# THREE-DIMENSIONAL HYDRO-ENVIRONMENTAL CHARACTERIZATION AND MODELING OF THE NORTHERN ARABIAN GULF

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A three-dimensional integrated hydrodynamic and water quality model of the Arabian Gulf has been developed in this study based on the hydrodynamic modeling program Delft3D. The model was forced by seasonal estimated discharges from all major rivers, validated tidal constituents, time- and depth-varying offshore boundary conditions, measured meteorological data and time- and space-varying wind and atmospheric pressure. The model performs well, especially when comparing results with measured coastal data in Kuwait, situated at the northwestern part of the Arabian Gulf. Simulation results suggests strong short-term dynamics and long-term seasonal variation of hydrodynamic and water quality processes of the Arabian Gulf including its northwestern part. It was pointed out from the results that the northwestern part of the Arabian Gulf has a strong dependency on river discharges and meteorology. Although only preliminary water quality modeling has been done in this study, results indicated relevant general characteristics of some water quality parameters and its great dependencies on forcing data.

*Keywords: Arabian Gulf; hydrodynamic; water quality; numerical modeling; Delft3D*

## INTRODUCTION

The Arabian Gulf (AG), also known as the Persian Gulf and Inner ROPME sea area, is a shallow semi-enclosed hypersaline sea surrounded by desert countries (Figure 1). The length of the AG is approximately 1000 km and the width is approximately 370 km. It has a surface area of around 239,000 km2 (Emery, 1956). The average depth of the AG is about 35 m. Extensive shallow areas of the AG are found along the eastern and southern coasts while deeper areas are found along the Iranian coasts. The main deep valley of the AG has depth reaching 100 m lining from a 56 km narrow strait (the Strait of Hormuz) to the northern part of the AG. Northern part of the AG (between latitude 28-30 degree north) is shallow with average depth 26 m. Kuwait terrestrial waters situated at one of the inner-most regions of the AG has average depth about 12 m and maximum depth about 30 m. The mouth of the AG has maximum depth of 110 m. There is no significant sills in the strait. The depth of regions beyond the AG's mouth drop very quickly to more than 2000 m within 200 km into the Gulf of Oman.

Surrounded by desert countries (i.e., Bahrain, Iran, Iraq, Kuwait, Qatar, Saudi Arabian and United Arab Emirates) the meteorological climate of the AG is extreme and being characterized as one of the harshest on Earth. The AG has very hot summers and moderate winters. Average low and high temperatures in Kuwait City are 30.7 and 46.9 $^{o}$C in the summer and 8.5 and 13.5 $^{o}$C in the winter. Precipitation is very low with yearly average of 22 mm. Winds are predominantly from the northwesterly through-out the year but with highest frequency in the summer. Southeasterly winds, usually hot and humid, are common between July and October. In the occasion of strong wind, dust storms are common.

The AG is hyper-saline water body and experiences large seasonal variations of water temperature between 13 $^{o}$C to 35 $^{o}$C. Except some very stagnant shallow regions (e.g., Gulf of Salman situted between Bahrain and Qatar) where salinity levels reach up to 70-80 ppt (http://cdn.intechopen.com/pdfs-wm/20140.pdf), general salinity of the AG waters varies between 38 ppt around offshore regions close to the Strait of Hormuz to 50 ppt around shallow regions along the eastern and southern coasts of the AG. The water circulation of the AG is inverse-estuarine governed generally by salinity gradient resulted from excess evaporation over river runoff and precipitation (Reynolds, 1993). Tide governs general short-term movement of water in the AG while long-term general residual circulation is related to the combined effect of tide-averaged residual currents, wind-induced currents, density-driven currents and currents to compensate for excessive evaporation. Previous studies (e.g., Kampf and Sadrinasab, 2005; Yao and John, 2010; Pokavanich and Al-Osairi, 2013) also mentioned that the water circulation feature of the AG is coupled result of the wind-driven

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and thermohaline-driven flow, complex meso-scale eddy fields, and constricted water exchange with the open ocean. Our on-going studies also indicated that some estuarine circulations dominates small regions at major river mouths (i.e., Shatt Al-Arab river, Hendijan river, Hilleh river and Mand river) situated at northern and northwestern end of the AG.

Despite its geopolitical significance, the AG has not received adequate attention and there is a limited systematic monitoring, knowledge sharing, understandings related to physical and biochemical oceanographic processes, integrated and cumulative impacts studies for coastal development by surrounding countries of the AG. One of the reasons is an absence of general tool in which the physical & water quality processes with their cumulative impacts can be investigated. The objective of this study is to develop a numerical tool to promote better studies and integrated planning among the surrounded countries. A better understanding of these processes is required if academic community aims at studying the physical behavior of the hydrodynamics and water quality in the AG, including for the example transports and dispersion of sediment, nutrients and other water-borne pollutant that are increasingly being discharged in to the water due to human/industrial activities. This paper presents the development of a three-dimensional hydro-environmental numerical model for the AG using a coupled hydrodynamic model (Delft3D-FLOW) with a water quality (biochemical) model (Delft3D-WAQ). Results of the three-dimensional Arabian Gulf Model (3D-AGM) will be used to characterize important hydrodynamic and the water quality features of the gulf with a special focus its northern part.

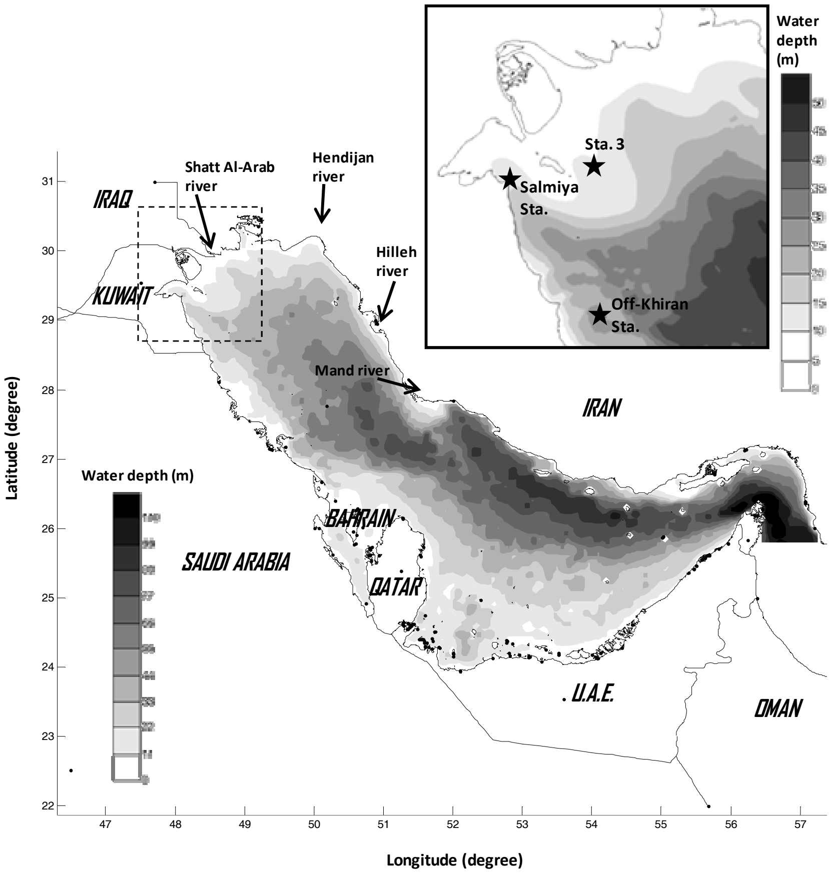


**Figure 1 Map of the Arabian Gulf, its surrounding countries, bathymetry and main rivers. Inset figure shows locations of marine field measurement station in Kuwait.**

