

Circulation in the Gulf of Khambhat - A Lagrangian Perspective

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Abstract

The circulation of the Gulf of Khambhat (GoK) is studied from a Lagrangian point of view using a 2D numerical model. The model-predicted tide elevation and current speed are in agreement with the observations. Seasonal variations of advection of particles are simulated by releasing 237 particles homogeneously distributed over the Gulf. After one month of simulation, no particles escaped from the GoK except a few from the southern GoK during southwest monsoon (June-September) and the advection of particles is maximum at the northern part. Residual eddies are present inside the GoK during northeast (October-January) and southwest monsoon seasons. Gulf circulation is studied with the combined forcing of tide and wind for different tidal conditions which had noticeable seasonal difference. The maximum simulated current speeds of 3.4 and 2.8 m/s are noticed during southwest monsoon near to Bhavnagar and Dahej respectively, where the tide elevations are maximum indicating that GoK is a tide-dominated system. A seasonal barrier could be found in the southern Gulf, which not only makes the Gulf circulation distinct from that of the Arabian Sea (AS) but also restricts water-mass exchange between the Gulf and AS during ebb condition. As the Gulf is a dump yard for anthropogenic wastes, the present study puts up an effort to determine the fate of the waste from a hydrodynamic point of view.

Keywords: circulation; residual eddies; tidal current; tidal hydrodynamics; Gulf of Khambhat

1. Introduction

The western continental shelf of India varied from south to north, and widens off Mumbai, leads into a strongly converging channel, the Gulf of Khambhat (GoK). The GoK, formerly known as the Gulf of Cambay, is a funnel-shaped indentation, situated between Saurashtra peninsula and the mainland of Gujarat (Fig. 1). The GoK has a width of 80 km at the mouth and funnels down to 25 km over the longitudinal reach of 140 km. The gulf is shallow with a maximum water depth of about 30 m and the northern part of the gulf is characterised by water depth less than 10 m and large tidal flats [1]. The tides in GoK are of semi-diurnal type with a large diurnal inequality and varying amplitudes, which increase from the south to north along the GoK. The amplification of tide inside the GoK is due to its shape and varying bottom friction coefficients [2] and the large width of the continental shelf off the central west coast of India [3]. In the north Indian Ocean, the maximum tidal range is found in GoK with an average tidal range of 10 m near to Bhavnagar [4]. The current measurements in GoK indicate a maximum current speed of 3.3 m/s and flows north-northwest during flood tide and south-southeast during ebb tide [5]. The main rivers that drain into the GoK are Narmada, Tapi, Mahi and Sabarmati and these rivers discharge a large amount of suspended sediment (more than 1000 mg/l/d) [6] which makes the Gulf more turbid as this oscillates within this region until a water flushes it towards the open sea [7]. These rivers discharge a substantial freshwater run-off into the gulf, especially during the monsoon seasons. The discharge of the Narmada River, which is the major river, ranges between 10000 and 60000 m³/s during monsoonal floods.

The climate of the study region ranges from semi-arid through tropical steppe in the north to tropical rainy in the south with average rainfall exceeding 100 cm per year in the coastal area [8]. The Gulf is exposed to seasonally reversing wind with winds veering from the southwest (SW) during the summer monsoon (June-September) and from the northeast (NE) during the winter monsoon period (October-January). The period between the winter and summer monsoon is the pre-monsoon period (February-May). Higher wind speeds up to 21 m/s are likely to occur during SW monsoon [9]. The Gulf is expected to be influenced by large-scale wind-driven circulation [10]. The jet currents on the proximity of 60 m depth contour are considered as the coastal ocean boundary, which do not allow the gulf-water advected/flushed out into the open sea directly [11]. The seasonal variability of GoK is due to the seasonality of the main forcing agents - the Arabian Sea at the Gulf's entrance and the monsoon wind regime. The Gulf is homogeneous and displays a one-layer structure and currents at deeper depths inside the Gulf follow the same velocity pattern of the surface due to the shallowness of the depths and high tidal amplitudes [11].

Study of the tidal hydrodynamics of a coastal area i.e. gulfs, estuaries, creeks, bays, lagoons etc. are of paramount importance as these data would be the baseline of any coastal development of that particular area. Tidal hydrodynamics of the Gulf of California was studied by Marinone [12] who inferred that the tide of that area is in oscillation with the Pacific Ocean and the semi-diurnal constituents are near resonance, with head amplitudes four times larger than those at the mouth. Further study concluded that a depth-averaged circulation could often be used to have an idea about the advection of the passive pollutants [12]. Sheng and Wang [13] used a single-domain coastal circulation model to study the non-linear dynamics of the barotropic tidal circulation in Lunenburg Bay. A study by Allahdadi et al. [14] surmised that currents in the Atchafalaya shelf follow the general circulation pattern of Louisiana coast and is influenced by seasonal wind, tides, river discharge and outer-shelf variations induced by the loop current eddies. A coupled hydrodynamic/ suspended sediment transport model was developed and successfully applied to Cleveland Bay, Australia [15]. Tattersall et al. [16] applied 2D depth-averaged models to simulate the tidal currents and suspended sediment concentrations in the Tamar estuary, England.

Understanding the circulation characteristics of the GoK is extremely important as hydrodynamics have a direct impact on the design of any engineering infrastructure, built in this area. The tidal strength is an important agent in driving and modulating net circulation in a semi-enclosed water body. Several economic activities (e.g. shipping, oil and gas extraction), as well as flora and fauna, can be directly or indirectly influenced by the tidal variations and associated circulation and the possible changes to those processes. Anthropogenic activities or long-term natural processes can affect those processes with often drastic and unexpected consequences. Studies on hydrodynamics are also essential to understand the interaction of the coastal and inland water in terms of the physical processes as well as the exchange of nutrients or pollutants between the two water bodies. Longuet-Higgins [17] showed the limitations of an Eulerian points of view to explain the long-term transport of water particles: he defined the mass transport velocity as the sum of the Eulerian residual current and the Stokes drift by carrying out a first-order approximation of the Lagrangian residual velocity. Numerical methods based on particle tracking enable calculation of the Lagrangian residual circulation for strongly non-linear system [18]. The ocean exhibits a huge range of dynamical motions, extending scales from millimeters to thousands of kilometers. The Lagrangian analysis is a powerful way to analyse the output of ocean circulation models and other ocean velocity data. This method employs an ensemble of passive Lagrangian particles of zero spatial extent whose trajectories are determined by the velocity field [19]. A large number of industries are present on either bank of the Gulf which discharge an enormous amount of treated effluent into the sea. At present, the fate of the particles

discharged in the Gulf is not known. The Lagrangian analysis along with the hydrodynamics could provide an insight to the fate of the sewage/industrial effluent released in the Gulf.

Thus, the main objective of this work is to study the seasonal variation of depth-averaged Lagrangian circulation of the GoK using a calibrated 2D numerical model. Section 2 presents the materials and methods.

2. Materials and methods

2.1. Hydrodynamic Model

The currents measured off Dahej at 12 m water depth shows that the currents are similar near the surface and the bottom (Fig. 2) indicating that the water is vertically well mixed. An unsteady and two-dimensional vertically integrated shallow-water equation for continuity and momentum balance given by Stoker [20] has been used to obtain the tides and tide-induced circulation in the GoK. In this study, the 2D model developed for simulating Thane creek tidal circulation [21] and to determine the flushing characteristics of Amba estuary [22] has been applied to the GoK. The model is barotropic, based on shallow water equations and neglects horizontal diffusion terms in the momentum equations. Due to the seasonal wind reversal in the study region, wind stress terms are introduced in the model. Wetting and drying in shallow areas were modelled.

(a) Continuity and mass balance

$$\frac{\partial \eta}{\partial t} + \frac{\partial(HU)}{\partial x} + \frac{\partial(HV)}{\partial y} = (\eta + h)m_v \quad (1)$$

where, $\eta=H - h$, t =time coordinate, x, y = set of horizontal, mutually orthogonal Cartesian coordinates, H =total instantaneous water depth, U, V =horizontal velocity components in x and y direction respectively, m_v =vertically integrated average rate of mass infection or withdrawal of fluid per unit volume divided by the fluid density, h =the depth of water measured positively downwards from the reference datum plane.

(b) Momentum balance equations

The vertically integrated momentum balance equations for a shallow water body are given by;

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} = -g \frac{\partial \eta}{\partial x} - \frac{1}{\rho} \frac{\partial P}{\partial x} + \Omega V + \frac{C_w W^2}{(\eta+h)} \cos \theta - \frac{C_f (U^2 + V^2)^{\frac{1}{2}}}{(\eta+h)} U + S_u \quad (2)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} = -g \frac{\partial \eta}{\partial y} - \frac{1}{\rho} \frac{\partial P}{\partial y} - \Omega U + \frac{C_w W^2}{(\eta+h)} \sin \theta - \frac{C_f (U^2 + V^2)^{\frac{1}{2}}}{(\eta+h)} V + S_v \quad (3)$$

Where, g =acceleration due to gravity, η =tide elevation, ρ =fluid mass density, P = fluid pressure ($P = H\rho g$), Ω =Coriolis parameter, C_w =wind stress coefficient, W =wind speed, θ =wind angle

measured from the positive direction of x towards the positive direction of y-axis, C_f =bottom friction coefficient, S_u and S_v = average rate of momentum generated or dissipated per unit volume derived by the mass density of water in x and y directions respectively.

