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3-D Comprehensive Hydrodynamic Modelling in the Arabian Gulf

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ABSTRACT

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A 3-D comprehensive hydrodynamic model in the Arabian Gulf was developed by employing the latest bathymetry data, multiple vertical layers, calibrated atmospheric conditions and tidal forcing, HYbrid Coordinate Ocean Model reanalysis data, as well as the spatial- and temporal- varying climatological data, including cloudiness, relative humidity, air temperature and net solar radiation. This 3-D comprehensive hydrodynamic model in the Arabian Gulf was extensively calibrated and validated across the whole Arabian Gulf for water levels, currents, salinity and temperature. Model results are in good agreement with measurements and satellite data. This newly developed model is proven to be capable of accurately simulating hydrodynamics and the climatology over the whole Arabian Gulf.

ADDITIONAL INDEX WORDS: hydrodynamics, modeling, heat flux, current, Delft3D.

INTRODUCTION

The Arabian Gulf and its coastal areas are the world's largest single source of crude oil, and related industries dominate the region. The rapidly increasing needs to explore, drill and transfer the oil and gas lead to a huge amount of acquisitions of high quality hydrodynamic data in recent years.

The Arabian Gulf is a semi-enclosed water area, and the local currents are related to other regions due to the dependent physics, e.g. wind or density gradient. Therefore, it is important to have a model to capably represent the hydrodynamics reasonably well over the whole Arabian Gulf. Currently, there is little work to adequately assess the performance of a hydrodynamic model over the whole Arabian Gulf, though there are plenty of studies on modelling hydrodynamics in Arabian Gulf over the last decade (e.g. de Graaff *et al.*, 2012; Elshorbagy *et al.*, 2006; Elshorbagy *et al.*, 2013; Elhakeema *et al.*, 2015; Pokavanich *et al.*, 2015). Furthermore, most of studies utilize the heat flux models by taking spatial-uniformly distributed climatology and monthly mean values. These assumptions neglect the daily, weekly and spatial variations, which are believed to be significant when the models are employed to forecast or study operational conditions. None of previous hydrodynamic models included the ocean circulating currents, salinity and temperature at the offshore boundaries, which are expected to be key important for better simulating the water exchanges at the entrance of Arabian Gulf.

In this study, a comprehensive 3-D hydrodynamic model was setup and implemented to study the hydrodynamics in Arabian Gulf. This model, incorporating HYbrid Coordinate Ocean Model reanalysis data and spatial- and temporal- varying climatological data, has been validated against collected measurements and satellite data across the entire Arabian Gulf.

METHODS

Delft3D-FLOW is an open-sourced hydrodynamic module, which calculates non-steady flow and transport phenomena under tidal and meteorological forcing, such as wind and air pressure, on a curvilinear, boundary-fitted grid. Delft3D-FLOW employs the sigma co-ordinate transformation in the vertical direction, which results in a smooth representation of the bottom topography. For significantly stratified flows, the z-layer methodology was utilized instead of sigma layer, to prevent extra diffusions.

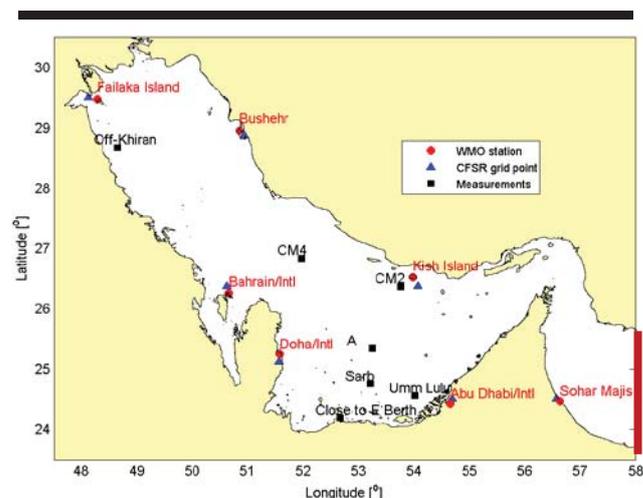


Figure 1. Overview of hydrodynamic model domain, selected WMO met-stations and collected measurement stations. Thick line represents the offshore boundary.

