Changes in Flow hydrodynamics over the Gulf under a Changing Climate

H. Shirkhani, A. Mohammadian & O. Seidou
Department of Civil Engineering, University of Ottawa

Abstract
The main objective of this paper is to model the flow hydrodynamics over the Gulf for the next decades with consideration of the climate change. The large scale triangular finite volume C-grid scheme was implemented in a large scale hydrodynamic model of the Gulf. The large scale model is validated using the observed water levels at WAKRAH and UMMSAID. Then, by employing the developed positivity preserving well-balanced central-upwind scheme the flow over a local coastal area along the Qatar coast is simulated. The outputs of the large-scale model are used as the boundary conditions for the local hydrodynamic model. Downscaled wind speed under different RCP scenarios are also used as an input into the local flow model. The results of flow field under the climate change can be implemented for a wide range of practical applications, from mixing of industrial outfalls to designing and maintaining coastal structures.

1 INTRODUCTION
Prediction of flow hydrodynamics over gulfs and estuaries is of essential importance and has many practical implementations. Indeed, evaluation of the effect of climate change on the flow field through the short, medium and long term is a requirement for a wide range of practical applications [1-5]. This study proves the applicability of the developed models in [6-9] for evaluation of flow hydrodynamics under changing climate. To this end, we consider the Gulf as an area of interest. As one of the most important climate variables which affects the flow field, we consider the wind speed to be projected within the future time spans. In line with this goal, we use the developed Quantile-Quantile downscaling method [6] to predict the wind speed over the coastal areas of Qatar. We use the historical data at the Doha International Airport together with the various GCM outputs under different RCP emission...
scenarios to develop the downscaling method. Later, we use the results of the projected wind speeds as an input to the flow models. In order to model the flow field in a large-scale, we employ the developed finite volume triangular C-grid in combination with the Leap-Frog time stepping technique [7-8]. The historical water level data is used as the boundary condition and also for validating the flow model. The results of the large scale model (water level) will be used as boundary condition for the local model.

Finally, we use the developed quadrilateral central-upwind scheme in [9] to simulate the flow hydrodynamics along the coastal area of Qatar. Fig. 1 shows the area of interest for both large-scale and local model. The results of flow models can be implemented for many practical applications.

![Fig. 1 - The study area over the Gulf. Large and small rectangles represent the domains of large-scale and local flow models, respectively.](image)

2 CLIMATE CHANGE MODEL: WIND SPEED

In order to consider the impact of climate change on the flow hydrodynamics, we consider the changes of wind speed, as one of the most important variables in deriving the flows and waves on estuaries. To this end, the Quantile-Quantile downscaling method, described in [6], is used to project the wind speed over the Qatar coastal areas. A multi-model multi-scenario approach has been employed to take into account the uncertainties associated with the GCM outputs. Since the area of the study is located along the Qatar coastal areas, we use the historical wind speed data at the Doha International Airport to project the wind speed. The results of the future wind speed can be directly implemented into the flow models as the wind stress in the shallow water equations. Since this part of the study intends to proof the
applicability of the developed models, we use the results of the predicted daily wind speed under the RCP85 scenario of the ensemble average model.

3 LARGE-SCALE FLOW MODEL

Various dispersion relations and Fourier analyses were used to investigate the behaviour of the triangular finite volume C-grid in combination with different time-stepping methods [7-8]. The various analyses were performed for both short fast gravity and slow long Rossby waves. Both of these flows are of essential importance and an appropriate numerical model should be capable of modelling them.

The C-grid scheme in [7-8] showed the ability to preserve the symmetric shape of different waves, and there is no significant damping associated with the results. The results demonstrated that the scheme is capable of simulating both short fast gravity waves as well as long slow waves. Various source terms such as Coriolis force, surface wind, bed shear stress and uneven bottom topography terms, which are very important in practical applications, were considered in the momentum equation through a number of numerical experiments, and the results were satisfactory. Both the linear and non-linear behaviour of the numerical scheme were also examined, and the scheme performed well in both cases [7-8].

