University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

Increasing the Accuracy in Forecasting the Surface Drifter Trajectory by Using Data Assimilation

Mahmud Reza Abbasi✉

Faculty of Basic Sciences, Imam Khamenei University of Marine Sciences, P.O.Box 43491-63439, Zibakonar, Gilan, Iran

Article Info

Article type:
Research Article

Article history:
Received: 20 Jan 2023
Revised: 4 March 2023
Accepted: 18 May 2023

Keywords:
Strait of Hormuz
Particle tracking
FVCOM
Nudging

ABSTRACT

Predicting the path of pollution in the marine area is one of the most important concerns for those involved in environmental studies. In this paper, we have discussed the capabilities of using the data assimilation method in the FVCOM numerical model in forecasting the movement path of a surface drifter in the Strait of Hormuz. Initially, the FVCOM model was implemented for particle tracking by using environmental data in the Strait of Hormuz. Then tidal gages data of the Strait of Hormuz were assimilated in the numerical model using the nudging method. The results of the two runs were compared with field measurements data using statistical parameters such as bias and correlation coefficient. Statistical analysis and visual comparisons depicted the ability of data assimilation in optimizing the model water level outputs and reducing the differences between drifter location and model results and also the rate of the distance between them.

Cite this article: Abbasi, M. R. (2023). Increasing the Accuracy in Forecasting the Surface Drifter Trajectory by Using Data Assimilation. *Pollution*, 9 (3), 1150-1161.
https://doi.org/10.22059/poll.2023.354063.1761

DOI: https://doi.org/10.22059/poll.2023.354063.1761

INTRODUCTION

Marine pollutions, regardless of their physical or chemical nature, have always been one of the unsightly problems of aquatic environments. Meanwhile, marine debris is one of the most complicated sources of marine pollution. The irresponsibility of humans towards the environment has caused the amount of waste dumped into the world's seas to double every ten years (Agamuthu et al., 2019) so that it is now impossible to clean the oceans from this waste. The accumulation of plastic waste in seas and beaches can have a negative effect on marine life. Many aquatic animals seek to feed on the food along with the garbage. These wastes endanger animal species, from seabirds to turtles. Many animal species mistake these wastes for food and eat them, and this causes various damages to them. Eating garbage by a group of large seagulls causes their stomachs to fill up and starve to death due to lack of food. Although there have been hundreds of different programs to clean the oceans, none of them have been effective. Environmentalists have always sought to find methods to predict their trajectories to control and finally eliminate them from the water bodies. One of the ways to deal with this marine debrises is to collect them. In this regard, it is better to predict the trajectory of these marine wastes. For this purpose, various methods have been developed to predict the trajectory of marine pollution. Mathematical methods and among them, numerical models are one of the

*Corresponding Author Email: *phys.ocean.abbasi@gmail.com*

best ways to do this as different models have been used for this purpose (Chassignet et al., 2021; Galgani et al., 2021; van Sebille et al., 2020; Handyman et al., 2019; Ondara et al., 2019; Zhao et al., 2018; Shafiei and Farzingohar, 2020; Gorman et al., 2020).

Numerical models have the ability to simulate marine parameters such as currents according to the real conditions of the ocean and can predict some features. One of the most important advantages of these models is that they can create a harmony between field measurements and numerical model results. Considering all the advantages, these models also have disadvantages. These models can never provide a complete description of ocean currents even if the equations are solved very accurately. Numerical models only provide information about the flow at grid points and do not provide any information at the inter-grid points.

Many efforts have been made to reduce the error of numerical models. Data assimilation is one of the newest ways to reduce errors in numerical model results (Wang et al., 2000; Darvishi, and Ahmadi., 2014; Nearing et al., 2018). In this method, accurate field data are assimilated into the model to prevent further deviation of the numerical model during the run. This method is used in many different fields of science to optimize the results of models (Abbasi et al., 2018; Moazzami et al., 2016; Serpoushan et al., 2013). In this paper, we have tried to use the nudging assimilation method in FVCOM numerical model to optimize the forecasting trajectory of surface drifter movement in the Strait of Hormuz. In this order, the numerical model was run in two stages: first without data assimilation (Control Run hereinafter referred to as CR) and then in the second run, using the assimilation method (hereinafter referred to as AR). Two stages setting were the same. In the AR run, the field data of water elevation from the local tide gauges were assimilated into the model using nudging method. Although the Nudging method is one of the most basic and simple methods of data assimilation, the output results of the AR run represent the improvement in the accuracy of the model and reduction in its error.

