

## Development of Oceanic Numerical Model for Persian Gulf (part 1)

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### ARTICLE INFO

#### Article History:

Received : 20 APR 2025

Accepted : 29 SEP 2025

#### Keywords:

Persian Gulf  
numerical model  
primitive equations  
sigma vertical coordinate  
forced tide.

### ABSTRACT

In this study, a three-dimensional numerical model (PersianGulfOceanicModel (ZSF974)) based on the primitive equations, in the Earth's Spherical Coordinates System with a sigma vertical coordinate, has been developed with the aim of predicting and calculating oceanographic parameters in the marine medium of the Persian Gulf. The finite difference method has been used for the numerical solution of the model equations. For discretization, the Lax–Wendroff scheme was applied to the advection terms, the DuFort–Frankel scheme to the diffusion terms, and the Matsuno scheme was used to eliminate instabilities arising from certain calculations within the program. The mesh used is the modified Arakawa C grid. This model, in addition to accommodating any type of non-level bottom, has the capability to vary resolution in both horizontal and vertical directions. The superiority of the process implemented in its design, the proper application of Nihoul's theory (1977) regarding the effect of surface stress induced by wind in the lower layers has enhanced the accuracy of the model's outputs. In this study is presented the process of designing the base model and the dimensions of its validation through models in laboratorial mediums. In all laboratorial oceanic mediums, the stationary state, the effect of neglecting the Coriolis force and earth's curvature, as well as the effect of applying a constant force have been investigated. Hypothetical (and approximate real) data and forced tide, have been used as the program's input. The results of the model's execution are consistent with ocean physics principles and the findings of previous researchers and can represent the overall behavior of an oceanic medium. This model can be used as a base model to examine the overall behavior of an oceanic medium. It also has the capability to be developed for implementation and conclusion in a real-world medium.

### 1. Introduction

The role of the oceans in climate regulation is fundamental. The strategic importance of the seas and oceans in transportation, fishing, energy supply, extraction of vast sub-sea mineral resources, and their contribution to national defense capabilities, as well as their role in maintaining biodiversity, is evident to everyone. One of the ways to proper use from the sea is to be aware of the dangers of working at sea by predicting sea conditions. This forecasting helps us maximize our benefits from the sea and minimize the

damages that may occur to us or non-human resources as a result of marine activities.

The complex and deep interrelationship between the parameters and non-linear terms in the governing equations; are the reasons that analytical solutions for governing equations is impossible nowadays. Therefore, numerical solutions are the most important and suitable approach for obtaining results from governing equations for getting oceanic states and predicting oceanic parameters in oceanic mediums.

The goal of ocean modeling is to understand the interaction processes between the atmosphere and the ocean, as well as ocean's state. The use of these predictions provides the foundation for aiding in the climate prediction of the relevant oceanic medium [1]. Among the oceanic numerical models, the primitive equation models can be the most comprehensive one. These models, due to their three-dimensional nature, offer high resolution in the vertical direction. In numerical models, oceanic mediums are divided into multiple layers in the vertical direction. Mmulti-layering means that at least one oceanic parameter will have a different value with the same parameter value in the other layer. On the other hand, in a single-layer or two-layer oceanic medium, phenomena such as double diffusion and internal wave cannot be well recognized. [1].

In numerical solutions, it is necessary to validate or calibrate these results. For this purpose, developing a theoretical ocean model can be highly beneficial. Theoretical models are defined by having some of the characteristics of a real oceanic medium. The model created in this form will contain accuracy of the response to a part of the final model and this model itself can serve as one of the foundations for the real models.

Researchers have designed various numerical models for different purposes that have been used in various research fields. In 1992, Khaleghi Zavare developed a non-linear barotropic model for the Persian Gulf. This model is based on the integration of shallow water equations in the vertical direction and is sensitive to the earth's rotation and the effects of bathymetric variations. The model was designed to determine the response to the Persian Gulf from wind and tidal forces through numerical simulation [2]. In 1994, Zamanian used a two-layer model to study the currents of the Persian Gulf. This model was designed on the primitive equations in Cartesian Coordinates System with a sigma vertical coordinate. This model, in addition to determining the current fields caused by wind and tides, predicts temperature, salinity in two layers, vertical velocity at a given level, and sea surface height at the grid points [3]. James (1998), a three-dimensional numerical model used to simulate the development of disturbances on shelf-sea coastal currents and fronts [4]. Kampf and Sadri-Nasab (2006) used a three-dimensional hydrodynamic simulator (COHERENS) to model the water circulation and water mass properties of the Persian Gulf – a large inverted estuary. These findings indicate that the Persian Gulf experiences a distinct seasonal cycle [5]. Ibrayev et al. (2010) used a three-dimensional primitive equation model including sea ice thermodynamics and air-sea interaction to study seasonal circulation and water mass variability in the Caspian Sea under the influence of realistic mass, momentum and heat fluxes [6]. Mehrfar et al., 2020,

employed COHERENS simulator as a three-dimensional hydrodynamic model to address the coastal currents in the western Persian Gulf. The obtained results suggested that a consequence of the influence of salinity flux, especially on the Iranian coasts, the speed of currents increases [7]. Heidari et al. (2018) designed a five-layer ocean numerical model based on primitive equations and the Earth's Spherical Coordinates System with a sigma coordinate. This research was conducted with the aim of predicting and calculating the currents caused by wind and oceanic parameter in the Caspian Sea [8]. Yining et al., 2024, proposed an ocean SWH (Significant Wave Height) prediction model, RIME-CNN-BiLSTM, for predicting 1, 6, 12, and 24 h SWH at three buoy observing stations in the Gulf of Mexico [9]. Deldar (2024) simulated wind waves in the Strait of Hormuz using the D3Delft three-dimensional simulation processor flow module hydrostatically and non-hydrostatically, where is prone to the formation of lee waves due to its many shallow channels. The results indicate the presence of lee waves in the Strait of Hormuz [10].

Fallahi et al. (2019) designed a "Five-Layer Numerical Ocean Model of the Persian Gulf." The aim of this study was to predict physical parameters in the Persian Gulf [11]. In the course of refining and enhancing the model, a laboratory-scale oceanic basin was configured to resemble the Persian Gulf. A two-year simulation revealed that the basin is dominated by semidiurnal tidal forcing, which prevails over wind stress and density gradient forces [22]. The consistency of the results with ocean physics principles and previous research findings provided a solid basis for further development of the model.

The Persian Gulf (Figure 1) is located in the south of Iran, with latitudes ranging from 24° N to 30°30' N, and longitudes from 48° E to 56°25' E from the Greenwich meridian.