## FIELD MEASUREMENT

Various kinds of physical and biochemical data used in this study result from research activities at Kuwait Institute for Scientific Research (KISR), Kuwait. At Salmiya station, long-term water level and water temperature were measured at 30 minute interval by a HOBO-Water Level Logger (Onset Inc., USA). Two weeks water level, flow velocity, water temperature were measured using a 600 kHz Teledyne RDI's Sentinel Acoustic Dropler Current Profiler (Teledyne RD Instrument, USA) at 10 minute interval and salinity was measured by a SBE 19plus V2 SeaCAT (Sea-Bird Electronics, USA) at 10 minute interval at Off-Khiran Station. Depth-averaged (between 0-1 m from water surface) water temperature, salinity data between 2011-2012 period were derived from measured CTD profiles at Station 3. The profiles were measured using a multi-parameter water quality sonde AAQ-1183 (Alec Electronics, Japan). Locations of all the measurement station are given in Figure 1. This study also compared simulated results with gulf-wide interpolated water temperature and salinity data from the Mt. Michell Expedition (Reynolds, 1993)

## HYDRODYNAMIC MODELING

The 3D-AGM hydrodynamic model was developed by means of the Delft3D-FLOW software (Deltares, 2011a). The model had a horizontal resolution of 1/20th degree and consisted of 10 sigma layers in the vertical. The 3D-AGM incorporated realistic combined effects of tide, meteorology and offshore boundary conditions. The thicknesses of the vertical layer from the surface to the bottom respectively are 5, 5, 5, 10, 10, 10, 10, 15, 15, 15 % of the total water depth. Finer layers near water surface is plan to take into account important the wind-driven currents. Bathymetry data was derived from digital nautical charts and local surveys. The 3D-AGM was forced by offshore validated astronomical tidal constituent set suggested by the Deltares, The Netherland derived by its previous studies. Seasonal varying river discharge from the Deltares, The Netherland derived by its previous studies and from literatures. The wind forcing was based on time- and space-varying wind data from ECMWF ERA-Interim model (http://data-portal.ecmwf.int/data/d/interim_daily/). Offshore boundary condition applies time and depth varying water temperature and salinity from MyOcean model - GLOBAL_ANALYSIS_PHYS_001_003 model (http://www.myocean.eu/web/38-modelling.php). Heat flux exchange at water surface applied meteorological data from measured weather data at Doha Airport, Kuwait Airport and from KISR meteorological station. Wind drag coefficients are linear function at 0.0006 and 0.0027 for wind speed at 0 m/s and 25 m/s, respectively. Bottom roughness was set to Manning coefficient 0.02 $m^{-1/3}s$. Constant horizontal eddy viscosity at 5 $m^2/s$ and constant horizontal eddy diffusivity at 10 $m^2/s$ were applied. Vertical eddy parameter applied k-epsilon model with $10^{-6}$ background values. The model was run for the period 2011-2012 at a 10 minute time-step. The model started from uniformly distributed water temperature (20 $^oC$) and salinity (38 ppt). The 2011 simulation was run for 1 time for model spin-up, to ensure that the hydrodynamics were in a dynamic equilibrium. Subsequently, the resulting space-varying distribution of water level, flow velocity, water temperature and salinity were applied as a realistic initial condition for the actual 2011 simulation. The 3D-AGM hydrodynamic model was calibrated and validated against field measured data from Kuwait waters. Figure 2 shows comparison between measured data and simulated results of the 3D-AGM forced by meteorological data from KISR weather station. Figure 3 and Figure 4 compare between gulf-wide simulated and measured results (Reynolds, 1993) in terms of water temperature and salinity, respectively. The figures suggested that the 3D-AGM model can reproduce general short-term dynamic and seasonal variation of all key hydrodynamic parameters.

## WATER QUALITY (BIOCHEMICAL) MODELING

The Delft3D-WAQ software (Deltares, 2011b) was used to develop a 3D water quality model of the Arabian Gulf. The model incorporated the major biochemical processes aimed at producing general characteristics of the key biochemical parameters, i.e., diatom phytoplankton and inorganic sediment distribution effecting light availability in the water column. The model computes the mass budget of phytoplankton (DIATOM), inorganic suspended sediment (SEDIMENT), detritus (DETRITUS), nitrate (N-NO3), ammonium (N-NH4) and phosphate (P-PO4). It is worth mentioning that the SEDIMENT has no direct effects on nutrients level, however the SEDIMENT has direct effects on light attenuation process. Figure 5 shows a structure of the water quality model in this developed in this study. There are several reactive processes in the mass budgets calculation; i.e. production and mortality of DIATOM, nutrient (N-NO3, N-NH4, P-PO4) assimilation of DIATOM from production, direct nutrient release from DIATOM mortality, production of DETRITUS from DIATOM mortality, production of N-NH4, P-PO4 from DETRITUS mineralization, production of NO3 from N-NH4 nitrification, sedimentation of DETRITUS, DIATOM, and SEDIMENT, light attenuation in the water column affected by availability of DIATOM, DETRITUS, SEDIMENT, salinity level and background extinction coefficient. Full descriptions of the involved processes can be found Deltares (2011b). For computational efficiency, the grid from hydrodynamic model was aggregated, resulting in grid dimensions 194x132x5. As the basis for transport of substances the water quality model uses the hydrodynamics calculated by the hydrodynamic model. Water quality model parameterizations are based on literatures and previous studies (Al-Yamani et al., 2004; Al-Osairi et al., 2011; Deltares, 2011b; Pokavanich and Al-Osairi, 2013). Some parameters were derived from sensitivity runs of the present study. General setup of the water quality model are given in Table 1.