MATERIALS AND METHODS

Study area

The Persian Gulf is a shallow semi-enclosed marine environment that is one of the most important strategic waterways in the world in terms of ecological, economic, and political. The Persian Gulf connects to the Gulf of Oman and the Indian Ocean via the Strait of Hormuz (Abbasi et al.,2017). The Strait of Hormuz is located approximately 26 degrees and 30 minutes north and 56 degrees and 30 minutes east (Figure 1).

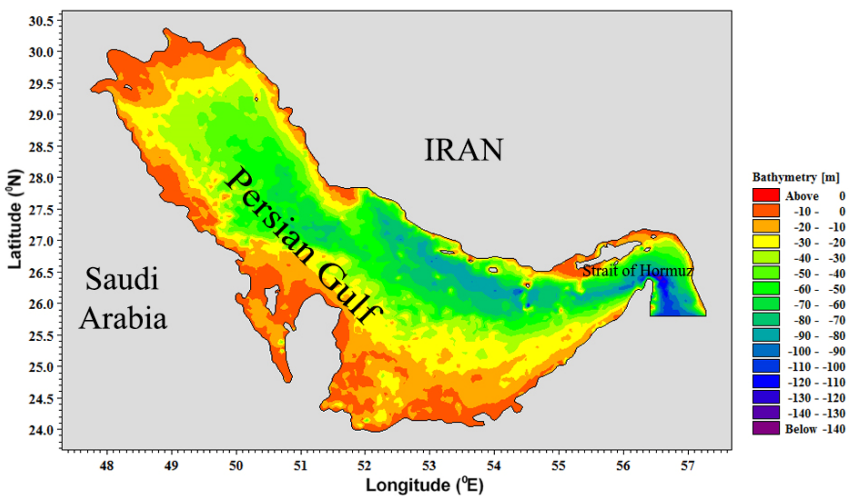

Fig. 1. Map of the study area

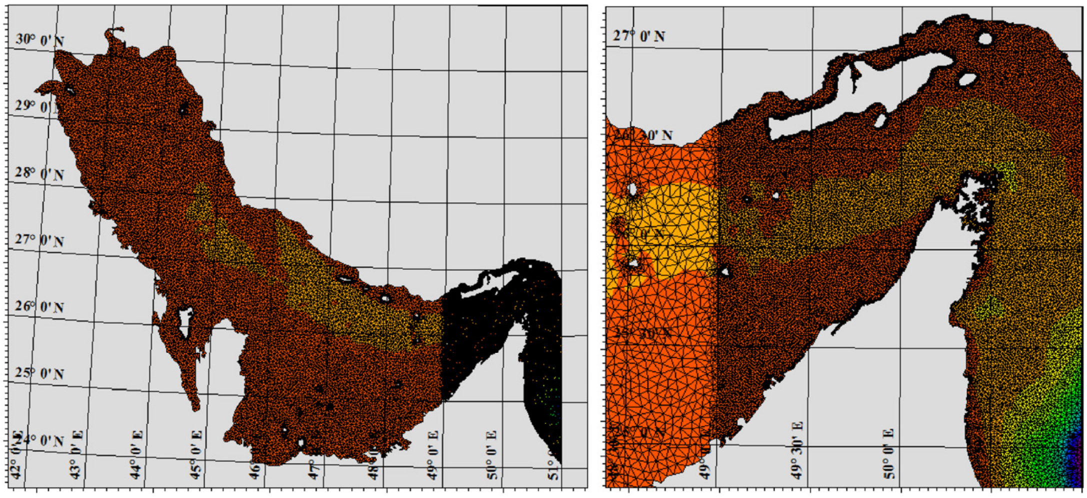

Fig. 2. Meshing of the study area: Left: Whole domain; Right: Strait of Hormuz

The Strait of Hormuz is a very important waterway in the south of Iran and is considered one of the most important trade routes in the world. The location of a significant part of the world's oil and gas resources in the waters of the Persian Gulf increases the importance of the Strait of Hormuz significantly. All countries that export oil from the Persian Gulf region send a significant part of their daily production to other parts of the world through the Strait of Hormuz (Al-Hajri et al.,1990).