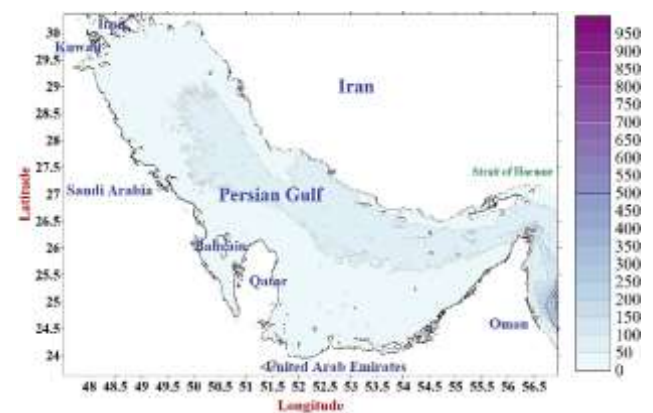


Figure 1- Location and bathymetry of the Persian Gulf

Since the Persian Gulf holds a vast maritime boundary for Iran, it has of significant medium and important for, economic, tourism, and strategic activities. Moreover, due to its unique geographical location, the Persian

Gulf holds special strategic and economic value in the western part of Asia. Therefore, any research or study for this basin is considered crucial and strategic in terms of planning.

Since numerical modeling can be a powerful research tool. The PersianGulfOceanicModel(ZSF974) was designed as a foundational model with the aim of predicting oceanographic parameters and sea state in this oceanic medium.

This model is not only enables the examination of complex dynamic processes but also plays a crucial role in marine resource management, provides prerequisite for knowing Persian Gulf's climate, and the enhancement of warning systems for atmospheric and oceanic phenomena.

The method employed in model's design allowing applicable to any hypothetical or real basin, whether closed or open. Another advantage of this model, is comparing to similar models designed by previous researchers, And the superior algorithm used in its design, which ensures that predictions and calculations are carried out correctly, is taking into account the proper relationships between the mathematical equations used in it. Furthermore, the correct application of Nihoul's theory regarding the effect of wind-induced surface stress on the lower layers in multi-layer mediums has made the model's outputs more accurate. [12]

This study presents the setup process of the "PersianGulfOceanicModel (ZSF974)" oceanic numerical model [11]. The technical notes for the design and development of the Base Oceanic Model (BOM) have been used to design and develop this model [1].

Therefore, the "PersianGulfOcean(ZSF974)" model is an development and expanded version of the "BOM" model to simulate real ocean mediums. The study was conducted in two stages: for laboratorial basins and real oceanic basins. This article presents the technical points of designing these models, and the aspects of "PersianGulfOceanicModel (ZSF974)" validation in laboratory mediums.

## 2. Method and Theoretical Framework

In design of this kind of oceanic models, in addition to there is utilizing and applying the governing physical principles of the atmosphere and ocean, such as Newton's laws, the conservation of mass, the conservation of salinity, and the conservation of thermal energy, the first and second laws of thermodynamics and the equation of state for seawater. In order for the proposed model to accommodate any non-level bottom as the actual topography of oceanic mediums during the operational stage, the Sigma vertical coordinate ( $\sigma$ ) has been utilized. In this study, the vertical coordinate is considered in the form introduced by Zamanian (2006) [1]:

$$\sigma = \frac{p - p_A}{p_b - p_A} \quad (1)$$

where  $\sigma$  presents the normalized vertical coordinate,  $p_b$  denotes the bottom pressure at any point in the oceanic medium,  $p_a$  refers to the atmospheric pressure over the oceanic medium and  $p$  stands for pressure at any point in the ocean medium. In this system,  $\sigma = 0$  corresponds to the ocean surface, and  $\sigma = 1$  presents the ocean bottom. The values  $0 < \sigma < 1$  correspond to the intermediate levels.

The unit vectors in The Earth's Spherical Coordinates System with the sigma vertical coordinate can be defined as:  $e_\lambda$  in the direction of increasing  $\lambda$ , the longitude,  $e_\phi$  in the direction of increasing  $\phi$ , the latitude and  $e_\sigma$  in the direction of increasing  $\sigma$ , downward. Also  $e_\sigma$  is a variant unit vector. The lengths components in this system are as follows:

$$\begin{cases} \delta s_\lambda = r \cos \phi \delta \lambda \\ \delta s_\phi = r \delta \phi \\ \delta s_\sigma = \frac{p_b - p_A}{\rho g} \delta \sigma \end{cases} \quad (2)$$

where  $\delta s_\lambda$  is a portion length in longitude direction,  $r$  is the radial distance of the length component from the earth's center,  $\phi$  is latitude,  $\delta \lambda$  stands for increment of longitude,  $\delta s_\phi$  refers to a portion length in latitude direction,  $\delta \phi$  denotes to increment of latitude,  $\delta s_\sigma$  represents a portion length in vertical direction,  $p_b$  indicates the bottom pressure,  $p_A$  stands for atmospheric pressure,  $\rho$  is the density, and  $g$  is the gravitational acceleration of the earth. The velocity vector in this system also write as follows:

$$\mathbb{w} = u e_\lambda + v e_\phi + w e_\sigma \quad (3)$$

where the components of velocity are:

$$\begin{cases} u = r \cos \phi \frac{D\lambda}{Dt} \\ v = r \frac{D\phi}{Dt} \\ w = \frac{p_b - p_A}{\rho g} \frac{D\sigma}{Dt} \end{cases} \quad (4)$$

Using equations (2), (3) and (4), the total rate of change of a variable in this system gives by:

$$\frac{D \dots}{Dt} = \frac{\partial \dots}{\partial t} + \frac{u}{r \cos \phi} \frac{\partial \dots}{\partial \lambda} + \frac{v}{r} \frac{\partial \dots}{\partial \phi} + \dot{\sigma} \frac{\partial \dots}{\partial \sigma} \quad (5)$$

In which  $\frac{D \dots}{Dt}$  is the total derivative,  $\frac{\partial \dots}{\partial t}$  represents the local rate of change,  $\frac{u}{r \cos \phi} \frac{\partial \dots}{\partial \lambda}$  denotes the eastward advection,  $\frac{v}{r} \frac{\partial \dots}{\partial \phi}$  represents the northward advection,

and  $\sigma \frac{\partial \dots}{\partial \sigma}$  refers to the representative of vertical advection or convection [1].