The equations 1-3 are solved in Alternate Direction Implicit (ADI) scheme which is a finite difference method for solving parabolic, hyperbolic and elliptic partial differential equations with finite difference grid system. Horizontal diffusion terms in the momentum balance have been neglected since contributions from them are small compared with the other terms. The contour -4 m in the bathymetry describes the inter-tidal region which behaves as part of the landmass during high tide and as water-mass during low tide. Thus, the model considers the wetting condition of it during high water and drying during low water. The input data was smoothed using the spline function to obtain the tide at closer intervals. The governing equations were solved with the initial and boundary conditions on a staggered grid system as described by Leendertse [23]. The tides at the intersection of two straight open boundaries i.e., the northwest and southwest corners of the model domain were derived from the OSU (Oregon State University) Global Tidal Model [24] and the tide at the other two corners were model-based. The model domain with the grid resolution of 500 m was tilted by an angle of 45° for ease of giving model input. The model results are represented with the actual geographic location of the system.

The bottom friction (C_f) was parameterized in terms of coefficient of Chezy using the formula, $C_f = (1/32) \times [\log_{10} (14.8 H)/K]^2$, where K is a roughness length. As, C_f is a function of depth, varying bottom friction values were applied in different regions of the model domain for the calibration and validation of the model. The magnitudes of the bottom friction coefficients for different area is taken from Sathish and Balaji [25]. Stability of the numerical scheme is governed by $\Delta t < \Delta x / \sqrt{2gH_{max}}$, where Δx is grid size in meters and Δt is the time step in seconds and g is the acceleration due to gravity and H_{max} is the maximum depth in the model domain. When H_{max} is 100 m and Δx is 500 m, the Δt is 12 s. It was assumed that initially the sea is at rest, i.e. at $t=0$, $u=v=0$. Since the model was initially at rest, it took more than 15 hours for the model to get stabilized. Thus, first one day data from the each model simulations have been discarded. The northern boundary of the model domain was closed. The model simulation was done by applying tides at Mumbai and Veraval along with the intersection of two straight open boundaries i.e. at the northwest and southeast corners of the rectangular model domain (i.e. boundary tide at the eastern, southern and western boundary of the model domain). For ease of simulation, model domain was rotated 45° in anti-clockwise direction. The results are represented using the actual geographical position of the area. A negative value in the bathymetry figure denotes land area. The model extends up to the inter-tidal area of the domain (-4 m in the bathymetry figure).

Reanalysis data of zonal and meridional components of wind speed at 10 m height at one hour interval with a resolution of $0.25^\circ \times 0.25^\circ$ for the entire study area were obtained from NCEP / NCAR [26] to use them as the model input for determining the influence of wind on sea level and currents. These data are provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado at <http://www.cdc.noaa.gov/>. The river discharge data of four major rivers (Narmada, Tapi, Mahi and Sabarmati) used in this study has been provided by the Central Water Commission (CWC), New Delhi. Due to the high dynamicity of the area, GoK was assumed to be a one layer system, and hence standard seawater density have been used for model simulation in the entire model domain.

2.2. Lagrangian circulation

Lagrangian circulation is analysed using a particle tracking method by releasing particles at a fixed time, tracking the path of these particles and the time when they reach the boundary and was performed in a 2-D mode, using a 4th order Runge–Kutta (RK) scheme for particle advection. The trajectories of the particles were obtained by time-integrating the horizontal velocity field. Lagrangian circulation was calculated using the equation [27] which has previously been used by Naidu et al. [22]. 4-point linear interpolation is adopted to calculate the velocity at an arbitrary point.

$$\bar{x}(t + \Delta t) = \bar{x}(t) + U \Delta t \quad (4)$$

where, \bar{x} is the particle's position, Δt = time step. In this work, diffusion term is neglected.

2.3 Residual circulation

The differences between the simulated currents and that derived from tidal harmonics were averaged over one lunar cycle to compute the steady residual circulation or mean currents. The model was run for one lunar tidal cycle (29.5 days) by storing U and V components of velocity at each grid at 20 min interval for three seasons. Using the following equation the residual velocity R_v is estimated.

$$R_v = \frac{1}{T} \int_0^T U \Delta t \quad (5)$$

The net velocity of u and v components were calculated by integrating the velocity components [22].

2.4. Model calibration for Hydrodynamics

Tide and current data from the model were compared with measured data for locations at Surat (Figs. 3a and 4a), Dahej (Figs. 3b and 4b) and Bhavnagar (Figs. 3c and 4c) which are inside the GoK and the details of the tide and current used are presented in Table 1. Bias and Root Mean Square Error were calculated for the observed and predicted tide elevation and current speed are presented in Table

1. The bias values of 0.09, 0.04 and 0.03 m/s for currents at Surat, Dahej and Bhavnagar depict that the modelled and observed datasets are in agreement with each other. The positive bias values indicate that the predicted data slightly over-estimated the observed datasets. At first single-valued friction co-efficient was applied at the entire model domain and the model results were found to differ with the observed one. After calibration of the model by comparing simulated and observed Eulerian currents, the bottom friction coefficients were found to be variable from place to place. Neutrally buoyant floats, released off Dahej and Bhavnagar were used to compare the simulated Lagrangian tracks at these areas. Further, the Lagrangian tracks were used for the validation of the model (Fig. 5). The validation was done with respect to the entire model domain but a small section is presented for better delineation. The advection of buoy was found to be 41 km and 26 km during flood and ebb conditions respectively which is well-captured by the model. It could clearly be noticed that the flood is much stronger than ebb in the Gulf. On an average the modelled track points were 260 m and 267 m ahead of the observed trails during ebb and flood conditions respectively. No stratification was revealed by the RDCP data moored at the eastern GoK (Dahej) (Fig. 2) and hence, a 2D numerical model was applied in this work instead of a 3D model.

3. Results

3.1. General circulation

Model was run for different scenarios, viz., the tide-driven, wind-driven and the combined tide and wind-driven circulation of GoK for three typical months of three seasons i.e. January (NE-monsoon), May (pre-monsoon) and July (SW-monsoon) with different tidal conditions viz. neap ebb, neap flood, spring ebb and spring flood. The circulation driven by the combined forcing of tide and wind are presented in the manuscript (Figs. 6 and 7). A barrier-like feature, separating inner and outer GoK could be identified during the neap-ebb condition in the NE-monsoon (red line in Fig. 6a), where the clear dissimilarity between Gulf circulation with that of the Arabian Sea was noticed. This type of formation was absent for the flood condition of neap and spring tide of the same season (Figs. 6b and 7b). During NE-monsoon, the maximum current speed (2.8 m/s) was identified inside the Gulf near to the Narmada mouth during spring peak flood condition (Fig. 7b). In spring ebb condition the barrier has shifted northward but it was not that significant as neap tidal condition. The barrier formation could be noticed during the pre-monsoon season in ebb condition of neap and spring tide (Figs. 6c and 7c). The barrier has shifted southward in this season which runs between Pipavav in the west and Daman in the east. The barrier was absent during the flood condition. Anti-cyclonic eddy was present off Pipavav during the flood condition of spring and neap tide. Maximum current speed of 2.4 m/s could be noticed at Narmada mouth during spring peak ebb condition. Similar type of barrier

formation between Pipavav and Daman could be identified during neap-ebb condition (Fig. 6e) during SW-monsoon. An anti-cyclonic eddy was identified off Pipavav in flood condition of neap tide (Figs. 6e and 7e) during pre-monsoon which was found to be absent in the ebb condition. Maximum current speed of 3.4 m/s was noticed for the spring flood condition during SW-monsoon.

Tide-driven circulation was obtained by omitting the wind in the model input and that was found to be quite similar to the combined tide and wind-driven circulation where the formation of the barrier separating the outer and inner Gulf was also visible during the neap-ebb condition in pre-monsoon and SW-monsoon while in case of NE-monsoon, the barrier was noticed further northward, at the central GoK. During the neap condition, the barrier could be found for pre-monsoon season in flood condition. The tide-driven circulation during the NE-monsoon revealed that maximum current speed was found during the spring flood condition inside the Gulf with an average magnitude of 2.2 m/s. A clear barrier formation was noticed during the pre-monsoon season in the neap-ebb condition and the barrier has shifted further downward in the spring-ebb condition. The maximum current speed in this season was found during the spring flood condition. A barrier-like formation could be noticed during the flood condition of spring and neap tide, but it is not well-distinguishable. The maximum tide-driven current speed of 2.8 m/s was noticed during SW-monsoon.

The wind-driven circulation was drawn by using only the wind as the model input and the circulation is completely different from that of the tide-driven or the combined circulation. During SW-monsoon, very small eddy structures are visible in and outside the Gulf. An eddy-like structure could be noticed off Bhavnagar in the spring ebb condition, which was found to be absent for the spring flood. Wind-driven eddy formation could be noticed in both the tidal scenarios of the neap tide in the south-western GoK. This kind of formation could be visible off Mumbai for the ebb and flood conditions of neap tide and the also for the spring ebb condition. A maximum current speed of 1.5 m/s was observed inside the Gulf at the mouth of Narmada estuary near to Dahej during the spring flood condition. Eddy formations are absent in the wind-driven circulation during NE-monsoon, except for a structure which is formed during the spring flood condition in the central GoK. A maximum current speed of 1.25 m/s was found in the northern GoK during the neap flood condition. Maximum current speed of 1.15 m/s was obtained in the middle of the Gulf during the spring peak flood condition of pre-monsoon season. Wind-driven eddy was noticed during the neap peak flood condition in the south-western GoK.