From the environmental point of view, a wide range of natural habitats can be found in this. The beds of marine plants to coral reefs, mangrove forests, tidal areas and coastal wetlands are suitable habitats for breeding and living of many fish, molluscs and mammals. "Hara Protected Area" with an area of 8,236 square kilometers is considered the largest mangrove forest in the Persian Gulf. This area is located between Qeshm Island and the southern coast of Hormozgan Province (Zangane et al., 2019).

Therefore, knowing the path of various marine pollutants in this strait such as oil spill pollution, industrial or urban wastewater can help to prevent the more spread and environmental damages to some specific ecological species in this strait such as mangrove forests.

FVCOM model

The numerical model applied for this study was FVCOM (finite-volume community ocean model). A three-dimensional model with unstructured griding (Chen et al. 2003). This model included the seven conservation equations of Navier-Stokes in the spherical coordinate. The model uses both finite difference and finite element methods in form of finite volume methods which takes advantage of both their features.

The domain was meshed with a triangular grid with the horizontal resolution as in the Strait of Hormuz, finer meshes were used than the rest of the domain (Figure 2).

The model contained 35242 nodes and 112325 cells. The bathymetric data were extracted from the ETOPO2 database from NOAA National Centers for Environmental Information(https://www.ncei.noaa.gov/products/etopo-global-relief-model) and the environmental data including surface wind, surface heat flux, precipitation, evaporation were provided from the ECMWF[1] database (https://www.ecmwf.int/en/forecasts/datasets) as model inputs.

In this research, the wind data of the European Center for Medium-Term Weather Forecast (ECMWF) for modeling time, at 6-hour time intervals, and on a .56-degree grid has been used, and this information has been converted into a netcdf file for inclusion in the model.

1 European Centre for Medium-Range Weather Forecasts

Tidal constituents

Tides in the sea are the result of a set of sinusoidal harmonic components that are different at each geographical point. The main tidal constituents are the diurnal constituents, K1, O1, P1, Q1, and S1, with periods of 23.93, 25.82, 24.07, 26.87, and 24.00 h, respectively, and the semidiurnal constituents M2, S2, N2, and S2, with periods of 12.42, 12.00, 12.66, and 11.97 h, respectively. These constitutes are harmonic elements for mathematical expression of tide-producing force and in corresponding formulas for the tide or tidal current. These constitutes are harmonic elements for mathematical expression of tide-producing force and in corresponding formulas for the tide or tidal current. Therefore, the tidal range changes every day, so that the time between the two modes is shifted by about 50 minutes per day (Yuliardi, 2022). The tidal force used in this present was included of eight tidal constituents: M2, S2, N2, K2, K1, P1, O1, and Q1.

Nudging data assimilation

Data assimilation is the technique of injection of observational data into a numerical model to optimize model outputs and provide an optimal initial condition for the next step run. There are many types of data assimilation such as optimal interpolation; 3D variational method (3DVar), 4D variational method (4DVar), and Kalman filter (with approximations). The nudging method is one of the easiest, simplest, and also low-cost methods in terms of computer computation in data assimilation. Simply in this method, the observations data is forced to the model. This method has been used in many studies to optimize model results and outputs (Antil et al., 2021; Abbasi et al., 2018; Swiatek., 2010).

The nudging scheme is described as follows:

Let $\alpha(x.y.z.t)$ be a variable selected to be assimilated and $F\alpha(x.y.z.t)$ represents the sum of all the terms in the governing equation of $\alpha(x.y.z.t)$ except for the local temporal change term, and then the governing equation of $\alpha(x.y.z.t)$ with the inclusion of nudging assimilation is given as

$$\frac{\partial\alpha(x.y.z.t)}{\partial t} = F\alpha(x.y.z.t) + G_\alpha \frac{\sum_{i=1}^{N} W_i^2(x.y.z.t)\gamma_i(\alpha_0-\hat{\alpha})_i}{\sum_{i=1}^{N} W_i(x.y.z.t)} \tag{1}$$