Based on the before-mentioned points, the model equations in the Earth's Spherical Coordinates System with the sigma vertical coordinate can be rewritten. These equations include, the eastward motion equation, the northward motion equation, the thermal conductivity equation, the temperature equation, the specific volume equation, the salinity equation, and the equation related to the first and second laws of thermodynamics.

To complete the design of the model, additional equations are required. These equations, referred to as the completion equations, are as follows: the hydrostatic equation, the equation for calculating geopotential, the equation for calculating bottom pressure tendency, the equation for the representative vertical velocity ( $\sigma$ ), and the equation for calculating the radial distance of each point from the earth's center. It is essential that all equations were written in the Earth's Spherical Coordinates System with the sigma vertical coordinate.

When the wind blows over an oceanic medium, the wind momentum is transferred to the ocean's surface due to the friction between the atmosphere and ocean. As a result, the wind speed decreases, and ocean's surface currents are generated.

Surface stress approximately depends on wind speed in the form of a quadratic. This stress is the aerodynamic force per unit area that is exerted by the wind on the sea surface [13].

$$\tau_s = c_d \rho_a (|\mathbf{v}_a| - |\mathbf{v}_s|) (\mathbf{v}_a - \mathbf{v}_s) \text{ Nm}^{-2} \quad (6)$$

where  $\tau_s$  is the surface stress,  $c_d$  is aerodynamic drag coefficient known as the aerodynamic drag coefficient,  $\rho_a$  is the air density,  $\mathbf{v}_a$  is the wind speed at the 10-meter level above the sea surface, and  $\mathbf{v}_s$  is the oceanic current velocity at the surface.

According to Wu (1985), aerodynamic drag coefficient, which is dimensionless, is given by:

$$c_d = (0.8 + 0.065 U_{10}) \times 10^{-3} \quad (7)$$

where  $c_d$  stands for aerodynamic drag coefficient and  $U_{10}$  denotes the wind speed at a 10-meter height. For bottom stress, the formulation proposed by Nihoul (1977) has been used. [12]

$$\tau_b = -m \tau_s + C_D \rho_w |\mathbf{v}| \mathbf{v} \quad (8)$$

Where  $\tau_b$  is the bottom stress,  $m = 0.7$  is the dimensionless coefficient for surface stress,  $\tau_s$  is the surface stress,  $C_D = 0.00211$  is the dimensionless drag coefficient for hydrodynamics,  $\rho_w$  is the water density,  $|\mathbf{v}|$  is the magnitude of the integrated current, and  $\mathbf{v}$  is the vector of the integrated current.

In general, the stress tensor in the Earth's Spherical Coordinates System with the sigma vertical coordinate is given as follows [1]:

$$\boldsymbol{\tau} = \begin{bmatrix} \tau_{\lambda\lambda} & \tau_{\lambda\phi} & \tau_{\lambda\sigma} \\ \tau_{\phi\lambda} & \tau_{\phi\phi} & \tau_{\phi\sigma} \\ \tau_{\sigma\lambda} & \tau_{\sigma\phi} & \tau_{\sigma\sigma} \end{bmatrix} \quad (9)$$

In this context, each term represents the stress associated with velocity changes in different directions of the coordinate system [1].

As an example,  $\tau_{\lambda\sigma}$  represents the stress associated with the changes of the vertical velocity indicator,  $\sigma$ , in the longitudinal direction;  $\tau_{\sigma\phi}$  represents the stress associated with the changes of the latitudinal velocity in the vertical direction and  $\tau_{\sigma\sigma}$  represents the stress associated with the changes in the vertical velocity indicator,  $\sigma$ , in  $\sigma$  direction.

The structure of a multilayer ocean model in Earth's Spherical Coordinates System with the sigma vertical coordinate is introduced as shown in Figure 2.

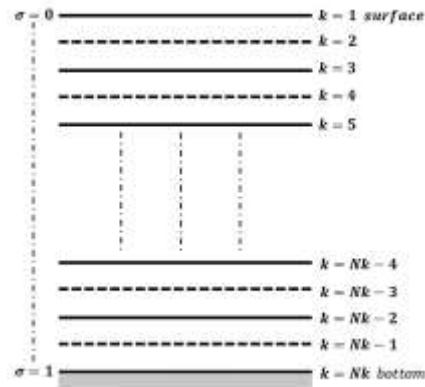


Figure 2- Vertical alignment scheme of a multilayer oceanic medium

Figure 2 shows the schematic of the vertical orientation of an n-layer (level:  $Nk = 2n + 1$ ) oceanic medium. The counter of the levels is  $k$ .

a) Odd numbers of  $k$  correspond to the boundaries of the layers, while even numbers are assigned to the inter-layer regions.

b)  $k = 1$  represents the first level or the ocean surface, which is indicated by  $\sigma = 0$  in the vertical coordinate system.

c)  $k = Nk$  represents the last level or the ocean floor, which is indicated by  $\sigma = 1$  in the vertical coordinate system.

In this study, the Modified Arakawa C-grid [14] has been employed for gridding the oceanic medium.

To perform the initial steps for predicting the future state of the target medium, the model equations must be solved. In this study, a numerical method is used to solve the governing equations. Accordingly, the model equations are discretized based on an appropriate numerical method and scheme, and then a computer program has been developed in C# based on the discretized equations.

Geometric conditions, slope and elevation of the bed, and initial data can be entered into the calculations.

Determining an appropriate time step for the stability of the program is an important and notable aspect in any numerical modeling. Finite difference numerical method is used to solve and discretize the equations. For this purpose, the two-step Lax-Wendroff scheme is used for advection terms, the Dufort-Frankel scheme for diffusion terms, and the remaining derivatives are discretized using the central difference method. Furthermore, the Matsuno scheme [15] is used to mitigate the instability caused by certain computations in the program.

The Dufort-Frankel scheme is an explicit scheme and is always stable, while the stability condition for the Lax-Wendroff two-step scheme needs the C.F.L (*Courant, Friedrichs and Lewy stability condition*) condition [16], defines the stability condition differently for the Cartesian Coordinate System, which in the Earth's Spherical Coordinates System with a sigma vertical coordinate becomes:

$$\Delta t \leq \min \left( \frac{r \cos \phi \Delta \lambda}{u}, \frac{r \Delta \phi}{v}, \frac{\Delta \sigma}{\dot{\sigma}} \right) \quad (10)$$

The initial execution begins with motion starting from rest. In this regard, assuming no forces are present, the local changes in the potentials whose gradients induce motion must be zero.