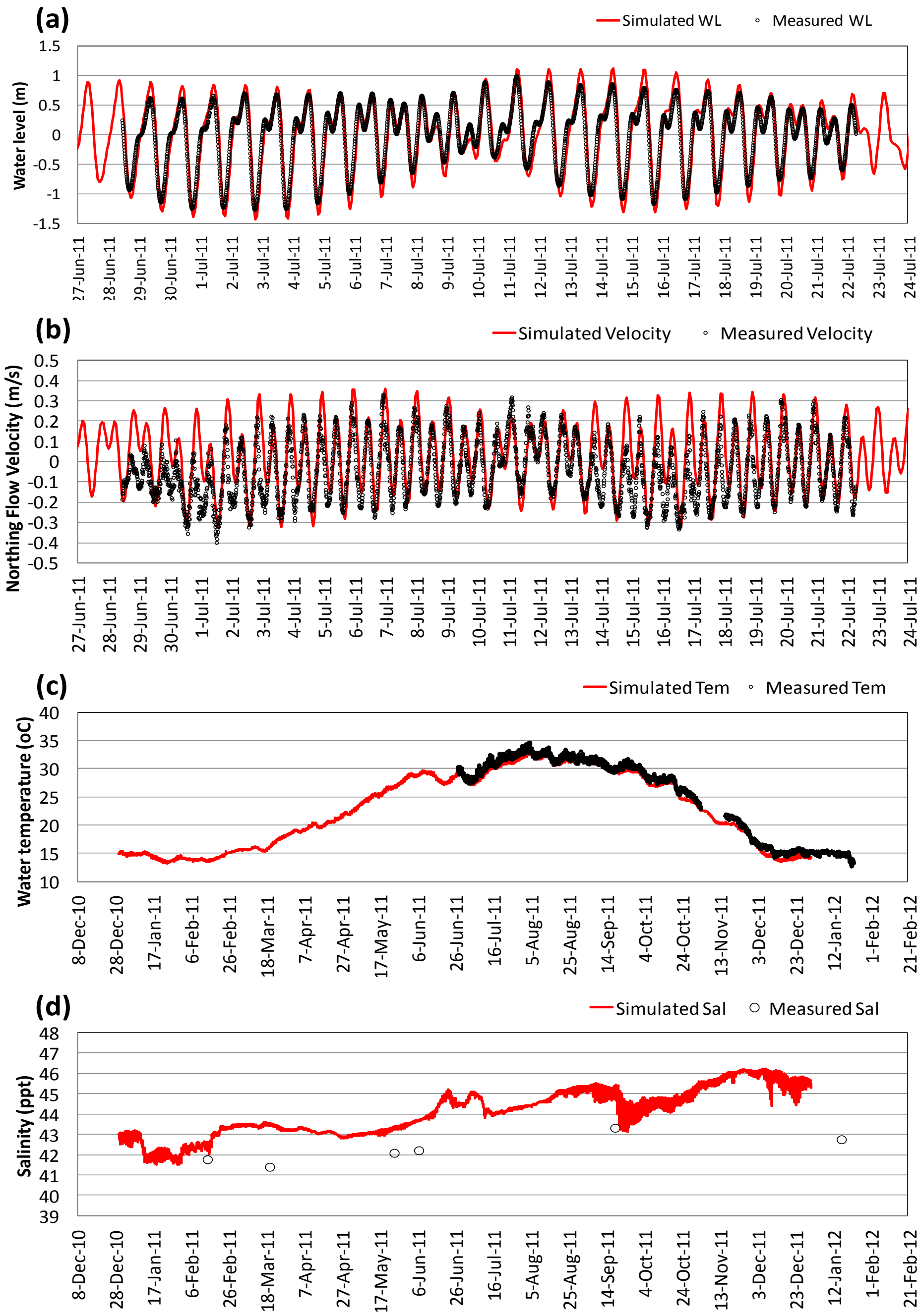


**Figure 2 Comparison between measured field data and simulated results of 3D-AGM hydrodynamic model showing in terms of measurement at (a), (b) Off-Khiran station, (c) Salmiya station and (d) Station 3.**

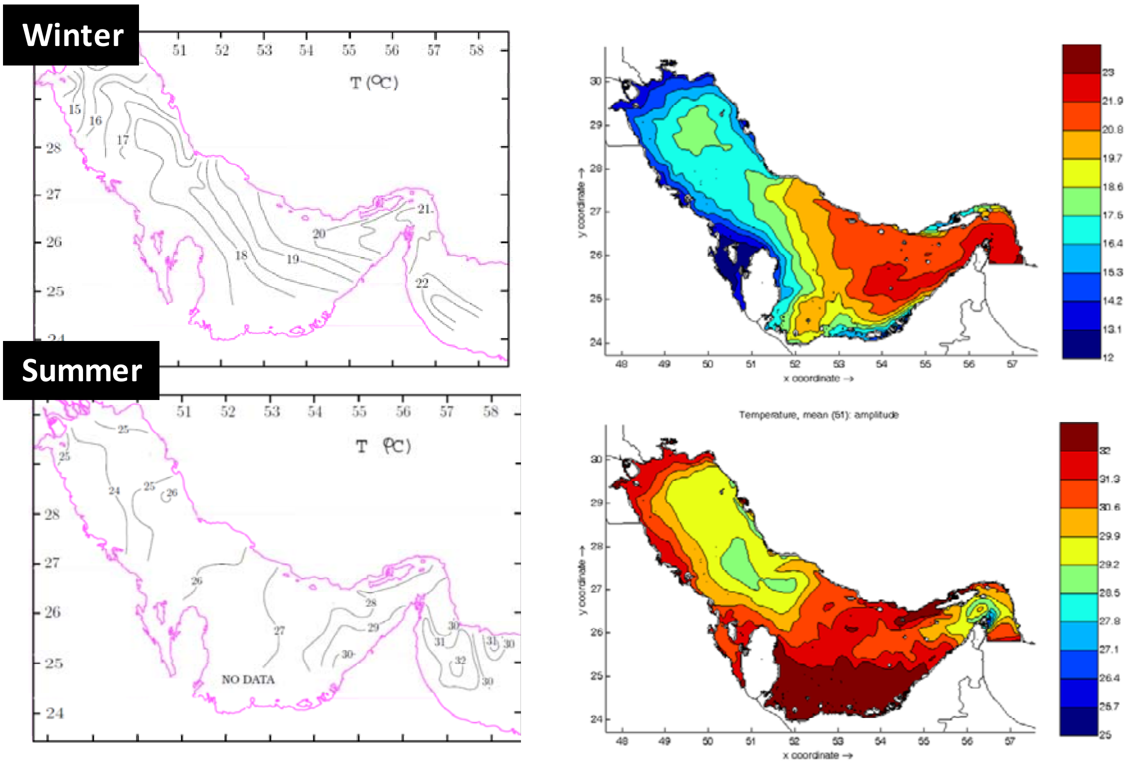


**Figure 3 Comparison of gulf-wide winter and summer water temperature distribution between the 3D-AGM simulated results and Reynolds (1993). Simulations show mean value between Nov-Dec-Jan for winter and June-July-August for summer.**

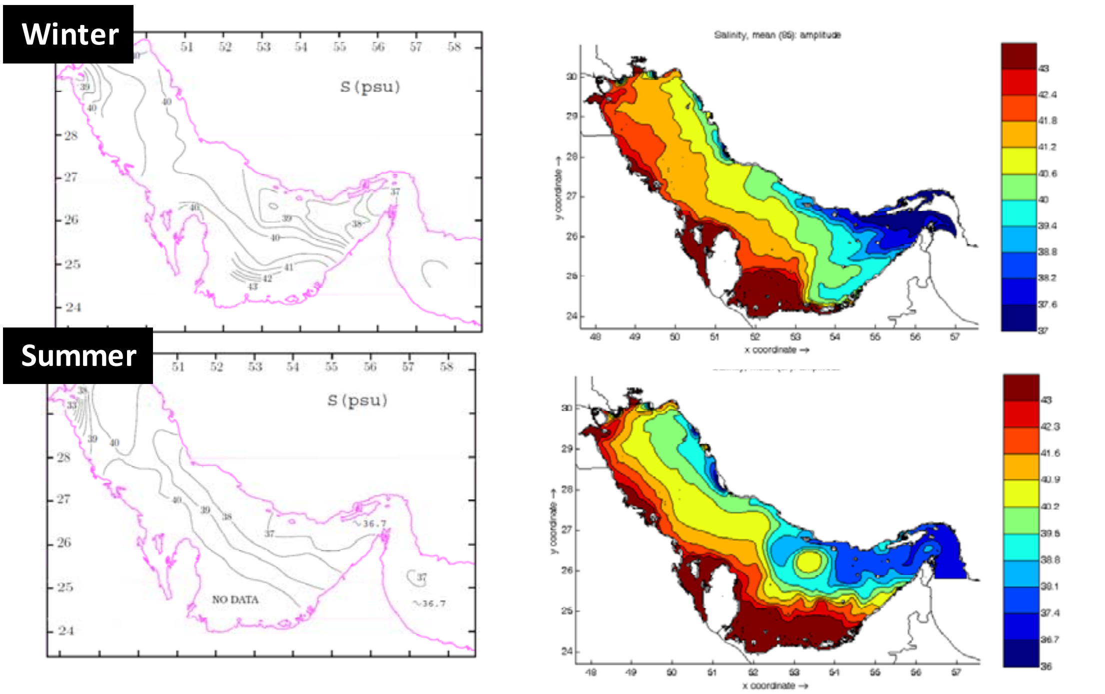


**Figure 4 Comparison of gulf-wide winter and summer salinity distribution between the 3D-AGM simulated results and Reynolds (1993). Simulations show mean value between Nov-Dec-Jan for winter and June-July-August for summer.**