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Gulf of Oman (Figure 1). The grid resolution is around 3 km in both x- and y- direction.

The bathymetry data used in the present model was obtained by bi-linearly interpolating from samples extracted from Global Electronic Chart Database CM-93 Edition 3.0 provided by C-MAP Norway. The water depths were adjusted as relative to Mean Sea Level (MSL).

In Delft3D flow model, the Z-layer model has been used to solve the momentum equations on the vertical grid. In total 12 layers have been schematized. The vertical layer thickness varies with the depth and the number of active layers is constant.

In this study, the offshore boundaries were located in the Gulf of Oman, where the general water depths are larger than 1000m. Since the Arabian Gulf is dominated by the northwestern wind, the northwestern wind induced surge levels at the offshore boundary (in Gulf of Oman) are not relevant to surge levels inside Arabian Gulf. It was decided to apply tidal levels, salinity and temperature along water columns at the offshore boundary.

The temporal- and spatial- varying salinity and temperature data along the water depths were extracted from the Hybrid Coordinate Ocean Model (HYCOM) Global 1/12° reanalysis datasets, for initial conditions and boundary conditions of the hydrodynamic model. The temporal- and spatial- varying atmospheric forcing in Delft3D flow model made use of hindcast data sourced from the American National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis. In the Iraqi marine water, the temperature and salinity distribution is heavily dominated by the influx of the Shatt Al-Arab River. Therefore, in this study the river discharge and salinity data in Al-Mahdi *et al.* (2009) were employed in the model.

The hydrodynamic model was forced with the comprehensive heat exchange ‘Ocean model’ of Delft3D-FLOW by applying temporal- and spatial- varying climatological data (6-hourly), including relative humidity, cloudiness, air temperature and net solar radiation. These data were also sourced from the American NCEP Climate Forecast System Reanalysis. The effective back radiation and the heat losses due to evaporation and convection are computed by the model. The evaporation and precipitation are computed from the heat flux model. According to the model calibration results, the Stanton number and the Dalton number were both set to 0.9e-3.

RESULTS

The employed CFSR wind data were compared against observations at the closet WMO meteorological stations, where the latter is believed to better represent the local wind features, *e.g.* sea/land-breezes, wind direction variation due to land frictions, etc.. Figure 1 demonstrates the selected WMO meteorological stations. Comparisons of wind speed at 10 m above ground between CFSR and observations show that CFSR agrees reasonably well with observations across the whole Arabian Gulf, being only slightly underestimated. Based on comparisons, the wind speeds over the whole Arabian Gulf had been increased by 7.5%. Results also show that the wind directions of CFSR data are in good agreement with observations.

For tidal model calibration, predicted tidal levels at 10 tidal stations were extracted from the DTU10 global ocean tide model

at a resolution of 0.125° x 0.125°. Figure 2 presents the comparison of final amplitude and phase of constituent K1 in the model against those of predictions extracted from DTU10 global ocean tide model respectively. Results show that the dominant tidal constituents by Delft3D hydrodynamic model agree well with those from DTU10 global ocean tide model. Small differences at a few of local stations can be observed. These differences at local stations are probably due to different sources of the local bathymetry, different bottom resistance and so on.

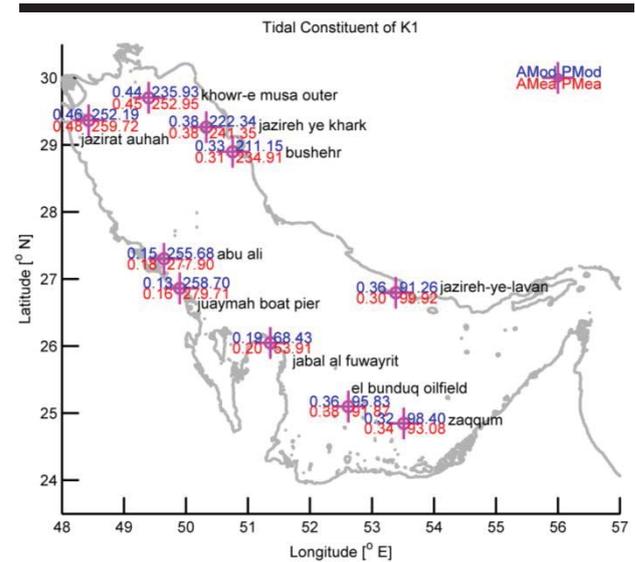


Figure 2. Comparisons of selected tidal constituents between modelled data (amplitude AMod in m and phase PMod in degree) and predicted tidal elevation (amplitude AMea and phase PMea) from DTU10 global tide model.