Regarding the boundary conditions, since water cannot pass through the surface and the bottom [3] closed boundaries are considered as rigid and no-slip condition is applied in this study. Therefore, the tangential and vertical velocity components at the boundaries are equal to zero, i.e.:

$$\mathbf{v}(\lambda, \phi, \sigma, t) \cdot \mathbf{n} = 0 \text{ and } \mathbf{v}(\lambda, \phi, \sigma, t) \cdot \mathbf{t} = 0 \quad (11)$$

In the above equation,  $\mathbf{t}$  and  $\mathbf{n}$  are the unit vectors tangential and normal to the rigid boundary, respectively. Since no flow passes through the bottom of the medium, it follows that:

$$\sigma = 1 \Rightarrow u = v = \dot{\sigma} = 0 \quad (12)$$

The dynamic boundary condition for the open boundary is considered as follows:

$$\frac{\partial p}{\partial \lambda} = \frac{\partial p}{\partial \phi} = \frac{\partial \Phi}{\partial \lambda} = \frac{\partial \Phi}{\partial \phi} = \frac{\partial p_b}{\partial \lambda} = \frac{\partial p_b}{\partial \phi} = 0 \quad (13)$$

And kinematic boundary condition imposes:

$$\begin{aligned} u = \dot{u}, v = \dot{v}, \dot{\sigma} = \dot{\dot{\sigma}}, \rho = \dot{\rho}, \eta = \dot{\eta}, T \\ = \dot{T}, s = \dot{s} \end{aligned} \quad (14)$$

And:

$$\left( \frac{D \dots}{Dt} \right)_{(\sigma=0)} = \left( \frac{D \dots}{Dt} \right)_{(\sigma=1)} = 0 \quad (15)$$

where in (14) parameters without prime are belong to original oceanic medium and parameters with prime are out of original oceanic medium after open boundary. One of the assumptions used in the development of the Basic Oceanic Model is neglecting the term  $-\vec{\Omega} \times (\vec{\Omega} \times \vec{r})$  in comparison to the other terms of the equation of motion in the Earth's Spherical Coordinates System with a sigma vertical coordinate.

Applying specific conditions to the program and comparing its outputs with theoretical physical principles can also serve as an appropriate validation for the designed model. Calibration during the model execution for experimental basins identifies the model's weaknesses and leads to its improvement.

For model's implementation in laboratorial oceanic basins (even real medium), hypothetical (and approximate real) data are used as input to the program. The tidal force is considered as a sinusoidal function with a hypothetical amplitude. However, tidal force have been made to incorporate water level variations in the Strait of Hormuz (which is the open boundary of the real medium). The water level variations in the Strait of Hormuz have been extracted from the hydrography information database of the National Cartographic Center of Iran [17].

### 3. Results and Discussion

Up to this point, the design process of the fundamental oceanic numerical model, PersianGulfOceanicModel (ZSF974), has been explained. The following sections present the results of the model's implementation in laboratorial oceanic basins, along with the validation aspects of these models. Finally, necessary strategies for improving the model and achieving an efficient version for real oceanic applications are provided.

The model design requirements necessitate the replication of fundamental experiments previously conducted by other researchers for model evaluation and validation, using the laboratory models of this study. The response of the present model to experimental conditions already tested by earlier researchers has also been examined, however, due to the repetitive nature and abundance of these tests, their details have not been included in this paper. ([8], [18], [19], [20]).

The immobility test is the first test conducted after each modification to the model or its execution for a new medium. In this study, the duration of model execution to achieve confirmation of the immobility test at each stage was at least ten years.

Another test examines the effect of removing the Coriolis force and earth's curvature. In this scenario, if a constant force is applied in a specific direction (such as uniform wind flow), the model's output, in the absence of the Coriolis force and earth's curvature, would result in a uniform current aligned with the applied force.

After the model's performance in these two tests yielded positive results, subsequent stages and additional tests, including the effects of wind in different directions, tidal effects, river inflow effects, and density gradient, were examined and analyzed to finalize the developed model. Instead, this chapter presents the results of other laboratorial models that were examined due to the more complex conditions of real mediums and the presence of multiple influencing forces in the actual oceanic system.

The theoretical mediums presented in this study are defined within the longitudinal range of 48.25 °E to 56.75 °E and the latitudinal range of 24.25 °N to 30.25 °N, with a resolution of 0.25 degree in both directions. All laboratorial mediums in this study are configured with 10 layers, and the time step is set to 100 seconds according to C. F. L. stability condition.

### 3.1. Results of the simulation of the effect of density gradient in a closed laboratorial medium with a concave bottom.

This type of bottom is used to examine the model's response to oceanic basins with a density gradient, as well as the effect of a non-level bottom with a specific and defined curvature (Figure 3).

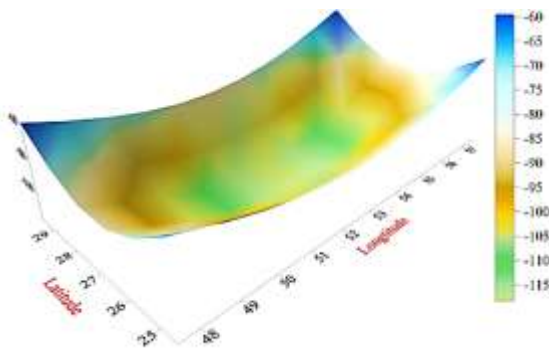


Figure 3- A scheme of the figure and the bottom of the laboratorial medium under study

The maximum depth of this medium is 99.93 m, and the minimum depth is 55.57 m. The surface salinity is 40 psu, with a salinity increased by 0.25 psu per level. The surface temperature is 25 °C, and the temperature decreased by 0.25 °C per level.

Therefore, the studied medium exhibits density gradient across various layers, and in the absence of other forces, it can motivate. This movement is caused by the horizontal gradient in the layers.

When the medium is released from rest, an initial flow toward the center develops. Over time, these vectors rotate to the right, forming a counterclockwise circulation (Figure 4). Similarly, a flow develops in all layers, including the bottom layer.

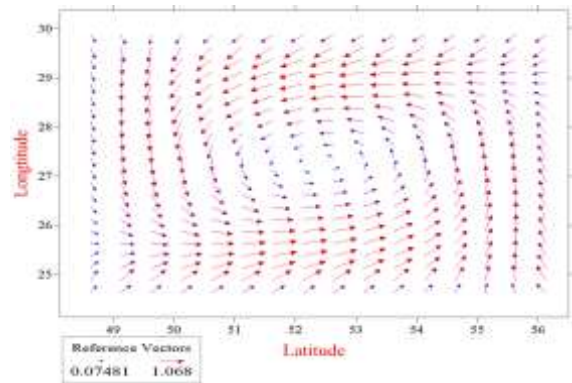


Figure 4- Flow field at the mid-level of the first layer at the end of the fifth day of model execution

The rotation of the current vector is caused by the earth's rotation and the Coriolis force. [21]

According to initial condition, the mid-level of the first layer had a salinity of 40.25 psu and a temperature of 24.75°C. The model results indicate the intrusion of salinity from lower levels into this layer and the diffusion of temperature from this layer to the lower levels (Figure 5 and Figure 6). On the third day of running model, the variations of these parameters reach to semi-steady state (stabilization of currents and water level) and become evident in the model results, continuing until the entire medium reaches uniform temperature and salinity.