| Table 1. General 3D-AGM water quality model setup | |
|---|---|
| Simulation period (spin-up time) | 1 May to 31 August 2011 (conditions at final time step after 12 months simulation from cold start) |
| Time steps | 1 hour |
| Mesh | 1/20th degree square grid in spherical coordinate with 5 layers in sigma coordinate |
| Initial conditions | Uniform distributed concentrations of SEDIMENT = 5g/m3, DIATOM = 0.04 gC/m3, DETC = 0.1 gC/m3, DETN = 0.04 gN/m3, DETP = 0.01 gP/m3, N-NH4 = 0.04 gN/m3, N-NO3 = 0.07 gN/m3, P-PO4 = 0.012 gP/m3, |
| Offshore boundary conditions | Same as initial conditions |
| River discharge | Same discharge rates as the hydrodynamic model, SEDIMENT = 300 g/m3, DIATOM = 0.05 gC/m3, DETC = 0.1 gC/m3, DETN = 0.1 gN/m3, DETP = 0. 1 gP/m3, N-NH4 = 1 gN/m3, N-NO3 = 1 gN/m3, P-PO4 = 1 gP/m3, |
| Wind & Solar rad. data | Hourly data from KISR meteorological station |
| Dispersion & Diffusion | Constant dispersion = 1 m2/s, Constant vertical diffusion = 10-7 (plus background vertical diffusion from hydrodynamic model) |

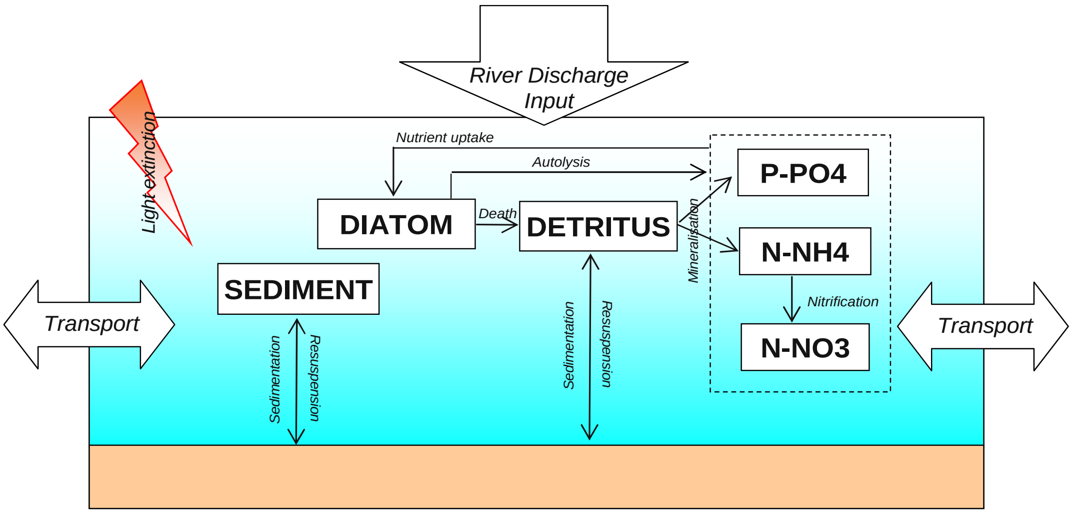


**Figure 5 Conceptual diagram of the 3D-AGM Water Quality Model.**

## INFLUENCES OF METEOROLOGICAL DATA SOURCE

Selection of representable meteorological data is of paramount importance for accurate modeling of air-sea heat exchange fluxes. The fluxes greatly influence thermohaline features of the water body so that selection of the meteorological data source was selected based on the best data source available for hydrodynamic modeling. All the model used the same wind speed and direction data from ECMWF ERA-Interim model. The wind data is the time- and space-varying wind- and air-pressure fields covering the AG. Figure 6 shows wind fields during predominate northwesterly and southeasterly wind. It was observed that wind has strong spatial variability which exemplifies the necessity to apply this spatial data for realistic modeling. It has been recognized that the AG water circulation in greatly governed by variation of its water density (water temperature and salinity) that largely affected by metrology. In this study, we examined the best source of meteorological data from three different sources, i.e., Doha International Airport, Kuwait International Airport and KISR's weather station. The data from the Doha and Kuwait International Airport are 3-hourly of relative humidity, air temperature and percentage of cloud coverage. Ocean Heat Flux Model (Deltares, 2011a) was used for heat exchange fluxes calculations. The data from the KISR's weather station is 1-hourly data of relative humidity, air temperature and solar radiation. Murakami Heat Flux Model was used. Results of the simulations from the three sources in terms of water temperature and salinity at Sta. 3 are compared in Figure 7. Clear differences of simulated water temperature and salinity between the three meteorological data sources can be seen. We preliminary utilized data from the KISR's weather station for the 3D-AGM modeling considering its best matching with measured field data. We noted that applying KISR's weather data to get best simulation results for Kuwait water does not guarantee that the 3D-AGM model will yield the best results for the other parts of the AG. More research and sensitivity analysis on the meteorological forcing data will be required (temporal and spatial varying data) to obtain general best results for the whole AG.