Table 1. Calibrated tidal constituents at the offshore boundary of the flow model.

Name	Amplitude [m]	Phase [degree]	Name	Amplitude [m]	Phase [degree]
Q1	0.04	351.7	NU2	0.04	173.5
O1	0.45	320.3	M2	0.99	128.8
K1	0.83	326.6	L2	0.02	210.9
P1	0.23	333.5	S2	0.31	169.7
N2	0.16	170.4	K2	0.06	211.8

The calibrated tidal constituents for astronomic tidal forcing are described in Table 1. These constituents were applied at the offshore boundary of the hydrodynamic model to represent the tidal forcing. In this study, long-term tidal constituents, *e.g.* SSA, SA, were not included, but it is necessary for the multiple years’ tidal level prediction in order to consider the seasonal or yearly variations.

For the purpose of the model validation processes, multiple measured data sets have been collected from previous studies. These measurements are distributed over the whole Arabian Gulf for validating the overall performance of the hydrodynamic

model. Stations where measurements were collected in previous studies were listed in Table 2 and Figure 1.

Table 2. Overview of stations where measurements were collected in previous studies.

Station	Longitude [deg]	Latitude [deg]	Depth [m]	Data Source
A	53.245	25.345	22m	Elshorbagy <i>et al.</i> (2006)
CM2	53.761	26.374	94m	Elshorbagy <i>et al.</i> (2006)
CM4	51.976	26.840	69m	Elshorbagy <i>et al.</i> (2006)
Off-Khiran	48.646	28.669	23m	Pokavanich <i>et al.</i> (2015)
Close to E Berth	52.675	24.205	16m	Elshorbagy <i>et al.</i> (2013)
Sarb	53.208	24.767	16m	de Graaff <i>et al.</i> (2012)
Umm Lulu	54.013	24.570	23m	de Graaff <i>et al.</i> (2012)

Pokavanich *et al.* (2015) presented measurements obtained from recent research activities at Kuwait Institute for Scientific Research (KISR). There are data from three locations consisting of a-month-long time-series data at Off-Khiran station in summer 2011. Figure 3 shows that water levels modelled by the present hydrodynamic model agree well with measured ones. This indicates that tidal levels and wind induced surge levels are well reproduced.

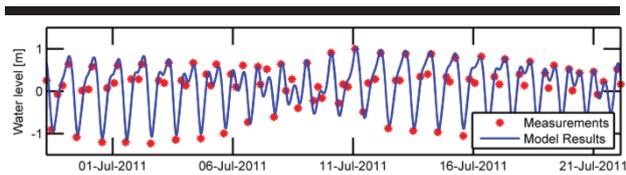


Figure 3. Comparison of water level between model data and measurements at Off-Khiran shown in Pokavanich *et al.* (2015)

In the northern Arabian Gulf, Pokavanich *et al.* (2015) also presented the northing current velocity at Off-Khiran station. The measured current velocity were used to validate the current hydrodynamic model. Figure 4 shows that the hydrodynamic model well reproduced the northing current at this location.