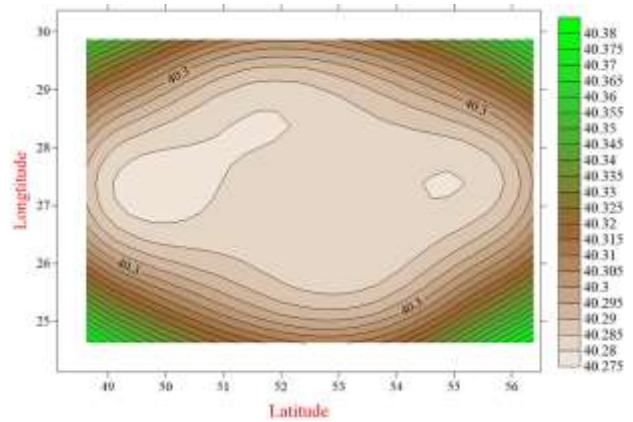


Figure 5- Salinity field at the mid-level of the first layer at the end of fifth day of running the model

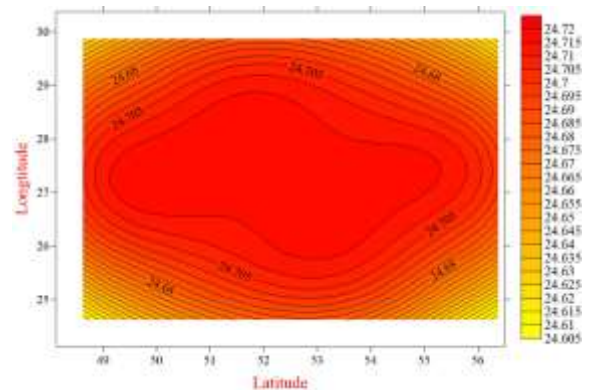


Figure 6- Temperature field at the mid-level of the first layer at the end of fifth day of running the model

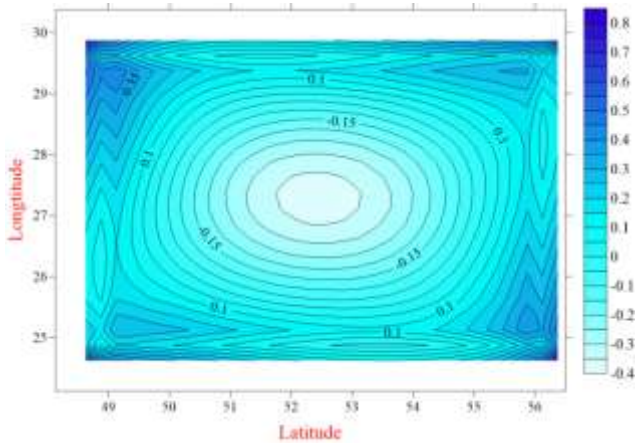


Figure 7- Departure from static equilibrium field at the mid-level of the first layer at the end of fifth day for running the model

The formation of flow in the direction of the density gradient and the counterclockwise rotation of the current vector under the influence of the Coriolis force, as well as the distribution of salinity and temperature, are in accordance with expectations and the principles of ocean physics.

### 3.2. Tide Simulation Results in a Laboratorial medium with a Level Bottom

As the simplest laboratorial oceanic basin with open boundary, a rectangular cuboid medium with a level bottom and a constant depth of 98 meters, where the eastern boundary is completely open, has been considered.

In this experiment, salinity and temperature are uniform throughout the entire oceanic medium, set at 40 psu and 25 °C, respectively. Tides are imposed as sea level variations at the open eastern boundary [17]. The model was run for 10 days to examine the response of the medium to tidal forces. The results of the isopleth analysis of the departure from static equilibrium indicate (Figure 8 and Figure 9) that the changes in water level at the eastern open boundary create a current parallel to the coast, which starts moving from the northern boundary of the oceanic domain, resulting in a counterclockwise rotation within the medium. If an observer stands in the direction of the current, the highest water level will be observed on the observer's right-hand side. [21]

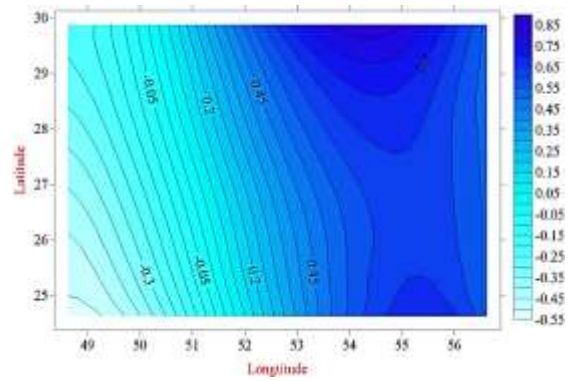


Figure 8- Contour Lines of departure from static equilibrium – mid-level of the first layer- hour zero of the tenth day

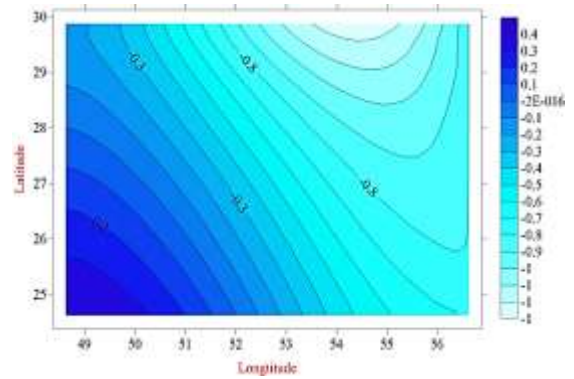
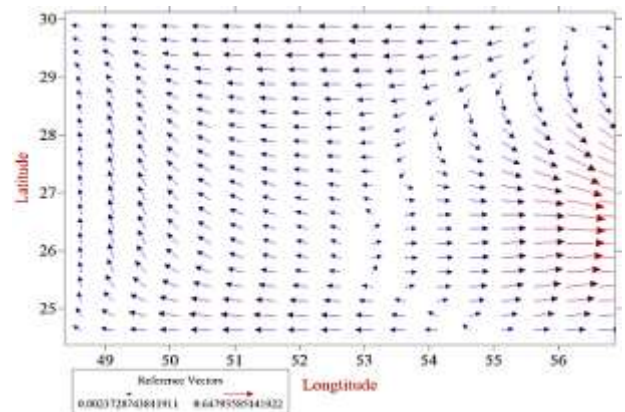