Three locations are selected in the northern (mouth of Mahi estuary), eastern (mouth of Narmada estuary) and western GoK (off Bhavnagar) where simulated u-v components of currents are obtained for different seasons to understand the contributions of tide and wind in the combined circulation of

GoK (Figs. 8 to 10). The results depict that maximum velocity of 1.44 m/s due to the combined action of tide and wind during SW-monsoon in the eastern Gulf where the dominance of u-component of current is observed while v-component dominates in the other two locations. Tidal action dominates the wind action during NE-monsoon and pre-monsoon season but the wind action contributes significantly during the SW-monsoon season. It could be noticed that there is a considerable difference between the tide-driven current and the combined tide and wind driven current during the SW-monsoon (Fig. 8) which was absent for the other two seasons (Figs. 9 and 10). Wind speed of more than 2 m/s prevailed during SW-monsoon and as a consequence the current speed had a magnitude around 2.5 m/s. Wind action is strong enough even during the NE-monsoon with a maximum u-component velocity of 0.66 m/s at the western Gulf. The mean wind speed had magnitude of more than 1 m/s during this period but its impact on current speed was found to be less. Minimum wind-driven u-component velocity of 0.08 m/s was found in the eastern Gulf during pre-monsoon season and contribution of wind towards the current speed was found to be negligible during this period. In each season, the maximum current speed is recorded for the combined circulation driven by both tide and wind in the eastern gulf. Minimum current speed is obtained for the northern GoK in each of the seasons. It could also be noticed from the figures (Figs. 8-10) that the tidal forcing dominates the wind forcing in the hydrodynamics of GoK. The study illustrates that the dominance of tide in GoK is much more than wind while considering the barotropic circulation.

Areas like GoK, where current speed is high are potential sites for extraction of current energy. Power can be generated commercially if the mean peak current exceeds 2 m/s [28]. The current speed exceeds 1 m/s in the western GoK (off Bhavnagar) for 40.5% during southwest monsoon and around 20% during remaining period. Whereas in the northern GoK (mouth of Mahi estuary), currents are low and exceeds 1 m/s only for 0.4% of the time in a year. In the eastern GoK (mouth of Narmada estuary), during 10% of the time in a year current speed is more than 1 m/s (Table 2).

The influence of Narmada river discharge was found to be noticeable from the magnitude of u-component of current speed which exceeded the magnitude of v-component near to the Narmada mouth. To understand the horizontal extent of the river discharge, three locations were selected from central GoK, Narmada mouth and southern GoK to obtain the u-v component of current speed at these locations during SW-monsoon. In the central and southern GoK (Figs. 11a, 11c), dominance of v-component was observed but near to the Narmada mouth, it was the opposite (Fig. 11b). Thus it could be inferred that the influence of Narmada discharge on the circulation of GoK is quite a localized phenomena and it does not impact the overall circulation of GoK. The area of extent of the river discharge was determined by obtaining the u-v components at different locations starting from Narmada mouth towards offshore (not shown in the figure). U-component was dominating at the

Narmada mouth and it was found that at a distance of 13 km from the river mouth, the v-component came into action and from that point onwards the dominance of v-component was observed. This result also manifests the limiting extent of the Narmada discharge into the overall circulation of GoK. Thus, horizontal stratification was not taken into consideration in the present study.

3.2. Lagrangian circulation

Lagrangian particle tracks were simulated by model forced by the combined action of tide and wind. Track results were obtained by the simulation of one month by releasing 237 particles in the model domain among which 27 particle trails are presented in the figures. The track results revealed that after one month of simulation, none of the particles came out of GoK during SW monsoon except for a few from the southernmost portion of the Gulf (Fig. 12). It can be noticed from the particle trajectories that maximum distances are travelled by those which are released near to Dahej at the Narmada mouth due to the high current in the area. Particles those are released in the mouths of Sabarmati and Mahi River, have a tendency to circulate at those particular locations. Particles released in the western coast of GoK have alongshore movement and those from mid GoK have circulatory movements. The particles which are released near to Mumbai coast have alongshore movement as well.

The particle trajectories extracted for the NE monsoon also have similar tendencies, but the distances covered in this case are quite smaller. Particles released in the northern GoK especially near to the mouths of Sabarmati and Mahi, could not come out of the northern part of the Gulf. Particles from mid GoK, traversed quite more due to the high current speed. They mostly had circulatory motions but particles released near to the coast have alongshore movement even in the eastern GoK, which is quite different from the SW monsoon. Particle trajectories of the southern GoK were found to be small and none of them came out of the Gulf after one month of simulation (Fig. 12). Near to Mumbai, particle trails were parallel to the coast. The trajectories are not very different in case of pre-monsoon. But during pre-monsoon, the particles from the southern GoK have tendencies to move further downward but none of the particles came out of it after one month of simulation. Particles released in either side of GoK near to the coastline revealed circulatory movement. Particles released inside the Narmada estuary had longshore movement and travelled to the northern GoK according to the tidal condition. A particle released near to the Mahi estuary travelled across the Gulf and moved further southward, but could not had an escape. Particles released off Mumbai have shown alongshore movement even in this case and those released inside the gulf travelled larger distances than those released outside in each of the three seasons.

3.3. Residual circulation

The residual circulation during SW monsoon revealed two residual eddies inside the Gulf, in the western GoK and mid GoK (Fig. 13a). Similar features are absent for other two seasons, but residual eddy was identified in the mid GoK during NE monsoon (Fig. 13b). No residual eddy is noticed during the pre-monsoon season (Fig. 13c). Maximum residual current speed is noticed inside the Gulf, during SW monsoon.

4. Discussion

The GoK is basically a not-so-simple system with extreme tidal conditions, river discharges and wind impacts. The tidal height is maximum near to Bhavnagar which is associated with the maximum current speed of more than 3 m/s. This behavior of tidal amplification is attributed to resonance which is the function of geometry and bottom friction [2,29]. Thus it could be inferred that the current speed in this area is modulated by the tidal amplitude as well as the local geometry effects. The very simplistic depth-averaged numerical model predicted the tidal amplitude as well as amplitude of the current speed quite accurately although minute variation in the predicted and observed phase was obtained. Maximum current speed was obtained near to Dahej and Bhavnagar in each season by the model simulation. The barotropic circulation of the model domain reveals that although GoK is directly connected to the Arabian Sea, there is a prominent dissimilarity between the circulation of the Gulf and the open sea. A barrier-like formation in the southern GoK demonstrates this difference. This result is well-reflected even in the Lagrangian Tracks where the particle trails of GoK is confined there itself. Although the barrier formation is a seasonal phenomenon, it could be associated with the mixing characteristics of GoK. It was hypothesised that this type of barrier formation is mostly associated with the bathymetry of the region which is purely a regional phenomenon [30-31]. It should also be noted that the minimal exchange of water-mass between the Arabian Sea and GoK could also be a result of this kind of formation [32-33] which would be the future aspect of the study. The barrier formation is associated with the topography of the Gulf as well as the tidal currents and a schematic diagram well-reflects this phenomena (Fig. 14) where it has been shown that due to high flood current, water could overcome the barrier and goes inside GoK but during ebb period the water exchange between GoK and AS is hampered. Mostly during the ebb condition, the barrier was noticed while during flood either it was vague or absent. During pre-monsoon season, the barrier was noticed for both the tidal condition. Thus it could be surmised that due to the high flood current speed, the whole water parcel surrounding GoK goes inside the Gulf but due to the comparatively smaller ebb current speed, the Gulf restricts the water exchange with the northeastern Arabian Sea during ebb; hence forms a barrier. This not only would restrict the water-mass to come out but also the suspended sediment as well as

anthropogenic wastes, which could have direct/indirect impacts on the biological community of the Gulf. The treated effluent discharged by the industries present on either bank of the Gulf will affect the Gulf-ecology since the Gulf has a tendency to accumulate particles which could include suspended sediment, pollutants, industrial or domestic wastes, spill of oil etc. Alongshore component of current dominated in the northern and western Gulf but the dominance of the cross-shore component of current was identified in the eastern GoK at the Narmada mouth which is due to the influence of Narmada river discharge into the sea. The influence of the river could be seen up to a distance of 13 km from the river mouth on an average and its impact was found to be purely localised. The Lagrangian track results revealed that the particles released inside the Gulf had a tendency to circulate there itself and did not leave the system. These trajectories revealed that the maximum distances are travelled by those particles which are released around the Mal Bank Island at the central GoK. This is associated with the strong current at the central portion of the Gulf [34]. Presence of eddy structures around the Mal Bank and Piram Island is manifested well by the track results. Thus, it could be surmised by the track results that GoK traps particles for more than a month. Even if the particles traverse towards the southern GoK, they could not escape the system. The Lagrangian circulation well-captured the Gulf behavior of accumulating particles. Study by Salim et al. [35] reinforces this behavior of the Gulf, where they inferred that the coastal current prevents direct flushing of high Chlorophyll a-rich water from GoK into Arabian Sea; as a result high chl a water is accumulated inside GoK. The results from the present study is compared with one another tropical macrotidal regime viz. the Gulf of California which is also a converging channel of the western United States. The latitudinal position of both the Gulfs are similar and both possess similar tidal characteristics (mixed-semi diurnal tide). Due to the similarity between the hydrodynamic properties, especially the Lagrangian Circulation [36], a comparison has been made between the results of the present study with the studies carried out in the Gulf of California. Lagrangian properties of particles, studied in the Gulf of California by a 3D numerical model has inferred that due to the strong current in the eastern and southern Gulf, the particle advections is more and the particles are trapped in the northern Gulf [37] which could be comparable with GoK. Surface circulation of the Gulf of California has been studied simultaneously by a 2D and 3D numerical model and the study has revealed that in the central Gulf, where the currents are stronger, the 2D and 3D horizontal advections are similar [12]. The semi-annual characteristics of the Lagrangian circulation of GoK are due to the variability of the hydrographic forcing of the numerical model. But it could be seen that the circulation of GoK is mainly driven by the tidal forcing rather than the atmospheric forcing. Gutierrez et al. [36] studied the seasonal circulation of the Gulf of California from a Lagrangian point of view and they concluded that the Gulf circulation was dominated by the presence of seasonal cyclonic and anti-cyclonic gyres. They have inferred that the Lagrangian

circulation had semi-annual characteristics due to hydrographic forcing of the numerical model and have established in their study that the northern region of the Gulf has captured more particles after one month of simulation which is similar to the present work where the particles released near to the mouths of Sabarmati and Mahi river circulated there itself. The core of the seasonal coastal current along the west coast of India is located on the shelf break which could exert some influence at the circulation of GoK [38]. Thus, the wind forcing of this region was taken into consideration. The time series data at the three locations of the Gulf suggested a considerable riverine influence on eastern GoK and as a result the u-component of current speed dominated in that region in each of the three seasons, which was found in a limited area of extent and does not influence the Gulf circulation as a whole. During SW-monsoon a considerable difference between the tidal current and combined tide and wind-driven current was noticed which is due to the presence of monsoonal winds. Due to weak wind forcing during the other two seasons, this difference is quite negligible. On a nutshell, the results indicate that even though there is an effect of atmospheric forcing on the circulation of GoK, it is mostly driven by the tidal forcing. There are residual eddies present inside the Gulf, which might act like systems to trap the particles inside GoK and these flow depict large asymmetry in flood and ebb flow of the Gulf. The seasonal barrier, formed by the combined action of tide and bathymetry could be of serious concern as it isolates the Gulf from the surroundings during ebb condition. Thus, suspended sediment, effluents or any anthropogenic waste could be accumulated inside GoK which could be a serious threat to the aquatic organisms.