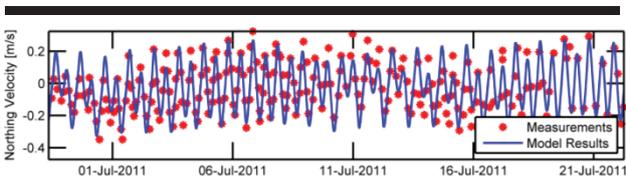


Figure 4. Comparison of northing current velocity between model data and measurements at Off-Khiran shown in Pokavanich *et al.* (2015)

In the coast of UAE, Elshorbagy *et al.* (2013) presented 3 days' field observations collected in 2002 at the station Close to E Berth, where the water is rather shallow, and the topography is complicated. Figure 5 presents the comparisons of current components between model results and measurements. It shows that both modelled eastward and northward velocities are in

good agreement with measurements. Although the modelled eastward velocity is slightly underestimated (showing an offset), the phases of current velocities well match those of measurements, indicating that the dominant tidal physics are well captured. This is a distinct improvement from those shown in Figure 16 of Elshorbagy *et al.* (2013).

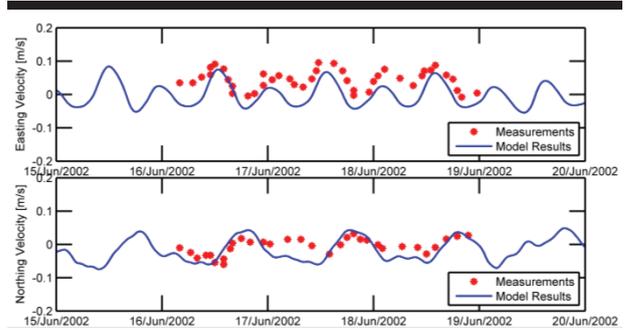


Figure 5. Comparison of current velocity between model data and measurements at Close to E Berth in Elshorbagy *et al.* (2013)

In the middle part of Arabian Gulf, where the water depths are generally larger than 20m, the modelled current speed and direction were validated against measurements by the NOAA (National Oceanic and Atmospheric Administration) research vessel Mt. Mitchell (shown in Elshorbagy *et al.*, 2006). Figure 6 to Figure 8 show comparisons of current velocity between model data and measurements at the stations of A, CM2 and CM4. Results by the hydrodynamic model are in good agreement with measurements, in both magnitudes and phases. For instance, Figure 8 shows that the modelled current magnitudes capture most of peaks, and the current directions align with the measured ones. The hydrodynamic model also shows a good performance to simulate the phenomena from mixed tides to semi-diurnal tides at this location.

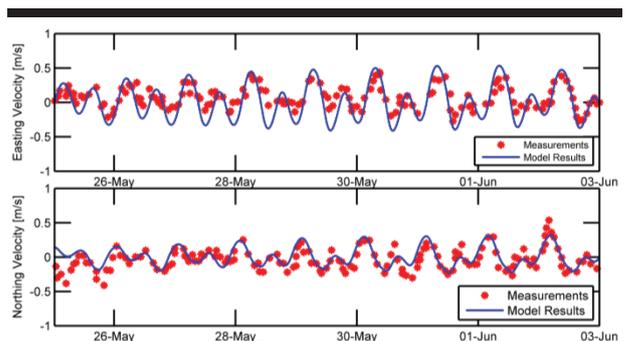


Figure 6. Comparison of current velocity between model data and measurements at A shown in Elshorbagy *et al.* (2006)

In the southern part of Arabian Gulf, de Graaff *et al.* (2012) presented comparisons of current velocities between their model data and measurements at stations of Sarb and Umm Lulu. These measurements were used here to assess the performance

of the hydrodynamic model in this region. Figure 9 shows that current speeds calculated by the model agree well with measurements at stations of Sarb and at Umm Lulu described in de Graaff *et al.* (2012), though the hydrodynamic model slightly overestimates current speeds at these two locations.

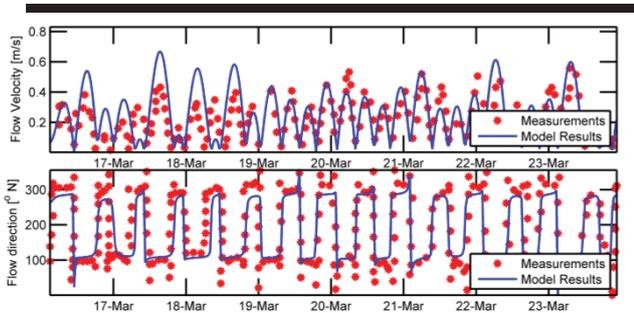


Figure 7. Comparison of current velocity between model data and measurements at CM2 at 15m below MSL shown in Elshorbagy *et al.* (2006).