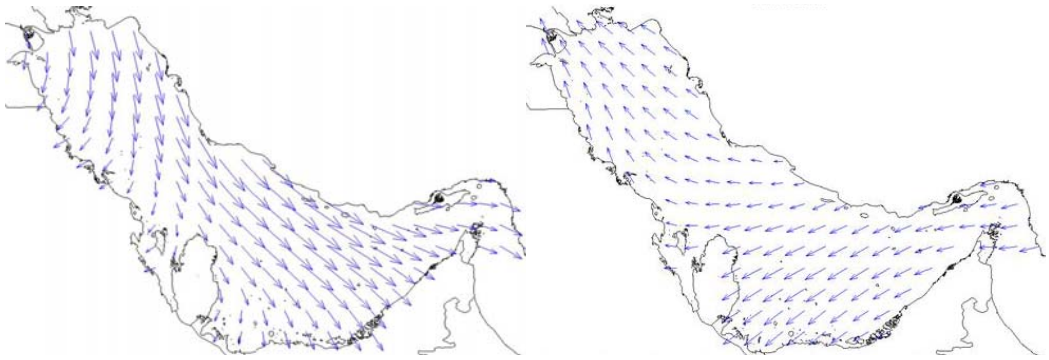

**Figure 6 Example of 3D-AGM forcing wind field during predominant northwesterly and southeasterly wind.**

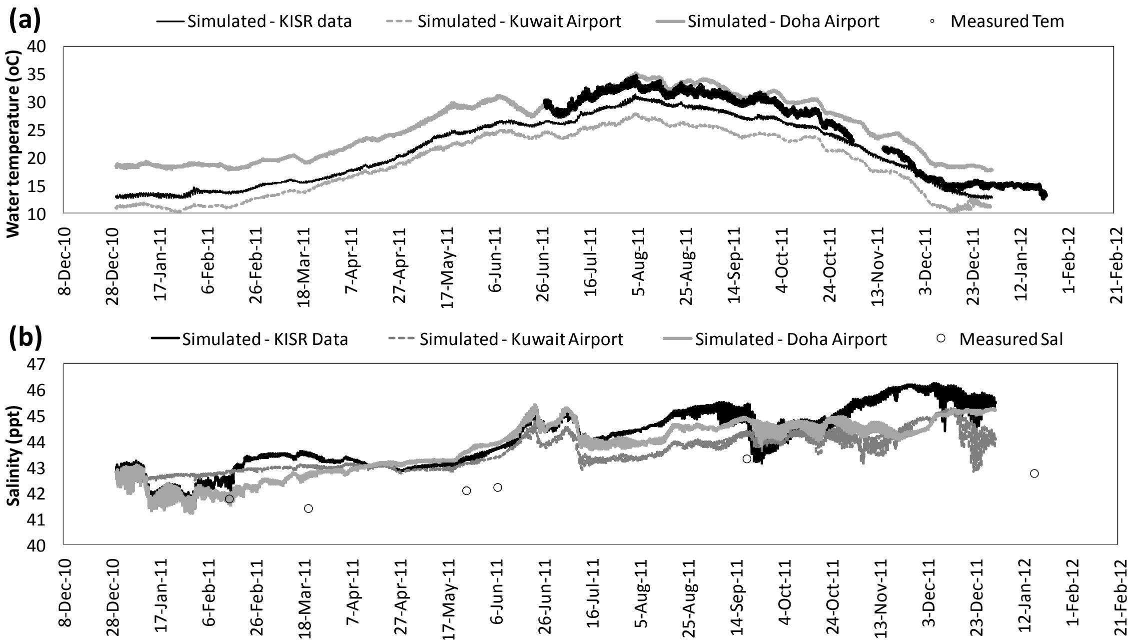


**Figure 7 Comparison of simulated (a) water temperature and (b) salinity at Sta. 3 between difference source of meteorological forcing data source**

## SEASONAL HYDRODYNAMIC CHARACTERISTICS OF THE ARABIAN GULF AND THE NORTHERN ARABIAN GULF

Simulated results in terms of water level, flow velocity, water temperature and salinity are shown as two-month mean values in Figures 8 to 12, respectively. Meteorological data record from KISR's weather station suggested that a typical range of atmospheric pressure is between 990 mbar and 1025 mbar. This results in the gulf-wide overall higher mean water level in summer and lower in winter as

Figure 8. The higher mean water level in the summer is a result of relatively lower pressure over the gulf region compared to the winter. This physical phenomenon is included in the ECMWF ERA-Interim data. The general predominate northwesterly wind piles up water toward the southern and eastern coast of the AG. Clear depressions of water level also can be observed in summer at the southern region resulted from meso-scale eddies.

Near-surface and near-bottom flow velocity fields (shown in Figure 10 and Figure 11), water temperature (shown in Figure 12) and salinity (shown in Figure 13) show clear strong seasonal variations. Water temperature has much larger variations compared to salinity. Higher salinity waters are found on the western coast especially at the shallow regions of the AG. Suggested by the water temperature distributions, water columns at the northern part of the AG tend to be more stratified during spring and summer. In winter and autumn, the water column mixed better. Homogeneous water columns were found at all seasons at the shallow northern part and southern coast of the AG. Results in terms of salinity and near-surface flow velocity also demonstrate that the northern part of the AG receive larger amount of fresher oceanic water in spring and summer than other seasons. Overall in-coming flows at surface layers and out-going flows at bottom layers depict clear inverse-estuarine circulation feature of the AG. It has been understood that the AG receive not enough freshwater from river runoff and precipitation compared to water mass loss from evaporation. To substitute the overall water mass loss, fresher oceanic water enters the AG through surface currents. The fresher water flows along the Iranian's coast, generates complex meso-scale eddies system along its way toward the northern part of the AG. Extend of the fresher water plume varies largely in seasons. Interestingly, it is seen also that the strength of well-documented general counterclockwise circulation (CCC) at the northern part of the AG varies seasonally. The CCC was enhanced in spring and summer (possibly by effect of fresh water plume) while diminished in autumn and winter. Near-bottom flow velocity field suggests that dense bottom waters flow strongly toward the mouth of the AG in winter and spring. This indicates that there is strong seasonally of interactions between the northern and southern part of the AG.

