabian Gulf should be based on sound and enough hydrodynamic data, most of which are scarce due to the limited conducted hydrodynamic studies.

A number of hydrodynamic studies conducted in the last decades have addressed the physical conditions of the Arabian Gulf [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15]. Out of a major research cruise study conducted on NOAA vessel Mt Mitchel in 1992, Reynolds[16] produced one of the most important and comprehensive studies addressing the Arabian Gulf Hydrodynamics. A number of physical and hydrodynamic issues were resolved and addressed by all aforementioned studies. However, several topics were still not fully understood and in some cases were variably presented and interpreted by different studies. Examples include the residual currents and their dominant contributing forces, the flow exchange with the Straits of Hormuz located along the northern eastern boundary of the Gulf, and the heat transfer processes and their effects upon the hydrodynamic simulation results. Such topics were further studied and evaluated by three recent studies[17], [18], [19]. The main objective of this paper is to briefly present and discuss the main findings and observations reported by those three recent studies.

Physical and Hydrographic Description

The Arabian Gulf is a semi-closed sea (Figure 1) extending over more than 1000 km along its axis and connected to the Arabian Sea through the Straits of Hormuz. The depths range between 10 and 90 m with an average depth of 35 m and with shallower areas toward the southern shelf and deeper areas toward the northern shelf.

Since the Arabian Gulf is located between the synoptic weather system of the mid latitude and tropical circulation (Hadley Cell), the descending air produces clear skies and brings about arid conditions. Perrone[5] reported that Shamal is the prominent wind blowing from northwest and occurs all around the year. The strong winter Shamal is known to attribute to the high winter evaporation whose mean rate ranges from 1.44 $m.yr^{-1}$ [2] to 5.0 $m.yr^{-1}$ [3].

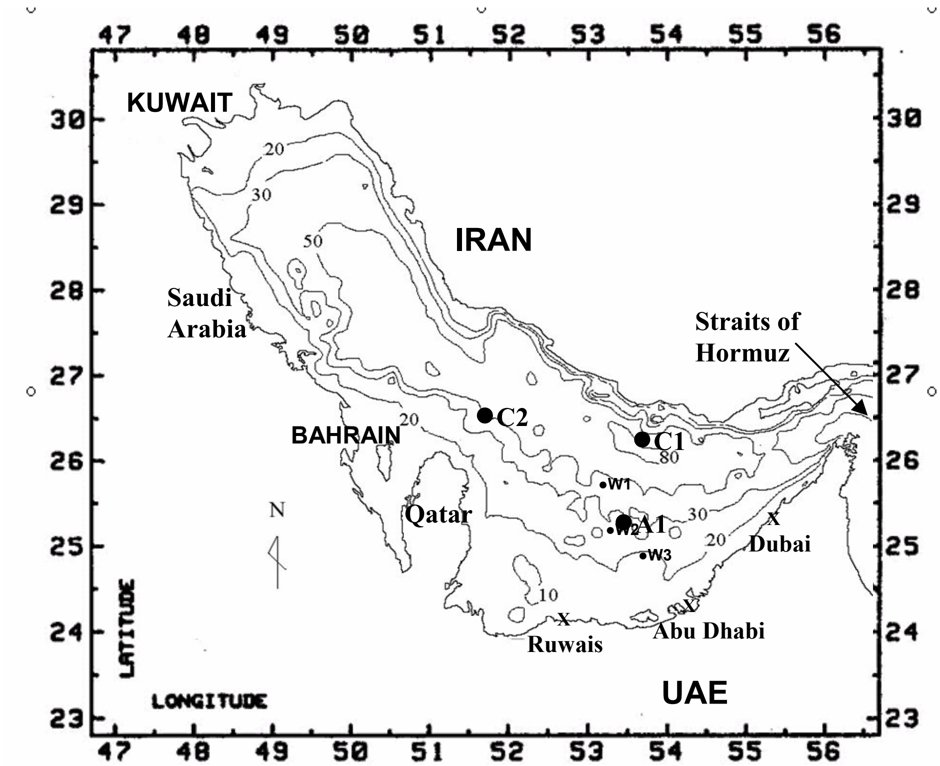

Figure 1. Geographic and physical features of the Arabian Gulf

Reynolds [16] published the most comprehensive salinity and temperature data for the Arabian Gulf obtained during the research cruise study conducted on NOAA vessel Mt Mitchel. Such data showed that the southern shallow areas have larger salinity with values mounting to 43 psu in the winter. Much less salinity prevails near the straits of Hormuz (36-38 psu) both in summer and winter. Winter salinity was generally higher by about 1-2 psu than summer salinity due to the higher winter evaporation rates. The summer temperature was reported as high as 30°C at the southern part while the winter temperature ranged between 15°C and 20°C.