We consider the shallow water equations with the Coriolis force, wind stress, bottom friction and bottom topography terms in the momentum equation, see equations:

\[
\frac{\partial \eta}{\partial t} + \frac{H}{A_i} \sum_{j=1}^{3} U_j d_j = 0
\]

\[
\frac{\partial u}{\partial t} + f v n_x - f u n_y + g \frac{\partial \eta}{\partial n} = \tau - \xi u n_x - \xi v n_y
\]

where \( \eta \) stands for the surface elevation, \( u \) and \( v \) are the components of the depth-averaged velocity vector \( \mathbf{u} = (u, v) \) in the \( x \) - and \( y \) -directions, \( f \) is the Coriolis parameter, \( g \) is the gravitational acceleration, \( H \) is the reference depth of the water, \( \tau \) is the surface wind stress vector and \( \xi \) is the bottom drag coefficient.

The bed friction terms are estimated by \( \tau_{bx} = \rho C_f u \sqrt{u^2 + v^2} \) and \( \tau_{by} = \rho C_f v \sqrt{u^2 + v^2} \) where \( C_f \) is an empirical coefficient based on bed roughness. We use the following equation based on the Chezy friction law:
\[ C_f = \frac{g}{C^2} \]

where \( C \) is the Chezy friction coefficient. In order to estimate the wind stress \( \tau = (\tau_x, \tau_y) \), we use the following equation:

\[ \tau_x = \rho \gamma V^2 \cos \psi \quad \text{(2)} \]
\[ \tau_y = \rho \gamma V^2 \sin \psi \quad \text{(3)} \]

where \( V \) is the wind speed, \( \gamma \) is the wind stress coefficient and \( \psi \) is the wind direction.

As the final step, we employ the triangular finite volume C-grid scheme to simulate the flow over the Gulf. Fig. 2 shows the unstructured triangular grids used for the large scale model. All the basin walls are closed boundaries except for the vertical boundary at the right side of the domain, which is an open boundary. We use the measured water level values at this boundary. The wind stress coefficient \( \gamma \) and Chezy friction coefficient \( C \) as the calibration parameters were considered. Using the available observed data of water level at UMMSAID, we calibrate the large scale flow model.

Fig. 2 - Unstructured triangular grids generated for the large-scale flow model. The vertical open boundary is shown at the right of the domain.
The calibrated parameters are found to be $\gamma = 5 \times 10^{-6}$ and $C = 70$. In Fig. 6.3, the computed water level is compared to the observed values at UMMSAID for a 15-day period from 2010-05-14 to 2010-05-29. As it can be seen, there is a good agreement between the computed and observed data.

Now, we implement the calibrated large-scale model to predict the flow hydrodynamics over the Gulf for the year 2016. As for the boundary condition, since the information of water level is limited to the observed historical data, one needs to use appropriate projected water level values for year 2016. As a matter of fact, there are many possible ways to extrapolate the available historical data through the time. For instance, one can perform a trend analysis on the historical data of the water levels. However, since this is not in the scope of this study, we use the results of analysis performed by Sultan et al. (1995) [10] on sea level over the Gulf. They reported the increase of $0.21 \text{ cm/yr}$ for mean sea level. Therefore, we shift the available water level data of year 2014 by $0.42 \text{ cm}$ and use it as the boundary condition in the large scale flow model.

We also use the bathymetry data for the Gulf and consider the topography term in the momentum equations. Fig. 4 shows a sample of results of the water elevation as well as velocity field over the Gulf.
The water surface and velocity components of the solutions can be employed as the boundary condition of the local model.

![Image](Fig. 6 - Results of the large-scale flow model within year 2016. Surface water elevation (m) (left) and velocity vectors (m/s) (right))

4 LOCAL FLOW MODEL

Finite volume schemes are useful tools for modelling shallow water equations. Finite volume upwind schemes denote a class of finite volume numerical discretization methods that take into account the direction of propagation of information in a flow field. The main advantage of the central upwind schemes is that they are Riemann solver free and no characteristic decomposition involved in the scheme. They are also high resolution, due to the smaller amount of the numerical dissipation. Moreover, they have an upwind nature, since they respect the directions of wave propagation.

We now employ the developed well-balanced positivity preserving central-upwind scheme for unstructured quadrilateral grids in [9] to locally simulate the flow over the Qatar coastal area. We generate a fully unstructured quadrilateral mesh grid for the selected domain which is shown in Fig. 5. As can be seen, all the basin boundaries are closed walls except for one horizontal and one vertical open boundary.
Fig. 5 - Unstructured quadrilateral grids generated for the local coastal model. Open boundaries are represented by the red lines at the top and left of the domain.