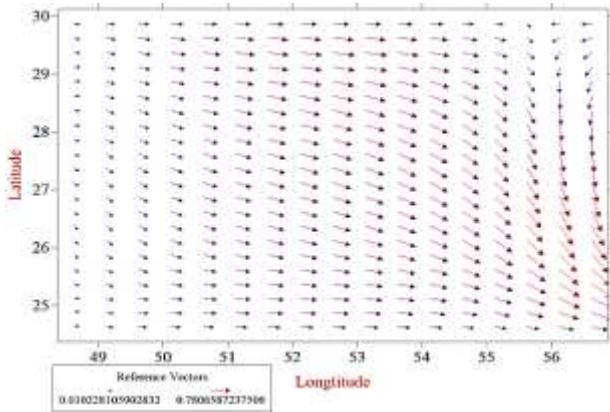
Figure 9- Contour Lines of departure from static equilibrium – mid-level of the first layer- at 12:00 of the tenth day

The presence of amphidromic points is also evident in these figures. The maximum total variation in water elevation relative to static equilibrium in this simulation was approximately 4.8m.

In the analysis of the current fields, a maximum current of 1.33m/s was obtained, which occurred at the open boundary (Figure 10 and Figure 11). The current vectors near the boundaries are parallel to the boundary [21]. Based on contour lines showing the departure from static equilibrium (Figure 8 and Figure 9), if an observer stands in the direction of the flow, the maximum water height will be located to their right and with good accuracy, it can be concluded that the component of the flow normal to the boundary is zero. Therefore, a Kelvin wave could be present in the region.



**Figure 10- Current field at the mid-layer level, first layer - zero hour of the tenth day**



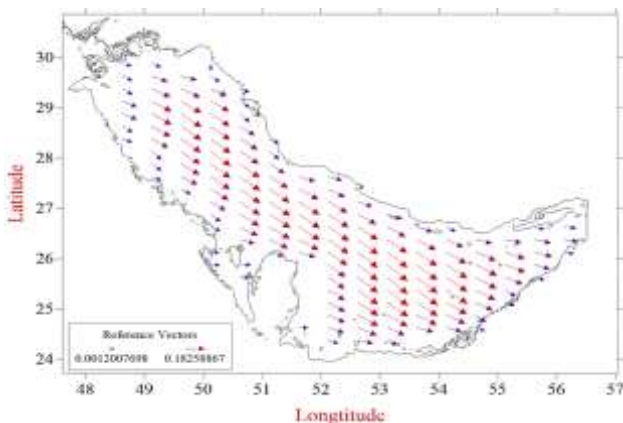
**Figure 11- Current field at the mid-layer level, first layer - at 12:00 of the tenth day**

**3.3. Simulation’s results of the effect of wind and density gradient for the laboratorial medium with a level bottom and the Persian Gulf**

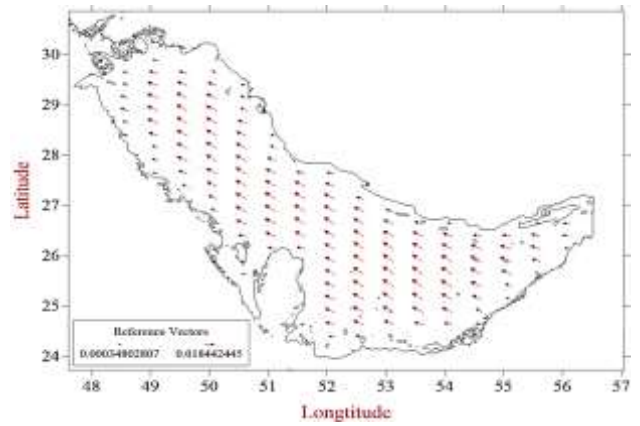
This closed laboratorial model has a flat bottom, but the shape of the oceanic basin and its boundaries correspond to the Persian Gulf and are used to examine the curvature of the boundaries.

The depth of this oceanic medium is constant at 98 meters. The surface salinity is 40 psu, with an increase of 0.25 psu per level. The surface temperature is 25 °C, with a decrease of 0.25 °C per every level.

Due to the flat seabed, an environmentally uniform increase in salinity and decrease in temperature with depth has been established. This means that the existing density gradient between the layers does not induce motion, and in the absence of other forces, changes in salinity and temperature will occur due to molecular diffusion. Under such conditions, a westerly wind of 10m/s was applied over the medium. At the fourth day, the effects of steady state formation in the current field and departure from static equilibrium were observed. The results of the tenth day of model execution are as follows:

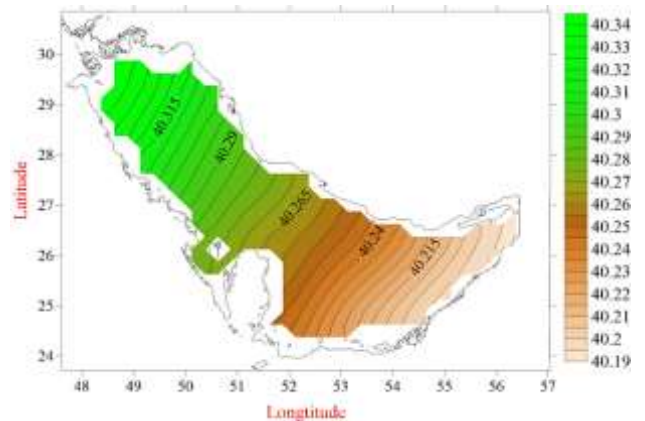


**Figure 12- Current field at the mid-level of the first layer**



**Figure 13- Current field at the mid-level of the tenth layer**

It is observed that a current has formed at the surface, with its vector deflected approximately 45 degrees to the right of the downwind direction. This phenomenon occurs under the influence of the Coriolis force [21], and according to Ekman theory, the current vector will rotate with depth, eventually reversing direction at a certain depth, where it will oppose the surface current direction [21]. This result has been observed in this study (Figure 12 and Figure 13). Additionally, the water level is higher at downwind side. The diffusion of salinity and temperature in this experiment follows the principles of ocean physics (Figure 14 to Figure 16), such that water with lower salinity and higher temperature exists in the downstream (east of the laboratorial oceanic medium). However, prolonged wind action could eventually homogenize the medium in terms of both temperature and salinity.