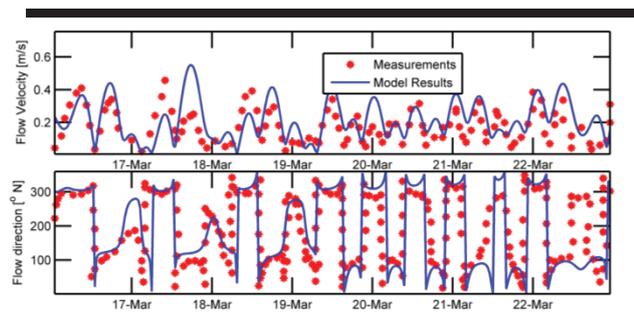


Figure 8. Comparison of current velocity between model data and measurements at CM4 shown in Elshorbagy *et al.* (2006).

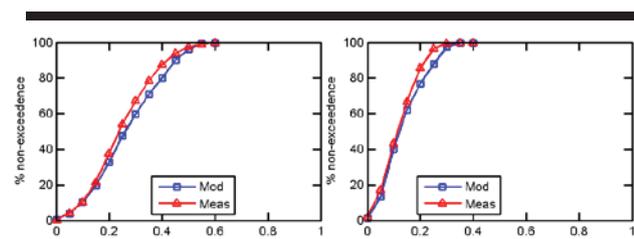


Figure 9. Comparison of current velocity between model data and measurements at Sarb (left) and at Umm Lulu (right) shown in de Graaff *et al.* (2012).

In this study, comparisons of monthly averaged sea surface salinity between model data and satellite data, sourced from World Ocean Atlas 2009 (WOA09, Antonov *et al.*, 2010), concluded a good agreement along the principal axis of Arabian Gulf.

NOAA High-resolution Blended Analysis for sea surface temperature (Reynolds, *et al.*, 2007) were employed to validate the sea surface temperature in the present hydrodynamic model. To model surface heat exchange, Delft3D-FLOW Ocean Heat Flux Model is used (Deltares, 2014). This model requires

temporally varying data on air temperature at 2 m height, cloud cover, relative humidity and wind speed and direction. The solar radiation were specified directly to assist calculations of the total heat flux.

Figure 10 presents comparisons of sea surface temperature between model data and satellite data. By initializing the surface temperature in the model with the satellite data on 29th Dec 2008, the surface temperature calculated by the model still agrees reasonably well with satellite data after 1.5 months. There are some deviations in the coastal regions of the western Arabian Gulf, where the model data has cooler temperature than satellite data. This may be due to the coarse resolution of atmospheric and climatological data, leading to excess cooling in these coastal regions due to the significant land effect. In order to verify the importance of the heat flux model in the hydrodynamic modelling, Figure 10 also displays the surface temperature at 15th Feb 2009 without considering the heat flux modelling. It is clear that the surface temperature is completely wrong if no heat flux model was used in the hydrodynamic modelling.

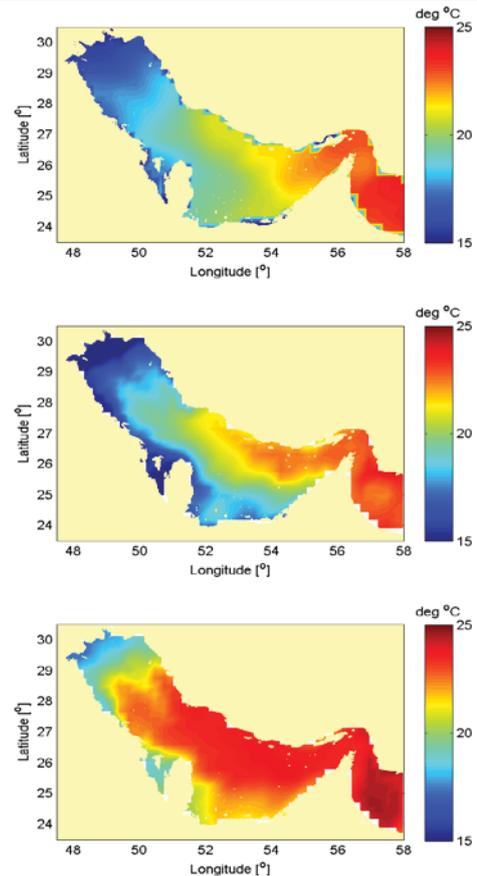


Figure 10. Comparison of sea surface temperature between model data and satellite data. (top) Satellite data at 15th Feb 2009; (middle panel) model data with heat flux model at 15th Feb 2009; (bottom panel) model data without heat flux model at 15th Feb 2009.