5. Conclusion

The Lagrangian circulation of Gulf of Khambhat was simulated using a 2D numerical model for three seasons, viz, pre-monsoon, monsoon and post-monsoon. The model results depicted the presence of residual eddies inside the Gulf during SW monsoon. The Lagrangian track results have shown that the particles released inside the Gulf, does not leave the system except for a few from southern GoK. This could be associated with the presence of the residual eddies which do not allow particles to leave the Gulf. The combined tide and wind-driven circulation of GoK have exhibited that though the two systems are connected, there is a clear dissimilarity between the Gulf circulation with that of the Arabian Sea. The present work infers that tidal domination is maximum in GoK than any other physical forcing. As the Gulf restricts water parcel exchange with the Arabian Sea, the present study manifests a serious concern on the Gulf health in future. Future work will concentrate on the suspended sediment transport as well as the mixing characteristics of the GoK, a highly turbid water body of the west coast of India.

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Table 1. Details of data used for calibration of tide and current

Tide					
Location	Coordinate	Duration		Bias (m)	RMSE (m)
Dahej	21° 39' 9.1"N 72° 33' 17.4"E	22 October 2015 - 01 November 2015		0.05	0.11
Surat	21° 04' 4.7"N 72° 37' 41.3"E	22 December 2011 - 01 January 2012		0.04	0.19
Bhavnagar	21° 27' 25.0"N 72° 15' 32.2"E	13 February 2011- 15 March 2011		0.035	0.012
Current					
Location	Coordinate	Duration		Bias (m/s)	RMSE (m/s)
Dahej	21° 39' 9.1"N 72° 33' 17.4"E	22 October 2015 – 01 November 2015		0.04	0.58
Surat	21° 04' 2.4"N 72° 37' 39.7"E	12 February 2013 – 22 February 2013		0.09	0.44
Bhavnagar	21° 27' 2.6"N 72° 15' 47.2"E	29 September 2011- 6 October 2011		0.03	0.04

Table 2. Percentage of time when the current speed is more than 0.5 m/s and more than 1 m/s in different seasons at 3 selected locations.

.	Current Speed > 0.5 m/s			Current Speed > 1 m/s		
	Southwest monsoon	Northeast monsoon	Pre-monsoon	Southwest monsoon	Northeast monsoon	Pre-monsoon
Eastern GoK	76.0	66.0	51.0	14.1	12.8	5.4
Northern GoK	22.0	13.5	11.2	0.4	-	-
Western GoK	77.0	67.0	58.6	40.5	20.1	18.8

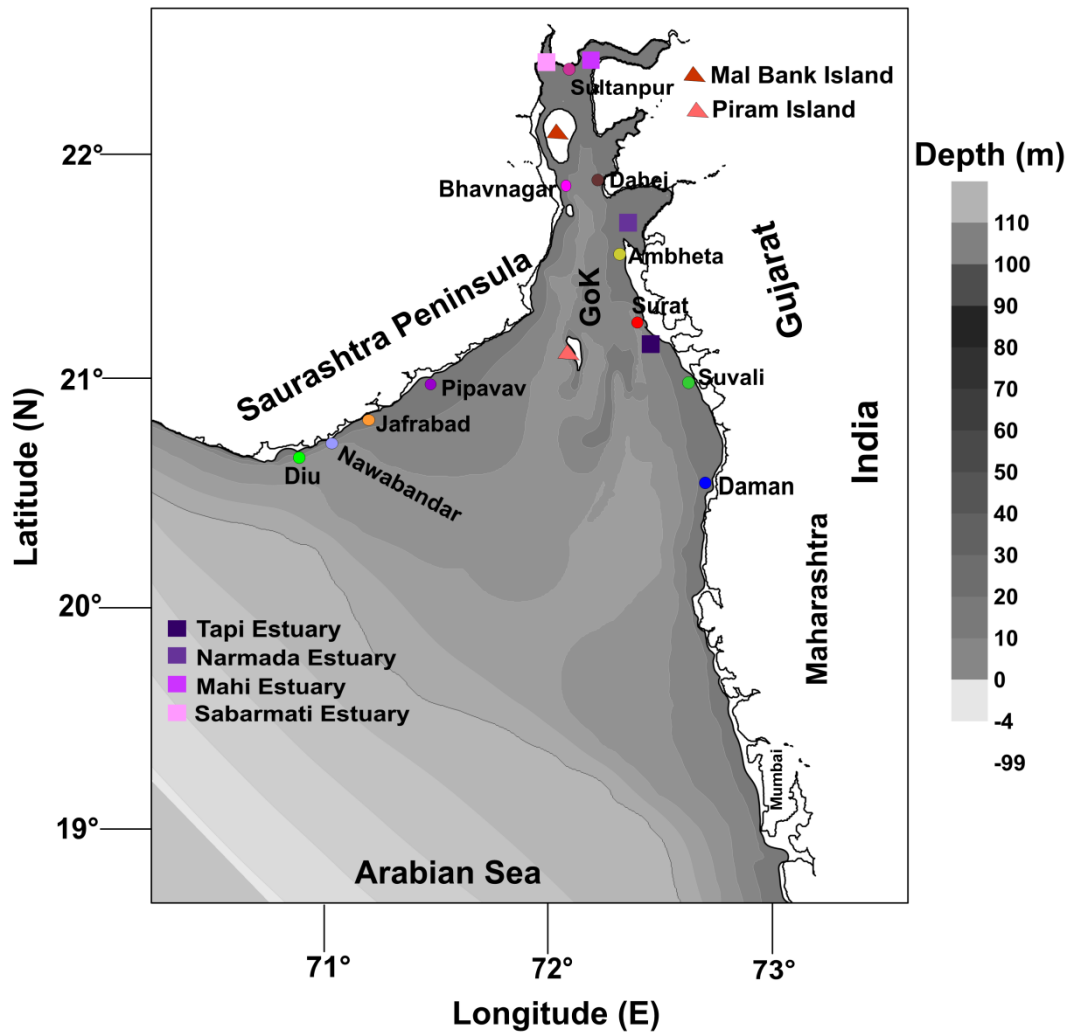


Figure 1. Study area (Gulf of Khambhat and surroundings) showing the bathymetry of the region. Maximum water depth in the model domain is more than 100 m. Total number of grid is 744x850 and the grid resolution is 500 m. The model extends towards land up to 4 m above the Chart Datum

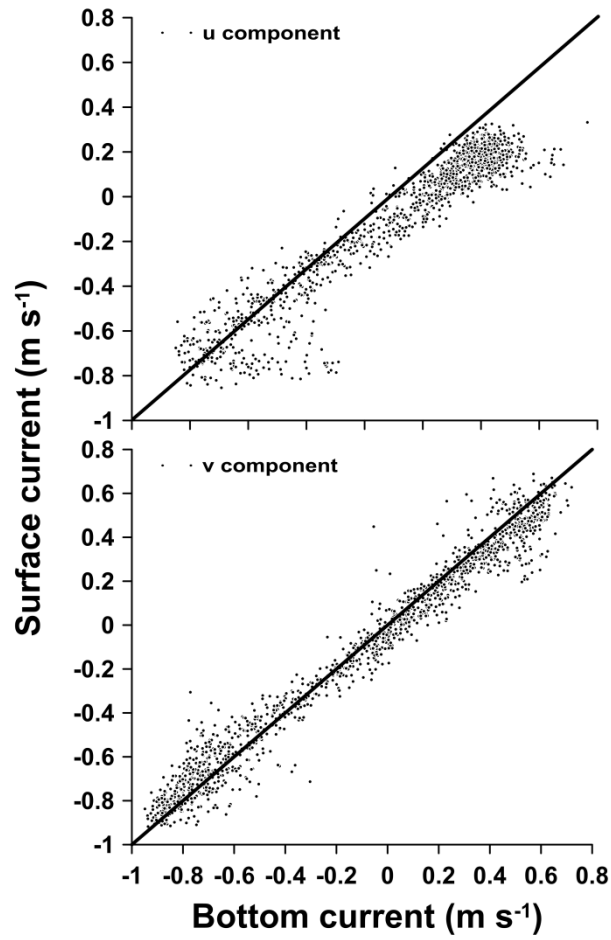


Figure 2. Near surface and bottom (2 m above seabed) currents measured with recording Doppler current profiler (RDCP) off Dahej at 12 m water depth from 18 to 28 March 2016.