**Figure 14- Salinity field at the mid-level of the first layer**

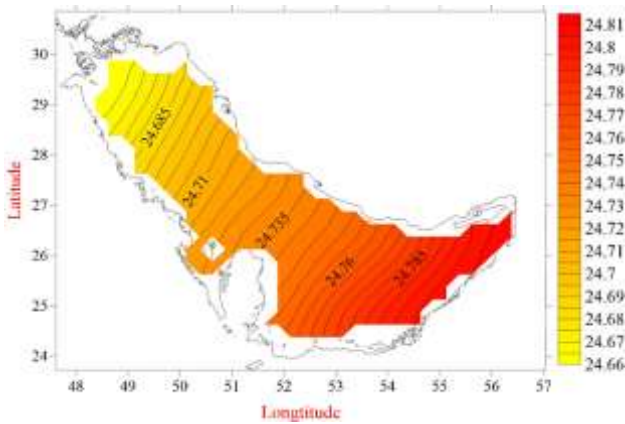


Figure 15- Temperature field at the mid-level of the first layer

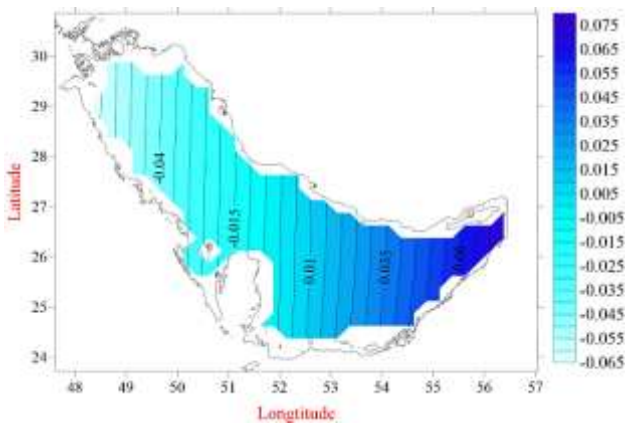


Figure 16- Field of departure from static equilibrium at the mid-level of the first layer

### 3.4. The results of the simulation of the effect of density difference, tide, river, and wind in a laboratorial medium with a non-level bottom

This theoretical basin is designed to resemble the oceanic medium of the Persian Gulf. Although the bottom slope and environmental conditions of the Hormuz Strait (Eastern open boundary) do not match the bottom slope or the strait of this condition (Eastern open boundary), However, general physical and geographical characteristics of the real medium have been assigned to it. Therefore, executing the model in this medium will yield valuable results.

In this experiment, the medium shown in Figure 17 is considered. The maximum depth of this oceanic medium is 97.94 m, and the minimum depth is 56.78 m. At longitude 56.875°E, the oceanic boundary is open from 27.625°N to 28.625°N. The surface salinity is 40 psu, increasing by 0.25 psu at each level. The surface temperature is 25°C, decreasing by 0.25°C at each level downward.

Two rivers, A and M, are assumed to be located at two points in the medium. The impact point of River A is at 29.875°N , 48.625°E (similar to the Arvand-rood River), and the impact point of River M is at 29.125°N, 51.125°E (similar to the Mond River).

The flow velocity at the estuary of River A is assumed to be 0.6 m/s, with a surface temperature of 19.5 °C, bottom temperature of 24 °C, surface salinity of 25 psu,

and bottom salinity of 27 psu. Also, the flow velocity at the estuary of River M is assumed to be 0.5654 m/s, with a surface temperature of 19.44 °C, bottom temperature of 25 °C, surface salinity of 22.21 psu, and bottom salinity of 31.35 psu.

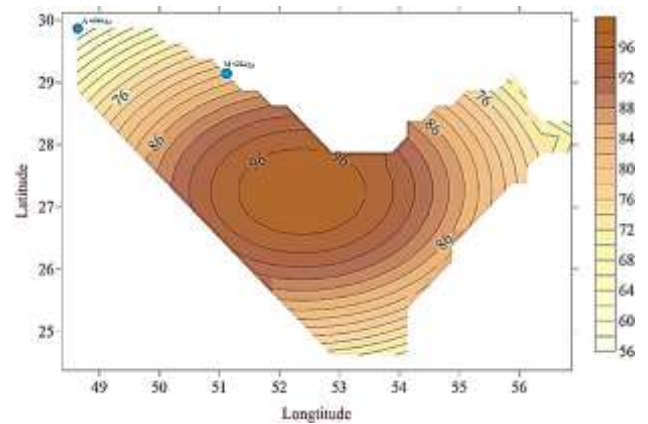


Figure 17- Schematic figure of the medium and the bottom of the laboratorial medium under study

The results of the ten-day model execution are presented in this section. The rivers were activated from the beginning of the model run. From the start of the second day, a westerly wind of 10 m/s was blown over the medium. Beginning on the third day, tides were also added to the forces acting on the system [17]. The current fields at zero and 6 o'clock on the tenth day are as follows:

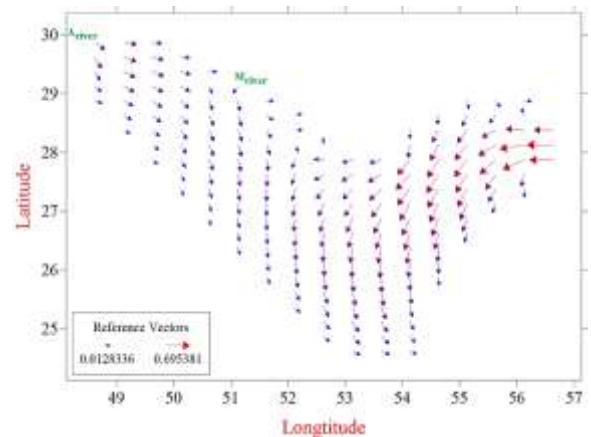


Figure 18- Current Field at the Mid-Level of the First Layer – Day 10, Hour 0

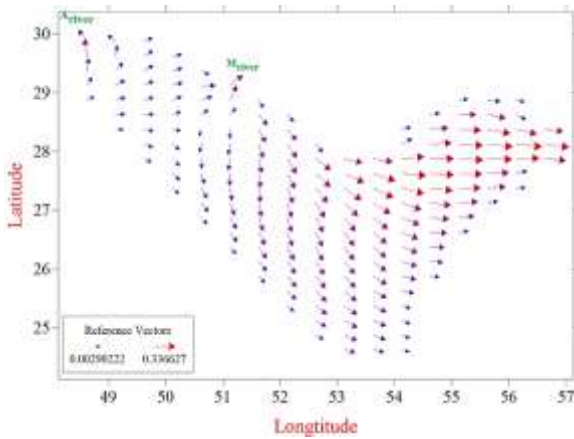


Figure 19- Current Field at the Mid-Level of the First Layer – Day 10, Hour 6

Investigating current fields show that in overall; the effect of tides is dominant. At hours (6:00, 15:00, 18:00), the tidal effect causes ocean water to flow into the M river. During these hours, high tide occurs in that region. At other hours (zero, 12:00 and 24:00), river water is entering the oceanic medium, and at this time, a low tide should have occurred in this area, and this can be better understood from the review of departure from static equilibrium fields. Tide data were taken from Hydrographic Management of National Cartographic Center of the Islamic Republic of Iran, 1983 [17] (Figure 20 to Figure 22).

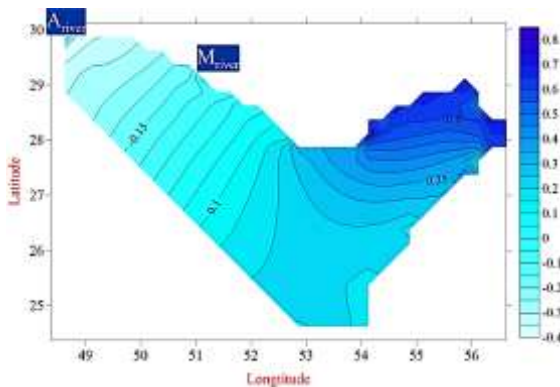


Figure 20- - Contours of departure from static equilibrium in the mid-layer of the first level – Day 10, Hour 0

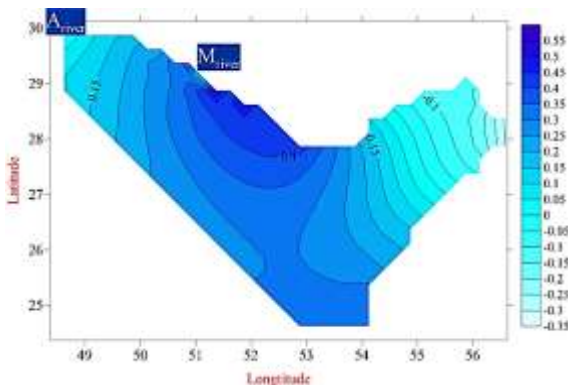


Figure 21 - Contours of departure from static equilibrium in the mid-layer of the first level – Day 10, Hour 3

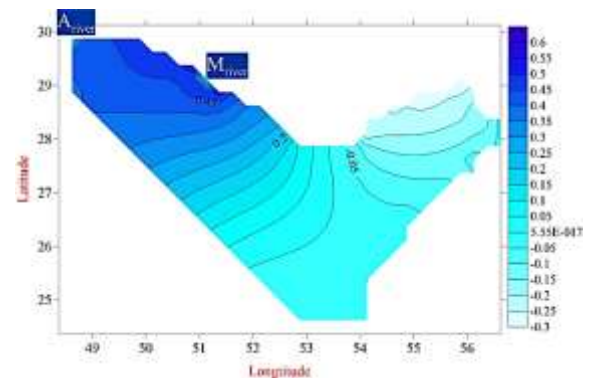


Figure 22- Contours of departure from static equilibrium in the mid-layer of the first level – Day 10, Hour 6

The maximum current speed over these ten days was 1.4 m/s, and the maximum total water level variation relative to static equilibrium during this period was 2.88 meters. An important conclusion is that the tidal current in the northwest of this oceanic medium is always weaker than in the central or eastern parts of the region. Changes in water level at the eastern open boundary generate a coastal-parallel current that originates from the northern boundary of the oceanic domain and induces a counterclockwise circulation within the medium. In that region, if an observer stands in the direction of the current, the highest water level is observed on the observer's right-hand side [21]. Consequently, the component of the current perpendicular to the boundary is effectively zero [21]. These indicators strongly suggest the existence of a Kelvin wave in this region.

The analysis of current fields in this experiment (Figure 18 and Figure 19) indicates that water flows into or out of the basin across the entire strait. This result is consistent with the findings of Hesari et al. (2006) [21] and Zamanian et al. (2022) [23]. It also demonstrates that River A can influence the direction of the circulation.

## 5. Conclusions

The results of analyzing the departure from static equilibrium in Experiment 3.2 and Experiment 3.4 indicate that tidal circulation in the water basin occurs on a semi-diurnal basis. Furthermore, the model results in Experiment 3.4 show the dominance of the tidal effect over the effects of wind, density gradient, and river input in driving the water circulation in this medium. In other word, tide can strongly influence in this kind of water basin as a body force.

Additionally, the inflow from the open boundary generates a coastal current along the northern boundary, leading to a counterclockwise circulation in the basin. The presence of an amphidromic point is also evident in the results.

These results have also been obtained in experiences implementing this model in other mediums [22].

An attempt has been made to consider laboratorial mediums similar to the geographical and physical

conditions of the Persian Gulf. It is expected that the results of the model implementation can generally show the interaction of this marine medium under the influence of environmental factors. Chao et al. (1992) [24], Reynolds (1993) [23] and Apel (1999) [21] reached similar conclusions regarding the oceanic medium of the Persian Gulf in their studies.

Moreover, the model results are consistent with the principles of ocean physics. This part of the study demonstrates that, even in its simplest configuration, the oceanic numerical model is capable of predicting the physical behavior of coastal and offshore waters. Therefore, it can serve as a suitable foundation for studying the hydrodynamics of coastal and oceanic waters, including the oceanic medium of the Persian Gulf. It is essential that real environmental conditions can be incorporated into the model. Considering the findings of fundamental studies in this field (e.g. [21], [23], [24]) would be highly beneficial. In this way, the groundwork for model improvement is laid. Nevertheless, enhancing the model for full compatibility with the behavior of a real oceanic medium requires further research aimed at determining the momentum, salinity, and temperature diffusion coefficients in oceanic domains.

**Acknowledgment (Optional):** To conduct this research, the facilities of the National Institute of Oceanography, especially the library of this research institute, were used. I consider it my duty to thank and appreciate the cooperation of the authorities, especially the esteemed director and the esteemed vice president for research of the National Institute of Oceanography.

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