In both summer and winter, the north part was relatively colder while a stratified bottom layer with higher salinity and colder temperature was observed especially in the summer.

Since Reynolds data did not extend downward to United Arab Emirates coast, a recent study[17] complimented these data by a set of data gathered in the southern shelf during 2003 for both summer and winter seasons. Such data showed the salinity near the southern shore gradually increases to as high as 45 psu in both seasons. The measured temperature was as high as 34 degree close to the shore in summer and decreased gradually offshore. Whereas lower temperature prevailed near shore during the winter and increased gradually offshore.

SIMULATION MODEL

The model used in recent simulations has been developed and verified in earlier works[20], [21], [22], [23], [24], [25]. It employs 3D multi-level and rectilinear-grid and comprises a system of equations that express the flow momentum, flow continuity, sea surface fluctuation and heat and salt transfer, in conjunction with equation of state.

The recent studies employ the hydrodynamic part of the modeling system that was originally developed as a part of a combined eco-hydrodynamic model. Hydrodynamic variables are obtained via solving the continuity, momentum and conservation of salt and temperature equations. Water is treated as a viscous incompressible fluid in a flow process that adopts a hydrostatic pressure assumption. The heat exchange calculation through the sea surface is done by including the contribution from the short term solar radiation, long term back radiation, the sensible heat flux, and latent heat flux. The turbulence conservation equations are used to compute internal kinetic energy transfer.

MODEL SETUP

A 5 km×5 km grid is employed in the developed model with 6 layers in the vertical direction and smallest thickness of 4 m at the surface. Four major tidal constituents (M2, S2, K1 and O1) at the Straits of Hormuz open boundary were obtained from Admiralty Tide Table[26] and used to drive and prescribe the sea-surface elevation. Water temperature, salinity and SGS kinetic energy density were also prescribed at the boundary as user-specified under the up-wind advective difference scheme. Depth-varying initial conditions of salinity and temperature were obtained from Mt. Mitchell Cruise data [16]. A constant bed friction coefficient was assumed (0.0026) and the horizontal eddy viscosity was set at 1.98×10^6 $cm^2.s^{-1}$. Heat flux parameters were obtained after consulting several references and after conducting comprehensive calibration tests [18].

For the wind fields considered in summer and winter simulations, typical and constant in time winds were based on combined data from two sources, Hellerman [27] and UAE Meteorology Department. The last 30 years of 106 available records of Hellerman wind data were averaged up and found adequate to develop typical seasonal conditions for the major portion of the Arabian Gulf except for the southern shelf. Recent records acquired by the Department of Meteorology, UAE, in the southern shelf were employed to provide typical wind representation in the southern shelf

MODEL CALIBRATION

Water Level

Water levels were measured using pressure sensor type gauges at Dubai, Abu Dhabi and Ruwais. These measurements were used in calibrating the developed model where close agreements between the simulated and the measured values at the three locations were obtained. Figure 2 shows the results for Abu Dhabi location. Moreover, the four tidal parameters were estimated at 15 locations and favorably compared with the predicted ATT values[18]. Slight disagreement occurs at the points in the east and west of the Qatar Peninsula where most of the K1 amplitudes were underestimated and the amplitudes of O1 constituent were overestimated.