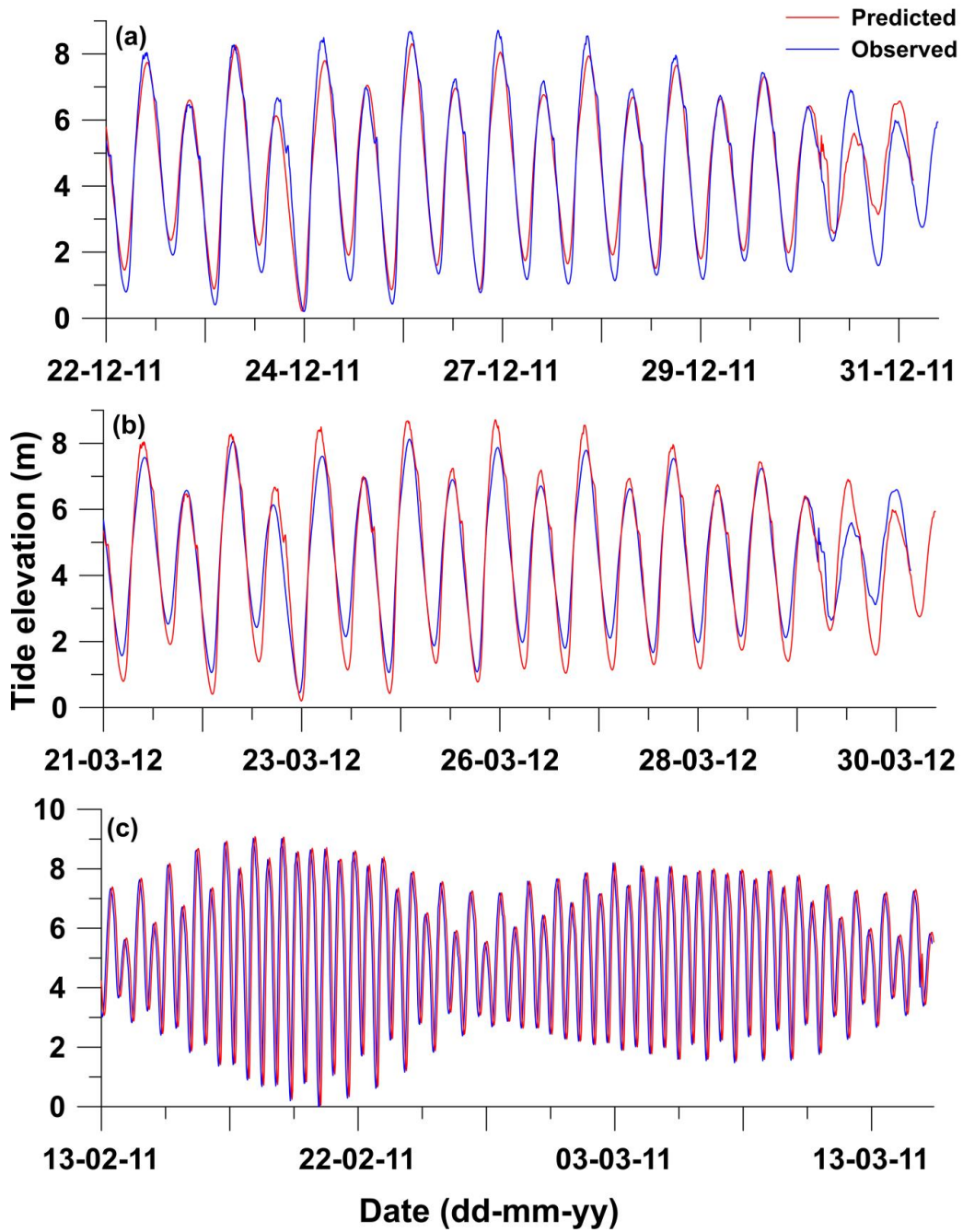


Figure 3. Comparison of observed and predicted tide elevation at three locations of GoK; a) Dahej, b) Surat and c) Bhavnagar. The location details along with comparison statistics are presented in Table 1

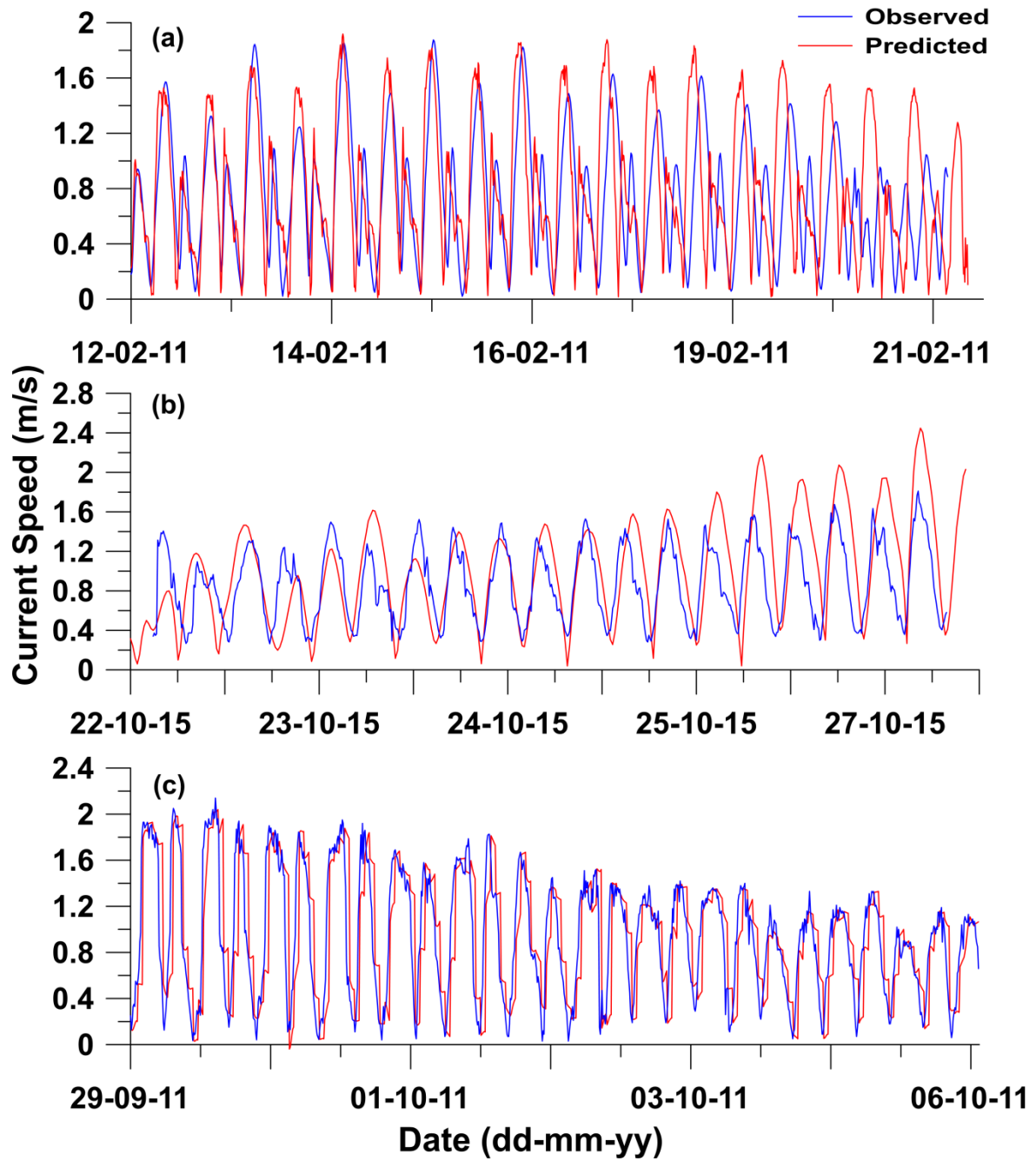


Figure 4. Comparison of observed and predicted current speed at three locations of GoK; a) Surat, b) Dahej and c) Bhavnagar. The location details along with comparison statistics are presented in Table 1.

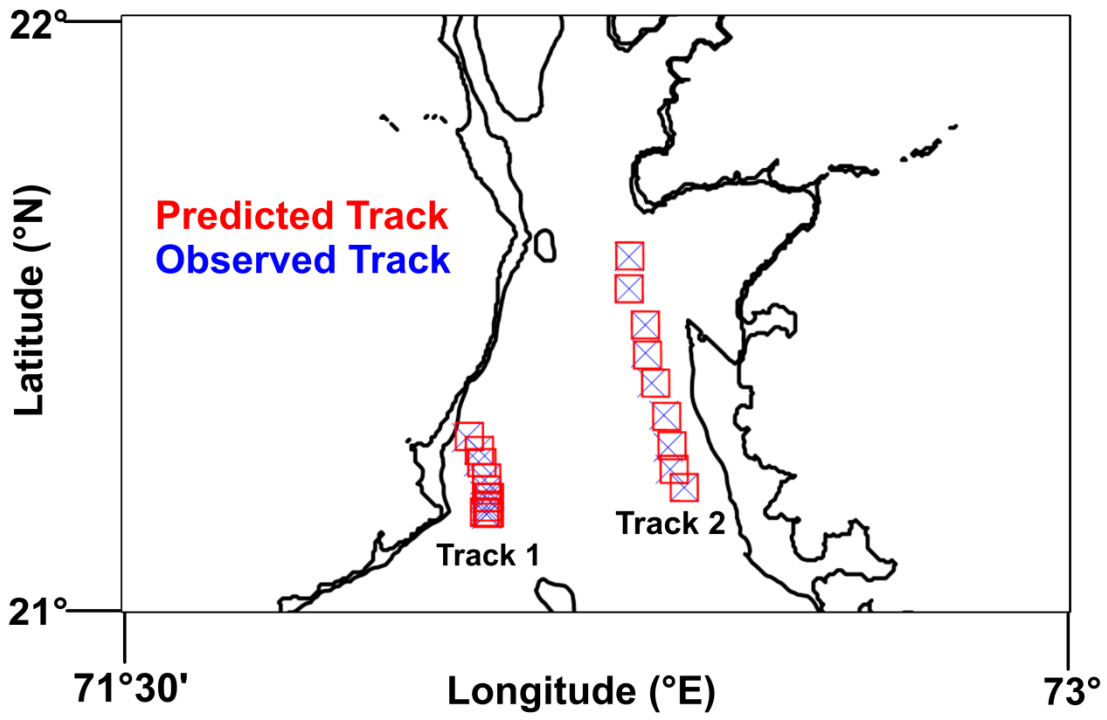


Figure 5. Comparison of observed and predicted Lagrangian particle track; Track 1 represents ebb condition while Track 2 represents flood condition