We apply the results of water level over year 2016 from the large-scale model as the boundary condition at the open boundaries. Beside the wind stress term, we also consider the uneven topography changes and bed friction terms. We use the same calibrated values, as the large scale model, for the bed friction and wind stress coefficients. A sample results of water depth and velocity field are presented in Fig. 6.

Fig. 6.6 - Results of the local flow model within year 2016. water depth (left) and velocity vectors (right)
By simulating the flow over the Gulf under the changing climate, one can evaluate the changes on the flow hydrodynamics. We now consider the flow hydrodynamics over a 1-month period in year 2012 and evaluate the changes under the climate change for the same month in year 2016. For year 2012 the historical daily wind speeds are used while in year 2016 the projected daily wind speeds are employed. In order to have a range of possible changes in flow hydrodynamics, the results of wind downscaling under two different RCP scenarios (RCP26 and RCP85) are used. The results are presented in Fig. 7 and Fig. 8 for three different points through the local coastal domain. Fig. 7 compares the time series of water surface elevation at different points for January 2012 and 2016. Comparing the results of year 2012, which are computed using the historical wind speeds, to those of year 2016, which estimated by using projected wind speeds, one can evaluate the changes in the water surface elevation. The figure shows that the use of various RCP scenarios will result in a different water level time series. For instance, at the second point (Fig. 7-middle), RCP85 and RCP26 hold different results at most times. Indeed, RCP85 predicts higher water elevation than RCP26. Note that the effect of climate change will not be the same through all the domains. As can be seen in Fig. 7 (top), under both RCPs, the results of projected water level is almost the same as the historical one, while this is not the case in the other two points.
Fig. 7 - Comparison of computed time series of water level elevation at three different points through the local domain.

Fig 6.8 shows the monthly statistical distribution of the waves at three different points. Again, the results of wave height under climate change in year 2016 are compared with those of 2012. This graph shows that the wave climatology at first point does not significantly change in year 2016. However, in the two other points some changes are observed. It can be seen that at the second point, the wave height under RCP26 and RCP 85 decreases and increases respectively compared to the historical one. Based on the definition, one may also extract the significant wave height (as the wave height of the highest third of the waves) from this graphs. Generally, it can be concluded that under RCP26, the significant wave height does not change while it increases under RCP85. It should be noted that one may use the proposed methodology for a longer time span and evaluate the short, medium and long term effect of the climate change on the flow characteristic, which is beyond the scope of this study.
5 CONCLUSION

The objective of this study was to simulate the flow over the Gulf under the changing climate. To this end, first, we have come up with the projected wind speed under the climate change. Second, we used different developed numerical schemes in [6-9].

In order to consider the climate change impacts on the flow condition over the coastal area of the Gulf, the wind speed as the main climate variable which affects the flow and wave fields has been considered. A multi-model multi-scenario approach was employed to project the wind speed over the Qatar coastal areas. Indeed, we have used three different models from CMIP5 experiments under various RCP scenarios. This allows us to take into account the high uncertainties associated with the general circulation models.
Fig. 8 - Monthly statistical wave distribution at three different points under various RCPs.

We employed the Quantile-Quantile method which performs better prediction, particularly for extreme events.

In regards with the numerical scheme for solving shallow water equations, we also used the finite volume unstructured C-grid scheme in combination with the Leap-Frog time stepping method in [7-8]. The triangular C-grid scheme also showed ability to preserve the symmetric shape of different waves while there is no significant damping associated with the results. The results demonstrated that the scheme is capable of simulating fast gravity waves as well as long slow waves, which play an essential role in transferring the energy. Various source terms such as surface wind, bed shear stress and uneven topography terms were considered in the momentum equation.

In order to consider the climate change impact, we considered the projected wind speed as the surface wind stress term in the shallow water equations. We simulated the flow over the Gulf under the changing climate. The water surface and velocity components of the solutions can be employed for many practical purposes.

ACKNOWLEDGEMENTS

This publication was made possible by NPRP Grant 4-935-2-354 from the Qatar National Research Fund (a member of the Qatar Foundation). The statements made herein are solely the responsibility of the authors.

REFERENCES