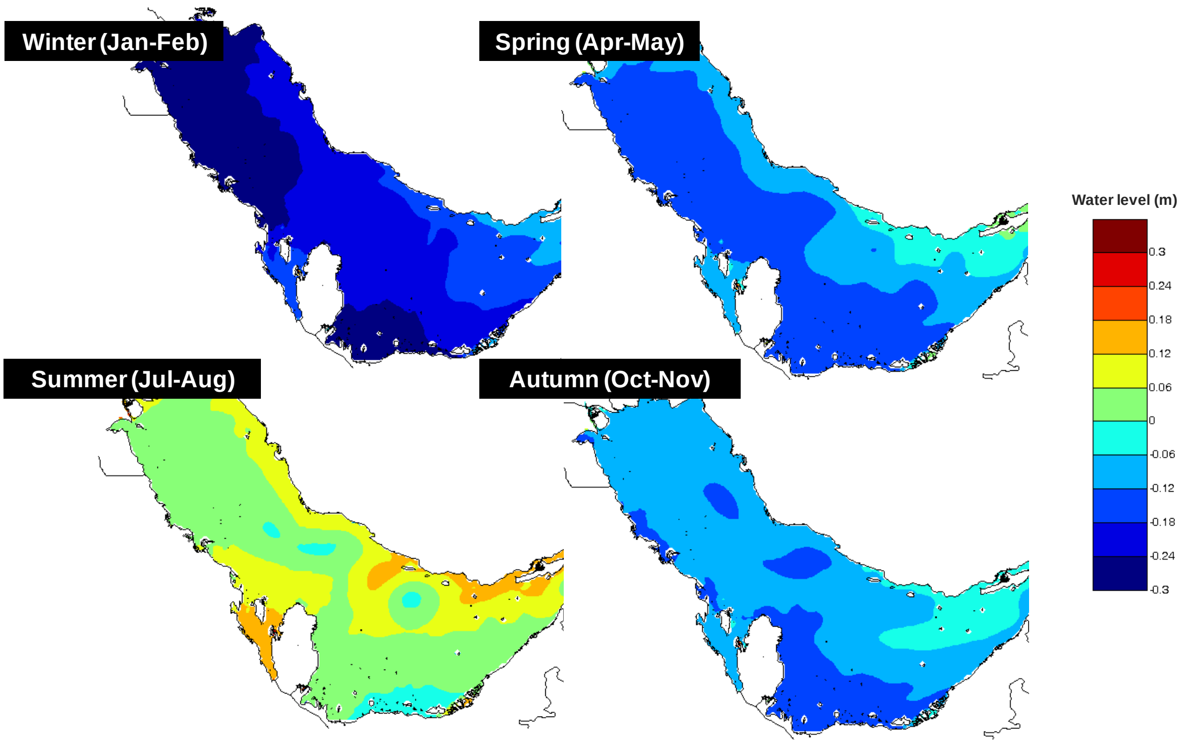


**Figure 8 Seasonal variation spatial water level in the Northern Arabian Gulf**

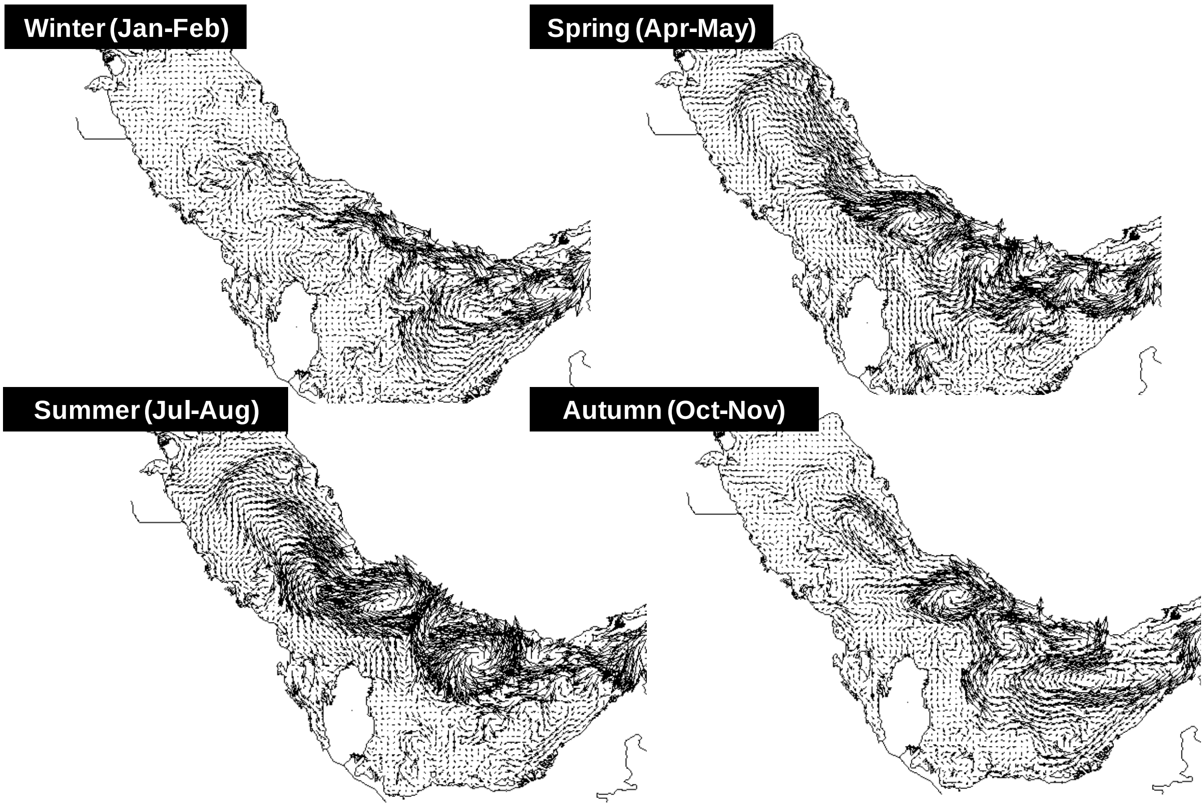


**Figure 9 Seasonal variation of near-surface 2-month mean current fields of the AG**

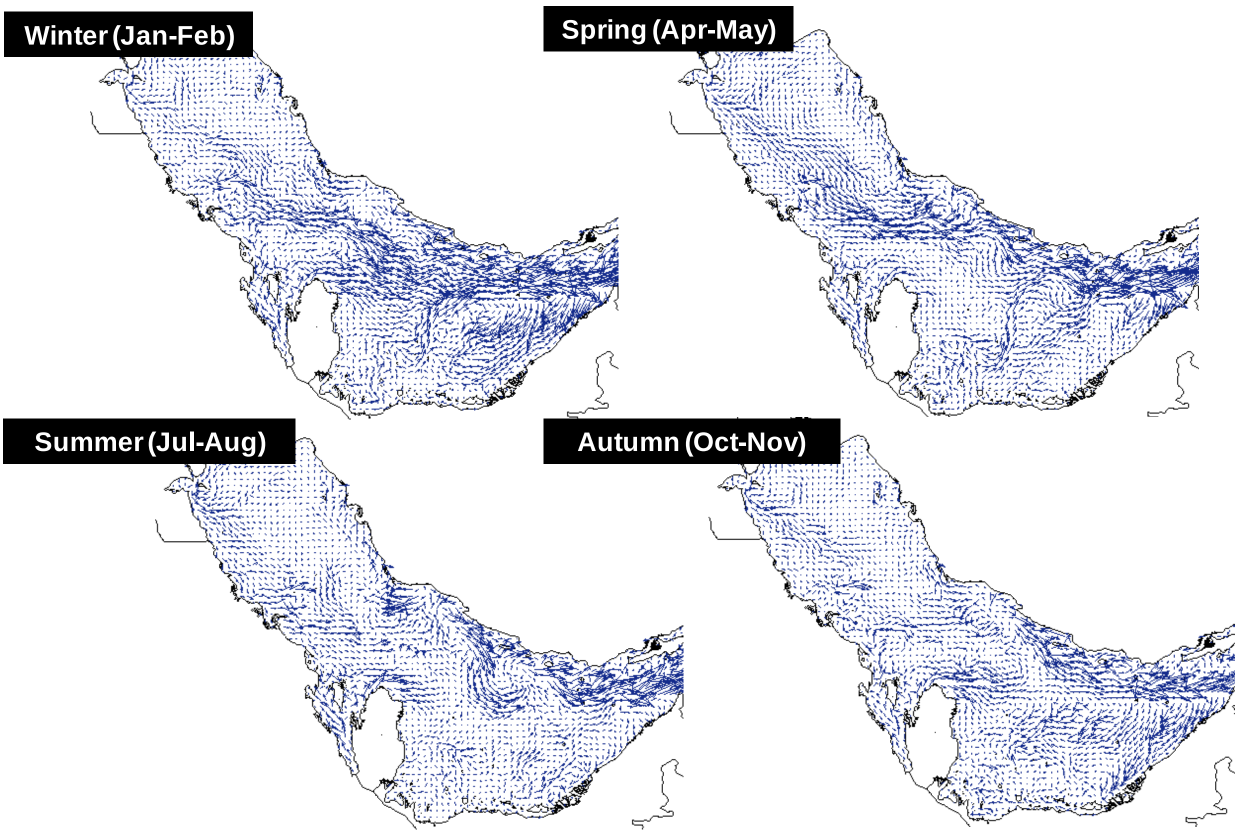


**Figure 10 Seasonal variation of near-bottom 2-month mean current fields of the AG**

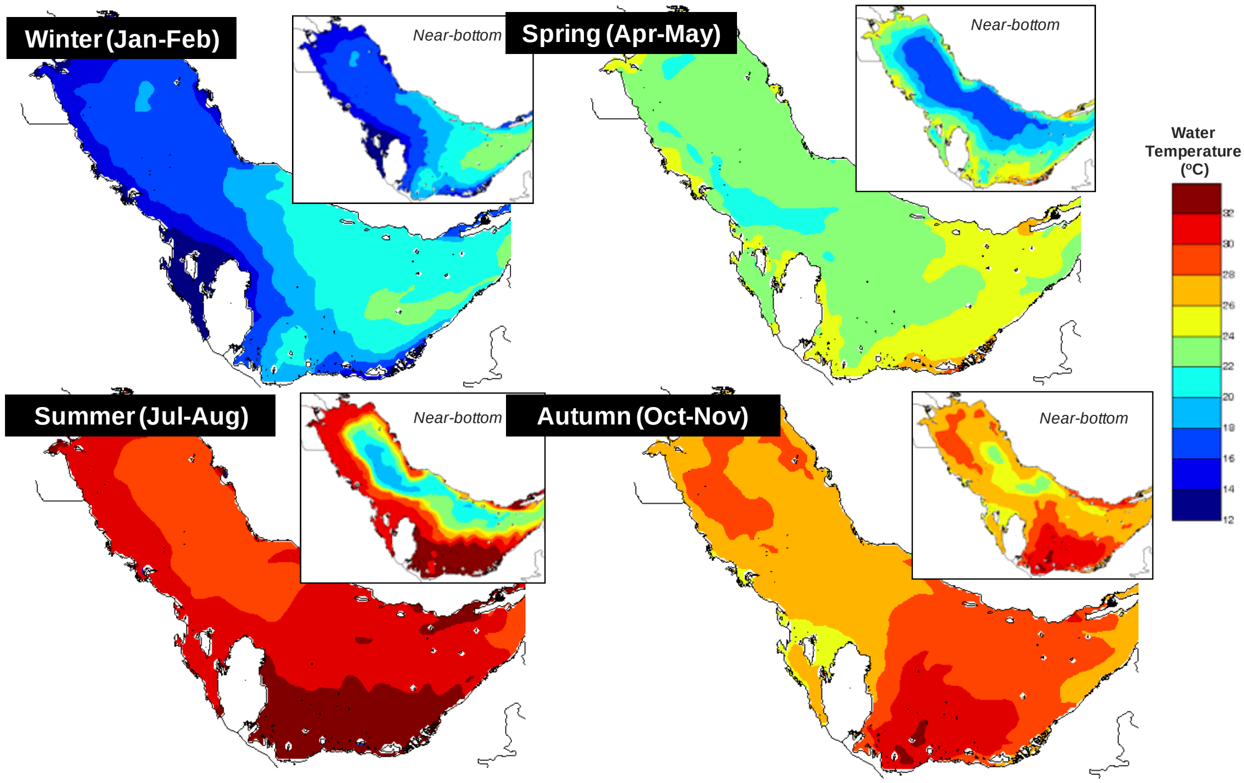


**Figure 11  Seasonal variation of near-surface and near-bottom 2-month mean water temperature of the AG**

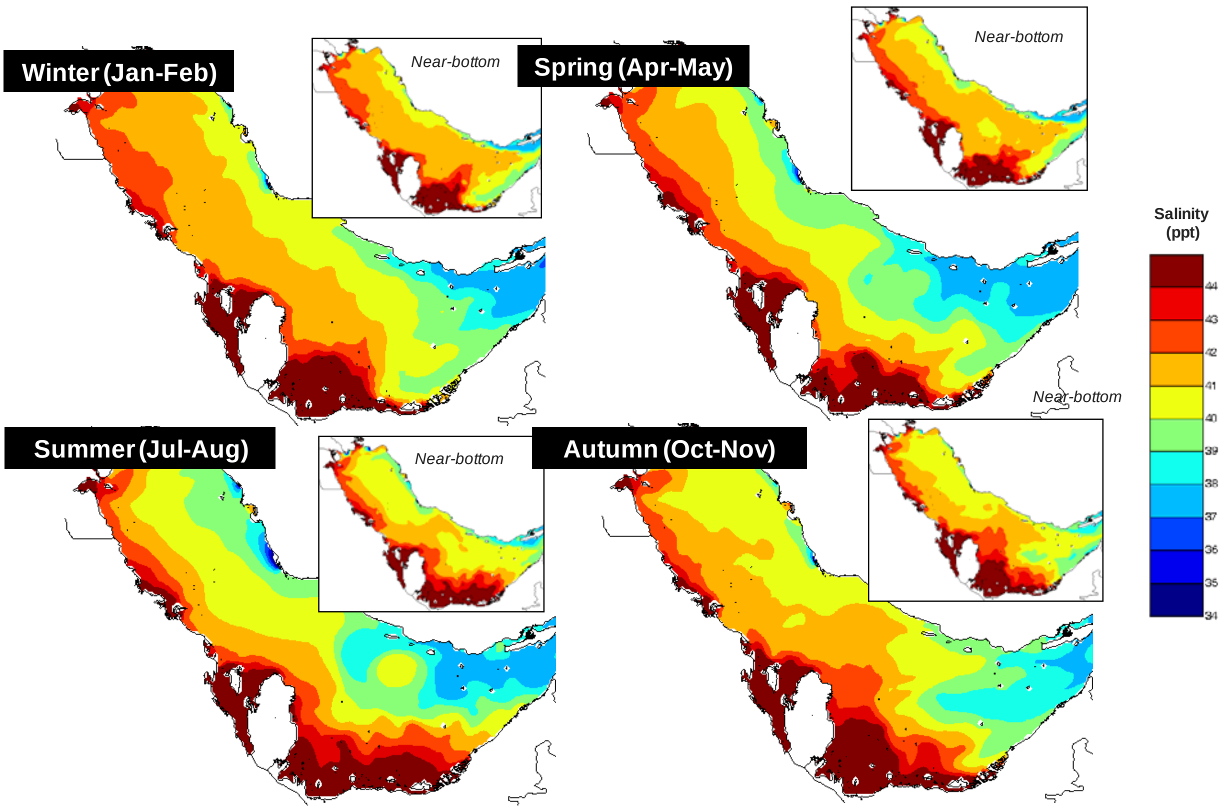


**Figure 12 Seasonal variation of near-surface and near-bottom 2-month mean salinity of the AG**

## SEASONAL WATER QUALITY CHARACTERISTICS OF THE ARABIAN GULF AND THE NORTHERN ARABIAN GULF

Figure 13 shows the distribution of simulated total suspended sediment (SEDIMENT in Figure 5) in different seasons. It can be observed that turbid waters (with higher suspended sediment concentration) are generally found more in the northern part of the AG, especially near the river mouth and shallow regions. This implies that rivers are an important sediment source (sediment re-suspension processes from the sea bed is ignored in the present model). Oceanic water is clearer water and contains less sediment. The modeling indicated that the sediment is transported out of the northern part of the AG by subsurface currents (denser water currents).

Figure 14 shows the distribution of simulated phytoplankton biomass (DIATOM in Figure 5) concentration in different seasons. Higher phytoplankton concentrations are found near the AG entrance and along the Iranian coasts, suggesting that the AG's biochemical system has tendency to depend on nutrient supplies from the fresher oceanic water. In other words, the AG is an oligotrophic system. Higher phytoplankton biomass regions can be found near the water surface, river mounts and regions where the fresher oceanic water reach. Results of this study also exemplify significant possible impacts of nutrient discharges from fast developed coastal cities, from rivers, from sea-bottom and from dust direct deposition to the water surface to biogeochemical processes of the AG. Not shown here, it is important to note that, time-series results of simulated water quality parameters at the northern part of the AG show strong interactions between Shatt Al-Arab river and biochemical features of the northern part of the AG. Simulation also computes strong correlation between dynamic of sediment and nutrient supplied from river and the dynamic of phytoplankton biomass. Field measurement and/or modeling sensitively analysis to obtain better realistic of discharges rate and quality of river runoff will be required if to pursue better ecological studies of the northern part of the AG.