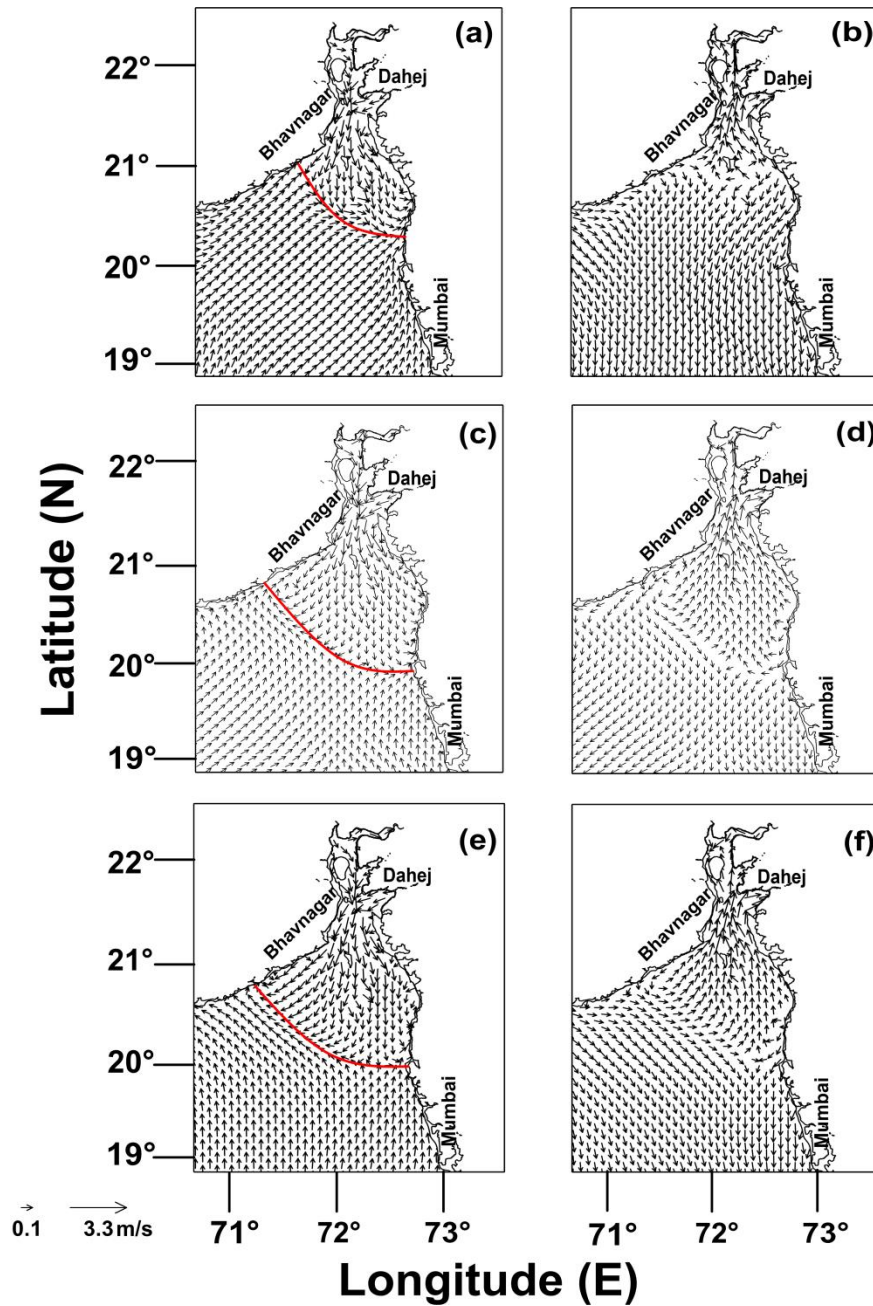


Figure 6. Circulation driven by combined action of tide and wind for various seasons in the neap tidal condition; a) neap ebb for NE-monsoon, b) neap flood for NE-monsoon, c) neap ebb for pre-monsoon, d) neap flood for pre-monsoon, e) neap ebb for SW-monsoon, f) neap flood for SW-monsoon; red line denotes the barrier.

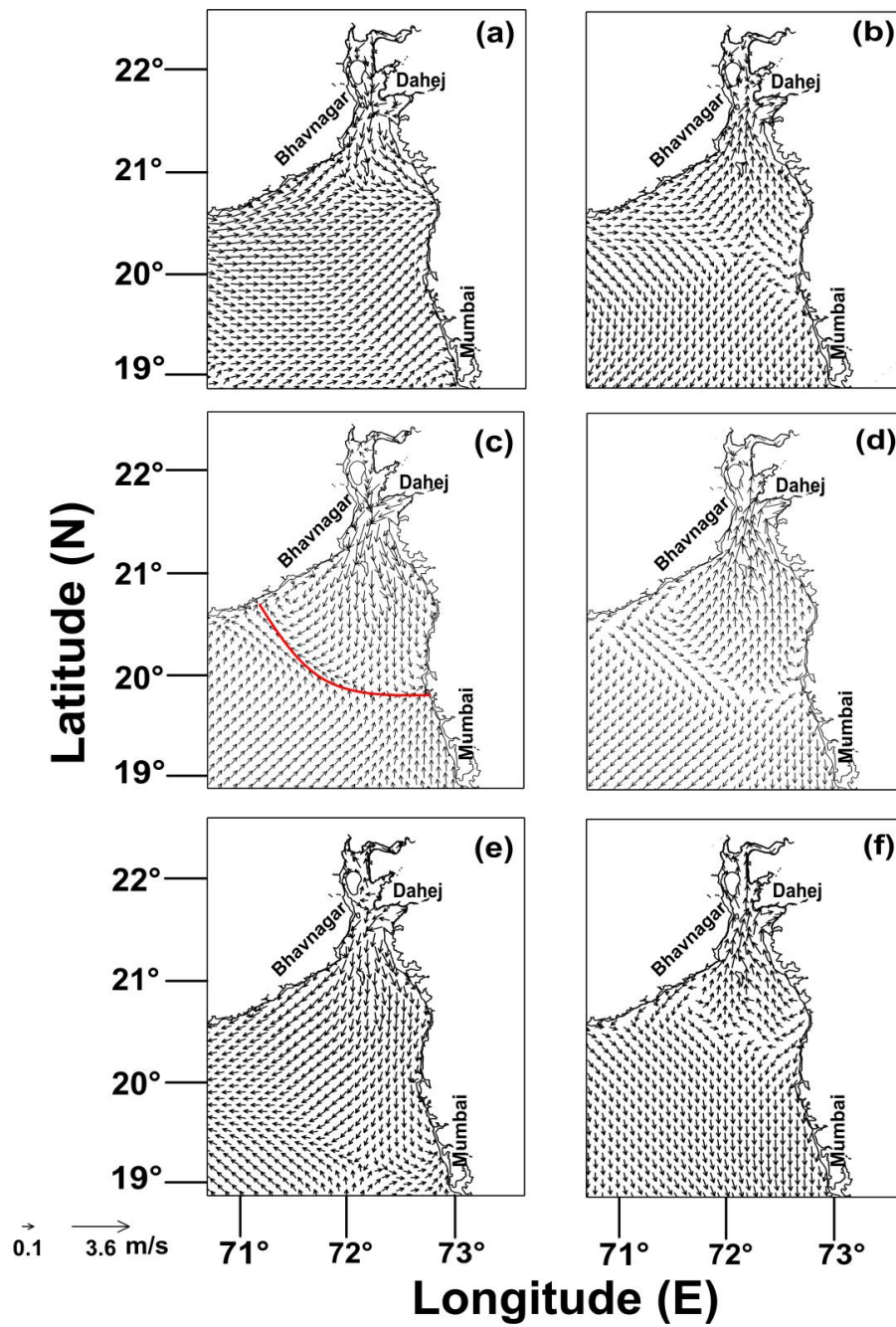


Figure 7. Circulation driven by combined action of tide and wind for various seasons in the spring tidal condition; a) spring ebb for NE-monsoon, b) spring flood for NE-monsoon, c) spring ebb for pre-monsoon, d) spring flood for pre-monsoon, e) spring ebb for SW-monsoon, f) spring flood for SW-monsoon; red line denotes the barrier.