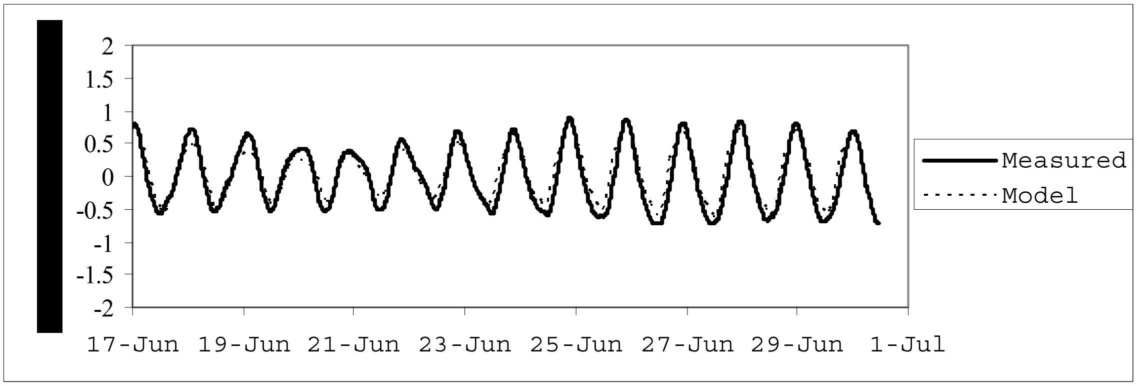

Figure 2. Measured versus simulated water levels at Ruwais (After Elshorbagy[18])

Currents

The simulated currents were calibrated and compared with measurements at three locations, A1, C1, and C2. Measurements of A1 location (northward and eastward components) were collected from NOAA. While the comparison at A1 and C1 locations were found reasonable for both magnitude and direction, some disagreements with measured data were noticed at C2. The non-inclusion of time dependent wind data in the present simulation may have contributed to such discrepancy.

Salinity and Temperature

Recent surveyed temperature-salinity data[17] were combined with the Mt. Mitchell data and used as initial conditions of selected simulations. Surface salinity and temperature distributions at the equilibrium of prognostic baroclinic simulations were obtained and compared with available observations. The comparison was quite reasonable especially the salinity results. Some discrepancy was reported in the temperature results in the southern basin where the new measurements were obtained. The simulated salinity in this region, in both summer and winter, is about 1 to 2 psu smaller than the observed values while the temperature is decreased by 1 to 3 ^{o}C. The non considered effluents of brine and warm industrial effluents may be contributing to the high observed salinity and temperature in this area, an observation still needs further verification.

Hydrodynamic Characterization

A semi-diurnal tide enters the Arabian Gulf through the Straits of Hormuz and travels faster along the Iranian side of the basin then reflects back from the northwestern boundary hitting the eastern side of the Qatar Peninsula. Higher diurnal tide ranges appear in some parts of the northern end of the Gulf and the eastern side of Qatar. The diurnal tides develop as a result of the combined tide waves entering from the eastern boundary and the one reflected back from the northwestern end. Snap shots of simulated water level and velocity field were produced for summer conditions at three-hour intervals [18] covering one day (June 9th, 2002). The plots explain how the tidal propagation affects the flow direction in different areas of the Gulf.

A Harmonic Analysis was conducted to show the distribution of amplitudes and phases of the four tidal constituents. Similar to results obtained from other studies[10], two semidiurnal amphidromes for M2 and S2 constituents develop; one in the northwestern part and one in the southern part near Ruwais. Diurnal tides prevail close to these amphidromes while semidiurnal tide prevails near the central basin in which a node of anti-amphidrome appears. Mixed diurnal and semidiurnal tides appear at the northwest and southwest ends of the basin. Comparison with Lradner results[10] indicates that the M2 amplitudes from the recent study have lower values and some degrees of phase lag. While S2 phase is found close to Lardner's value, its amplitude is slightly lower in the central and northern parts of the Gulf. The recent study shows lower amplitude for K1 in the northern part than the one showed by Lardner while the amplitude is damped near the UAE coast. A slight lag also appears in the K1 phase.

On the other hand, a power spectrum analysis conducted on water level data gathered on three locations (Dubai, AbuDhabi, and Ruwais) did not report consistent fluctuation so that the existence of a basin wide low frequency wave is not evidenced.

In terms of flow exchange with the Arabian Sea, surface influx and bottom outflow were observed through the open boundary of Straits of Hormuz during winter simulations. The surface influx was the result of local balance at the boundary, major evaporation losses in the basin, and the small amount of fresh supplies from the three northern rivers. The one-month simulated mean bottom outflow near the Straits of Hormuz was found 0.07 Sv. The simulated mean outflow rate resulted in a residence time of nearly 3.9 years for the gulf water that is about 8630 km^3 in volume. This value is close to the 5-year estimation of Hunter[7] but much larger than the value of 350-500 days calculated by Johns and Olson[14].