DISCUSSION

Table 3 and Table 4 present a summary of errors statistics between model results and measurements at selected stations. The correlation coefficients are good at certain locations with relatively regular currents. Once the currents become irregular, e.g. CM2 in Figure 7 and CM4 in Figure 8, correlation coefficients get low. This, however, may relate to the deviations in data digitization, where the accuracy of calibrations depends on the resolution of figures presented in publications. The irregular currents at CM2 and CM4 are due to combinations of significant water depth and density gradients, strong residual currents due to the surface winds from the northwest and varying tidal patterns. There are no time series data available at stations of Sarb and Umm Lulu, hence it is not possible to derive the statistics.

Table 3. Statistics of current velocity errors (model - measurements)

	Eastward				Northward			
	Corr.	Bias (m/s)	Std (m/s)	rmse (m/s)	Corr.	Bias (m/s)	Std (m/s)	rmse (m/s)
Off-Khيران	-	-	-	-	0.78	0.06	0.17	0.18
Close to E Berth A	0.79	-0.04	0.02	0.05	0.69	-0.01	0.03	0.03
	0.82	-0.05	0.16	0.16	0.72	0.04	0.11	0.12

Table 4. Statistics of current velocity errors (model - measurements)

	Magnitude				Direction			
	Corr.	Bias (m/s)	Std (m/s)	rmse (m/s)	Corr.	Bias (°)	Std (m/s)	rmse (°)
CM2	0.62	0.04	0.13	0.13	0.5	-3.5	95.4	95.2
CM4	0.53	0.05	0.11	0.12	0.4	-4.2	116.9	116.6

Among previous researches of hydrodynamic modelling in Arabian Gulf, there are no statistical data available regarding the performance of each model. Therefore, in this study, there are no direct comparisons between the present model and previous ones. However, comparing this work (Figure 3 to Figure 9) to others, modelled currents in this study are in good agreement with measurements, in certain cases proving that the present model is, better than or at least comparable with, previous models for simulating hydrodynamics. Particularly, this is the first time that one specific hydrodynamic model was well validated against measurements and satellite data over the whole Arabian Gulf.

Besides the adequate assessment of hydrodynamics over the whole Arabian Gulf, this study also presents model calibrations on tides and wind speed over the whole Arabian Gulf against available data, e.g. observations. This further enhances the reliability of the present model.

Another distinct feature is that this study incorporates the spatial- and temporal- varying climatological data, consisting of cloudiness, relative_humidity, air_temperature and net solar radiation, to compute the heat flux. Modelled sea surface temperatures agree well with measurements in most areas of Arabian Gulf after a relatively long period. Further study would be needed to better simulate heat convection and heat diffusion near the coasts.

Furthermore, the present model makes use of the HYCOM reanalysis data at the offshore boundary together with the tidal forcing. This feature is to ensure the completed physical processes at the entrance of the Arabian Gulf, and thus could help improve the accuracy of water exchanges through the Strait of Hormuz.

CONCLUSIONS

A comprehensive 3-D hydrodynamic model in the Arabian Gulf was developed by employing the latest bathymetry data, multiple vertical layers, calibrated atmospheric conditions, HYCOM reanalysis data, and spatial- and temporal- varying climatological data. This comprehensive 3-D hydrodynamic model in the Arabian Gulf was extensively validated for water levels, currents, salinity and temperature. This newly developed model is proven to be capable of simulating hydrodynamics and the climatology in the whole Arabian Gulf accurately, considering the vast water area and the asymmetric bathymetry.

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