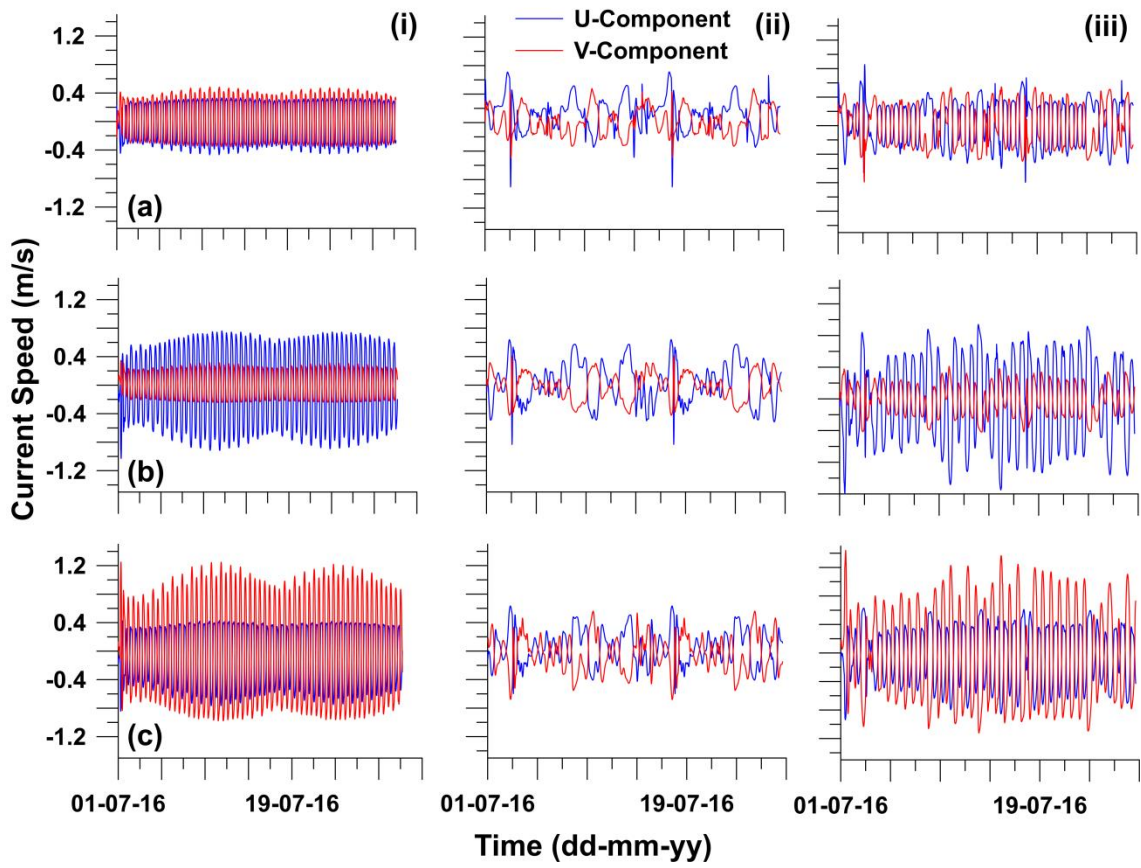


Figure 8. Time series of currents in SW-monsoon forced with (see column-wise) i) only tide ii) only wind and iii) tide and wind; for (see row-wise) a) northern Gulf b) eastern Gulf and c) western Gulf

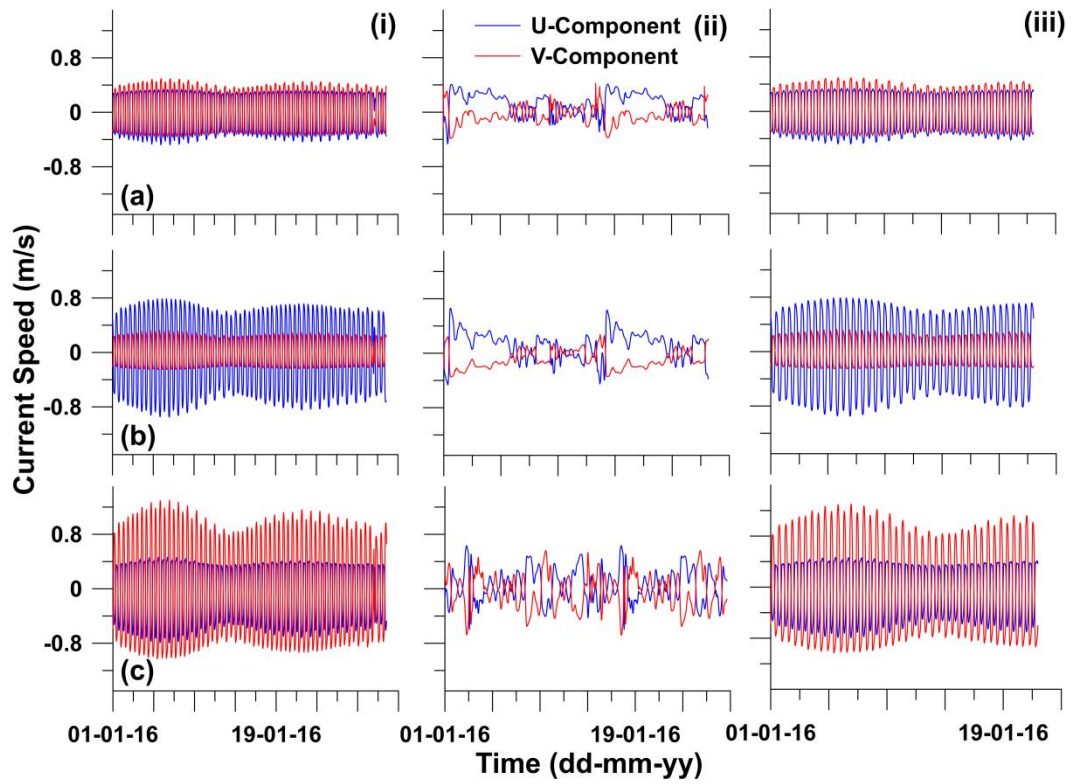


Figure 9. Time series of currents in NE-monsoon forced with (see column-wise) i) only tide ii) only wind and iii) tide and wind; for (see row-wise) a) northern Gulf b) for eastern Gulf and c) for western Gulf.

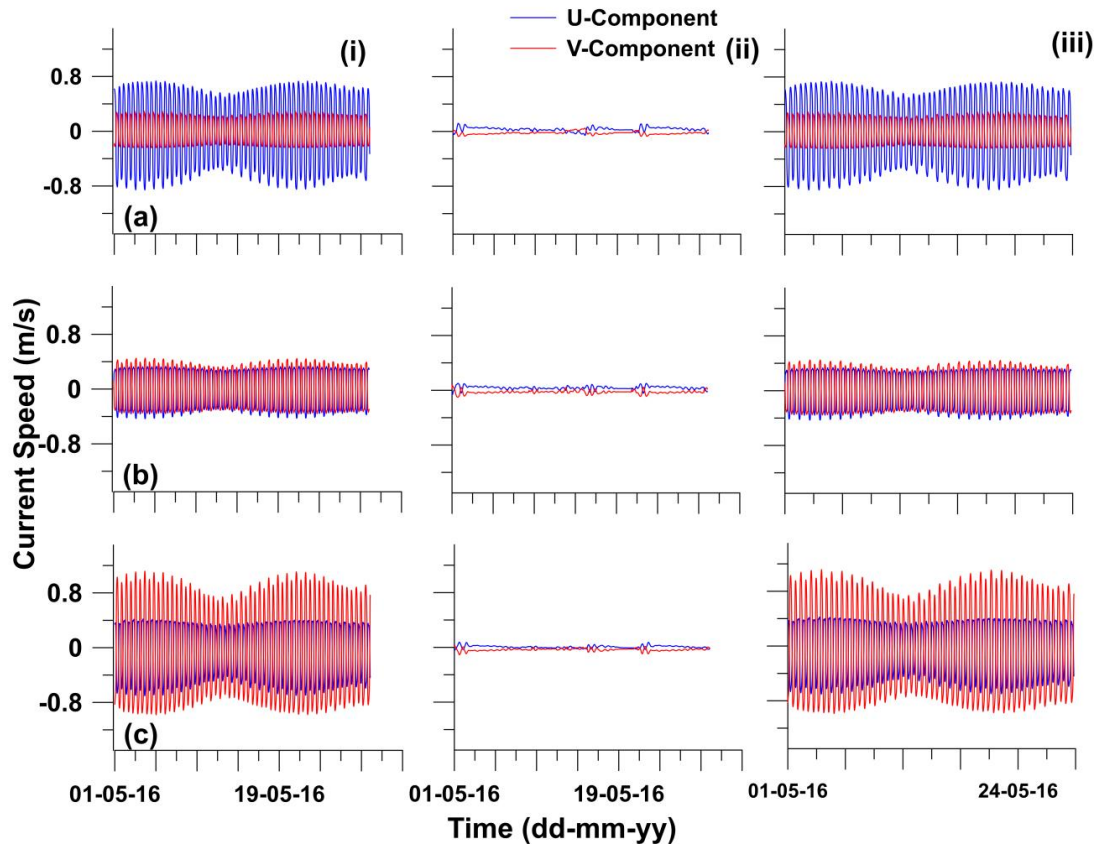


Figure 10. Time series of currents in pre-monsoon forced with (see column-wise) i) only tide ii) only wind and iii) tide and wind; for (see row-wise) a) northern Gulf b) eastern Gulf and c) western Gulf.