Residual Flow And Driving Forces

The net flow pattern of the Gulf was investigated by averaging the current field from 30 day simulation for summer and winter conditions. The combined wind field (Hellerman and recorded) was applied in a prognostic setup considering the combined temperature-salinity data (Reynolds and recent southern records) for the initial conditions. In general, the mean current tends to move southward except the eastern and southern coasts where it flows along the shoreline. The shallow shelf of the UAE is subject to strong wind-generated current in winter developing positive gradient of surface elevation towards the coast and generating downwelling current.

In terms of the driving forces contributing to the residual currents, four classes of simulation scenarios were investigated[19]: barotropic scenarios, de-tided density-driven scenarios, diagnostic baroclinic scenarios, and prognostic baroclinic scenarios. Some of the tested simulation scenarios were conducted with no winds, some with a constant wind field, and some with the typical combined wind field presented earlier.

For the barotropic simulations, very small mean currents were reported in the absence of wind forces indicating that the tidal force does not create significant residual flow. For the de-tided density driven scenario, the density field was adjusted during the summer simulation and wind was applied. Results showed the density gradient develops pronounced anticlockwise flow in the Northern Gulf. The denser water in the Saudi Arabian side of the Gulf started to sink at the beginning of the simulation and moved towards the west developing a front in front of the Qatar peninsula. This bottom flow generated a surface flow and produced a northwestward current in the central gulf and an anticlockwise current in the north. In winter, the density force developed a west flowing current from the Straits of Hormuz along the Iranian coast and a northern anticlockwise flow as well.

For the diagnostic baroclinic scenarios, summer and winter simulations were conducted without any wind forces to keep the density field undisturbed. The summer flow pattern was found similar to the one produced without tidal force at the boundary but with much weaker clockwise circulation. For winter case, a pronounced anticlockwise circulation was found in the north with relatively stronger flow along the Iranian coast and weaker flow along the Saudi Arabian coast. Very strong inflow was observed at the southern side of the Straits of Hormuz.

In terms of the prognostic baroclinic scenarios, summer and winter flow patterns were produced for three layers; the first top layer, the lower second layer, and the lower third layer to analyze the behavior of residual currents in vertical direction as well. This was done once with no winds applied and once with applying the typical combined wind field presented earlier. Summer simulation showed a major anticlockwise surface flow in the northern Gulf similar to the one reported by Lardner et al (1993) in their study with relatively coarser resolution model. Two mild circulations developed in the central Gulf, one was clockwise and one was anticlockwise. The clockwise circulation in the north of Qatar Peninsula was the main difference in results from what was found by Lardner et al (1993). Results did also show that residual flow significantly weakened in the lower layers. The prognostic simulation for winter condition produced surface flow similar to the diagnostic one but with intensified flow in the Straits of Hormuz and reduced velocity in the Northern Gulf. An out-flowing current was developed in deep layers as the heavier water sinks from the upper layers.

Including the wind forces in simulations showed that the wind field sensitively steers the current towards the south even when the summer or winter density forces are present. The effect of wind spreads up to the Straits of Hormuz in the summer. However, the density force dominates the current field close to the Straits of Hormuz in winter although the wind-driven current is much stronger. The wind-driven currents over power the density-driven currents at the surface layers while the opposite prevails for deeper layers.

Conclusions

Understanding the hydrodynamics of the Arabian (Persian) Gulf is a critical necessity for any environmental study needed in one of the most world strategic seas. This paper reports main results and findings obtained from recent studies conducted to enhance such understanding. The studies were based on comprehensive modeling that produced well calibrated water levels, currents, and salinity and temperature fields. Salinity and temperature data in the southern shelf close to UAE coast were obtained in these studies and incorporated in the modeling work. The results show that the entire Gulf is tidally active with no clear existence of a basin wide low frequency wave. The mean currents were found to be significantly affected by wind forces both in summer and winter. The inflow-dominated water exchange through the Straits of Hormuz compensates some of the water lost by evaporation. Residual flow becomes weaker and the surface circulations tend to disappear in deeper layers. The results did also show that the evaporative loss of water intensifies the mean current along the Iranian coast causing increased inflows from the Straits of Hormuz. The importance of incorporating the heat flux process for studying the physical dynamics of the Arabian Gulf was highlighted in recent studies.

Acknowledgment

Japan Cooperation Center, Petroleum (JCCP) sponsored the research work conducted in the recent studies undertaken at the United Arab Emirates University. The authors would like to acknowledge the great support received from ADPOC and ADMA-ADNOC Companies during the hydrographic surveys.

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