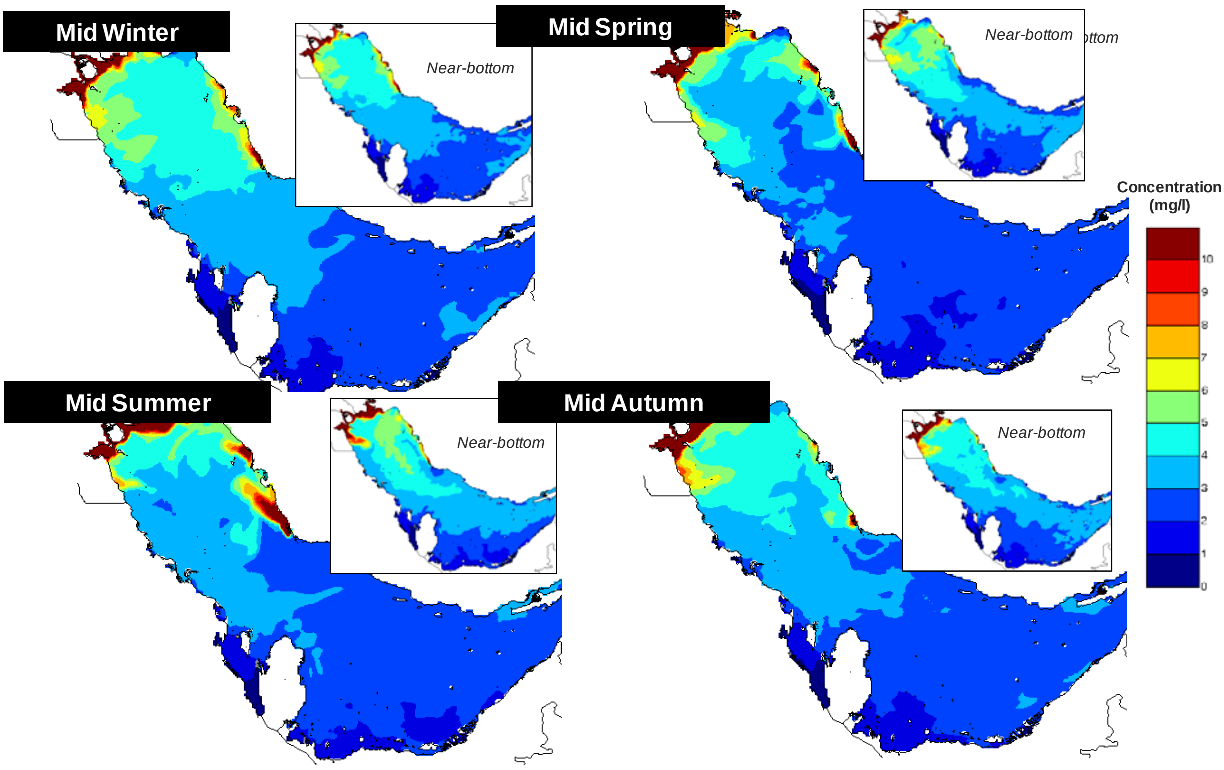


**Figure 13 Seasonal variation spatial near-surface total suspended sediment in Arabian Gulf**

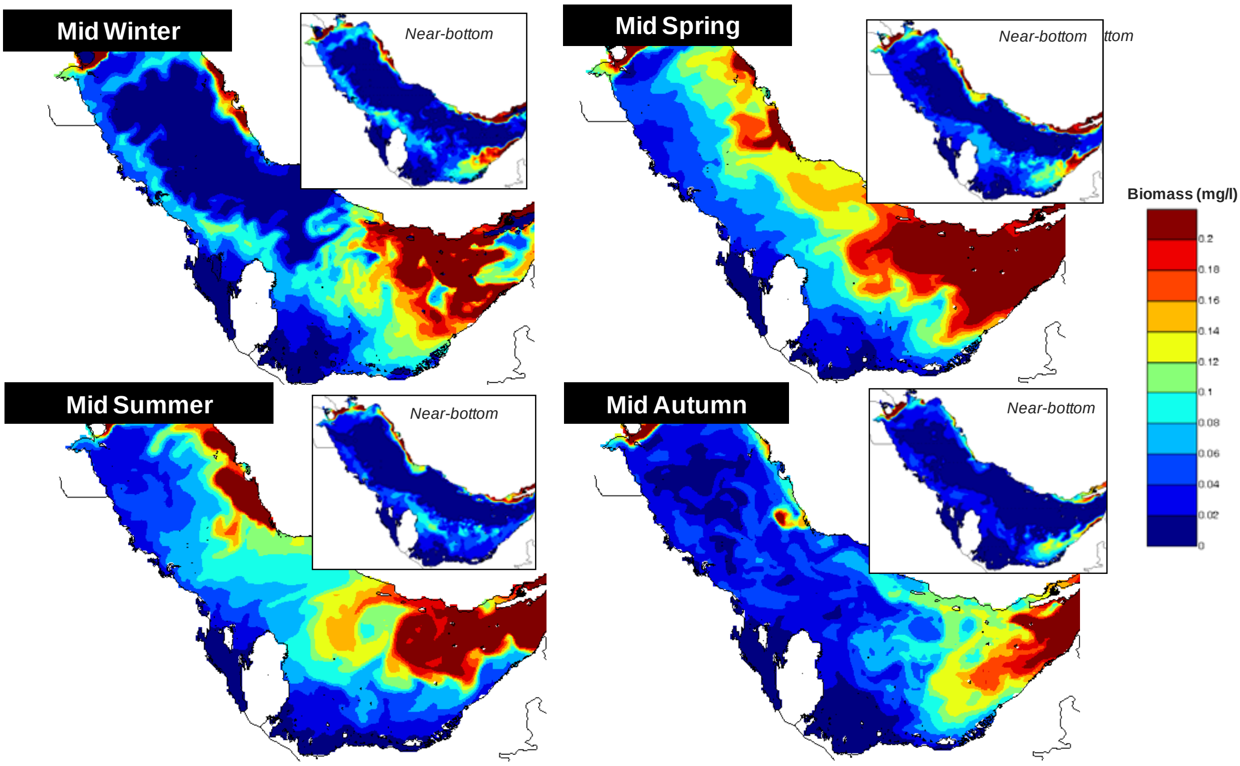


**Figure 14 Seasonal variation spatial near-surface phytoplankton biomass in Arabian Gulf**

## CONCLUDING REMARKS

Further development of the model is necessary if to pursue better realistic modeling system the AG. Next steps include refinement of grid resolution, bathymetry, improve air-sea interaction model and comparison of the simulation result with observed data at the other part of the AG, applying full spatial meteorology data forcing (i.e., humidity, air temperature, solar radiation), refining of better validated input data (e.g., river, city, power and desalination plant discharges), improving estimation of evaporation rate estimation by sensitivity analysis of heat exchange module settings, validation of the simulation results with additional data sources (e.g., remote sensing data).

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