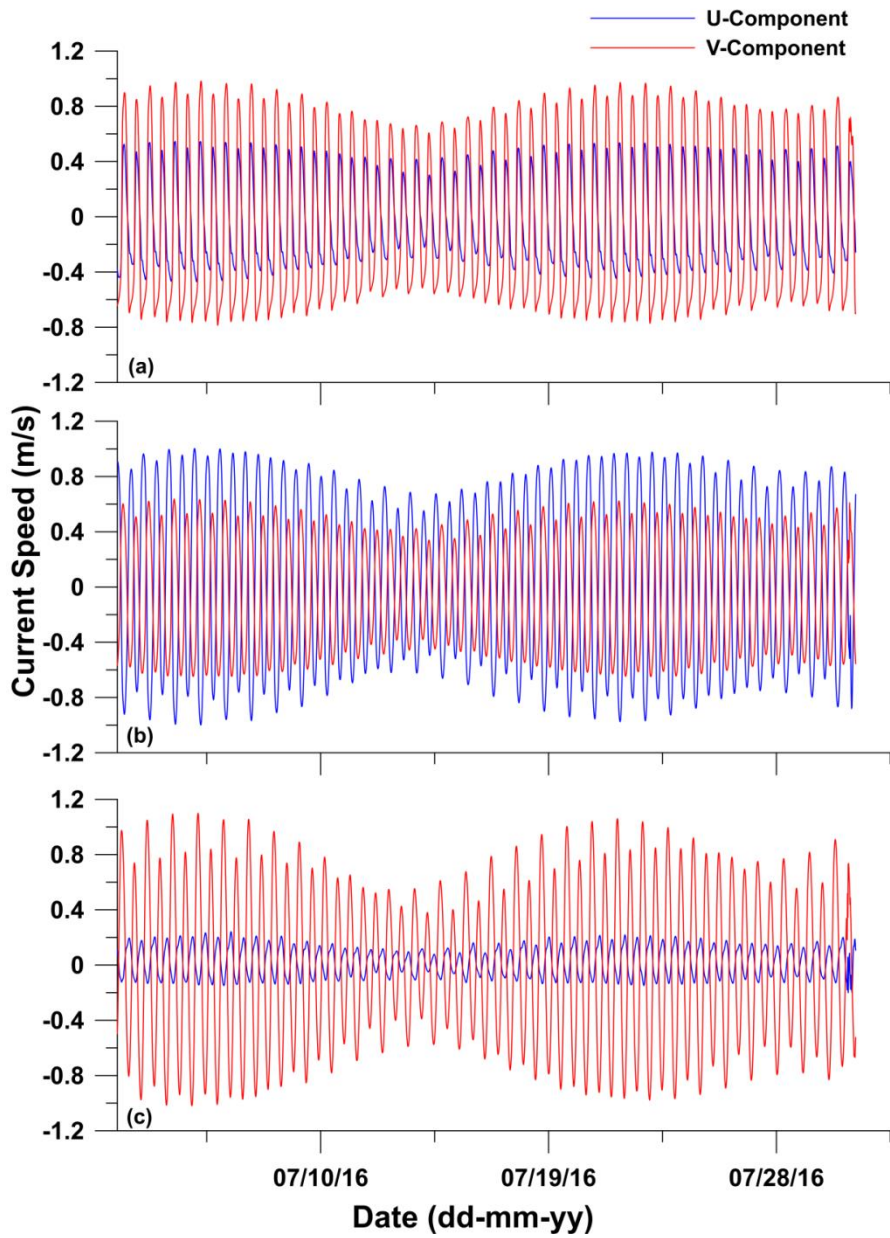


Figure 11. Simulated U-V component during SW-monsoon without river discharge at a) central GoK, b) Narmada mouth and c) southern GoK.

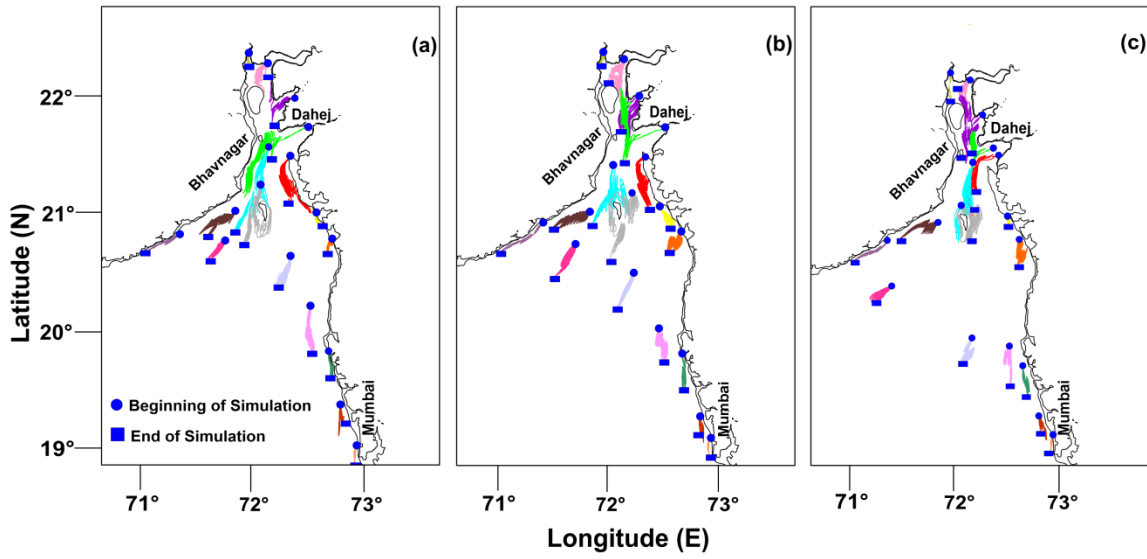


Figure 12. Lagrangian particle track results simulated for one month period during different seasons; a) NE-monsoon, b) pre-monsoon and c) SW-monsoon. Total 27 particle tracks in each season are represented. Particles released inside the Gulf have tendency to circulate there itself in different season.

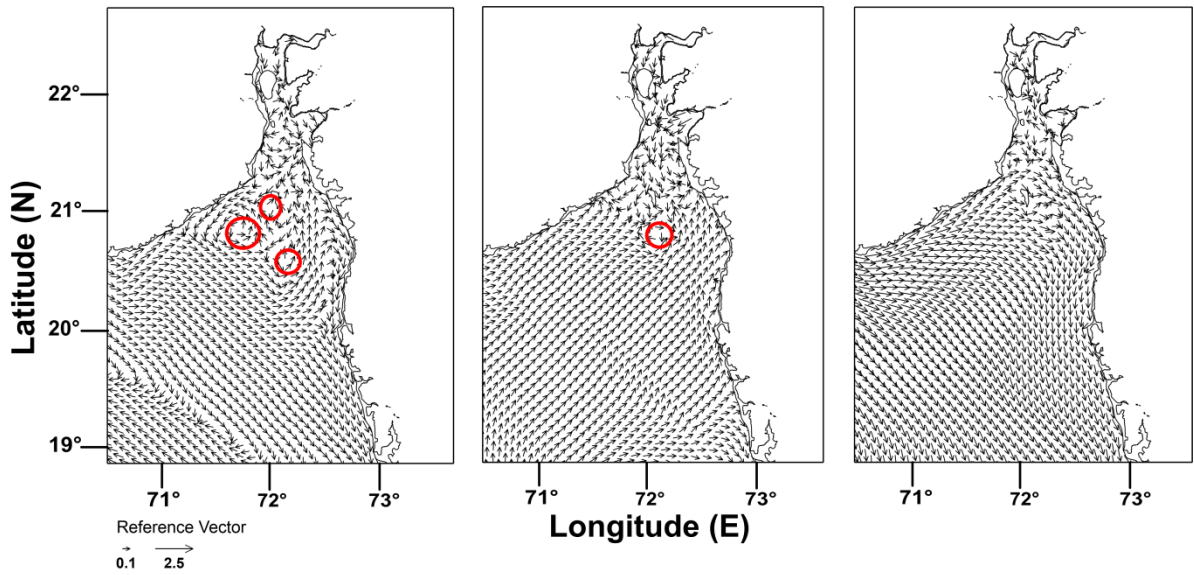


Figure 13. Residual circulation simulated during a) SW-monsoon, b) NE-monsoon and c) pre-monsoon where the red line denotes the residual eddies.

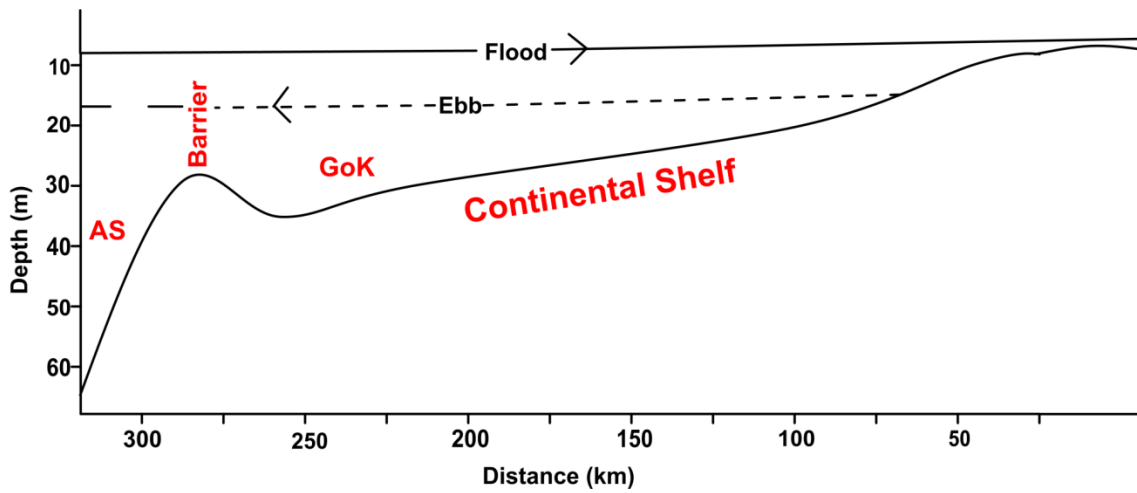


Figure 14. Schematic figure showing the formation of barrier due to the combined action of bathymetry and tide where water enters the Gulf due to high flood current speed but the barrier restricts the water exit during ebb.