Where α_0 is the observed value; $\hat{\alpha}$ is the model-predicted value; N is the number of observational points within the search area; γ_i is the data quality factor at the ith observational point with a range from 0 to 1; and $G_\alpha$is a nudging factor that keeps the nudging term to be scaled by the slowest physical adjustment process. The selection of G_α must satisfy the numerical stability criterion given by

$$G_\alpha < \frac{1}{\Delta t} \tag{2}$$

Normally, $G_\alpha$is set to approximately the magnitude of the Coriolis parameter. $W_i(x.y.z.t)$ is a product of weight functions given as

$$W_i(x.y.z.t) = W_{xy} \cdot W_\sigma \cdot W_t \cdot W_\theta \tag{3}$$

Where $W_{xy}.W_\sigma.W_t$ and W_θ are horizontal, vertical, temporal, and directional weighting functions, respectively. The mathematical expressions of these functions are given as

$$W_{xy} = \begin{cases} \frac{R^2-\hat{r}^2}{R^2+\hat{r}^2}. & 0 \le \hat{r} \le R \\ 0. & \hat{r} > R \end{cases} \tag{4}$$

$$W_\sigma = \begin{cases} 1 - \frac{|\sigma_{obs}-\sigma|}{R_\sigma}. & |\sigma_{obs} - \sigma| \leq R_\sigma \\ 0. & |\sigma_{obs} - \sigma| > R_\sigma \end{cases} \tag{5}$$

$$W_t = \begin{cases} 1. & |t - t_0| < T_w/2 \\ \frac{T_w-|t-t_0|}{T_w/2}. & T_w \leq |t - t_0| < T_w \\ 0. & |t - t_0| > T_w \end{cases} \tag{6}$$

$$W_{xy} = \begin{cases} \frac{R^2-\hat{r}^2}{R^2+\hat{r}^2}. & 0 \leq \hat{r} \leq R \\ 0 & \hat{r} > R \end{cases} \tag{7}$$

$$W_\theta = \frac{||\Delta\theta|-0{\cdot}5\pi|+c_1\pi}{(0{\cdot}5+c_1)\pi} \tag{8}$$

The weight function used here considers the temporal and spatial variation. Total Weight likewise has a value between 0 and 1. where R is the search radius, $\hat{r}$ is the distance from the location where the data exists, R_σ is the vertical search range, T_w is half of the assimilation time window, and $\Delta\theta$ is the directional difference between the local isobath and the computational point with c_1 a constant ranging from 0.05 to 0.5.

Tidal gauges observation data

In this study, the water surface elevation data from local tidal gauges were assimilated into the FVCOM model using the nudging method. These data with 1 hours' time interval were obtained from the Hydrography and Tidal Measurements Department of the National Cartographic Center of Iran (NCC). Because the drifter release point was located in the northern part of the Strait of Hormuz and the south of Qeshm Island, therefore, the field data were obtained from the nearest local tidal gauge as marked with a red star in the Figure 3.

Drifter

To achieve the study goal, first, a drifter along with an "electronic device for sending

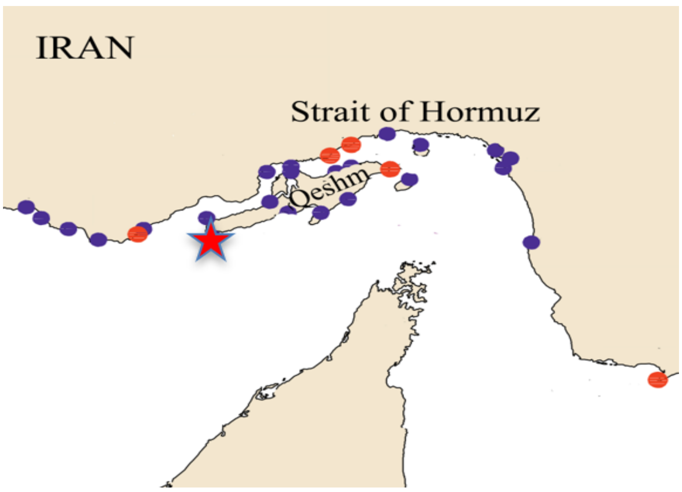

Fig. 3. Local tide Gauges. red star remarks nearest tide gauge.

geographical location" was built, and then it was released in the northern part of the Strait of Hormuz and south of Qeshm Island. After the drifter was released in the desired initial location, the drifter moves due to the movement of surface water currents. Because the drifter was completely submerged in the water, the only factor in the movement of the drifter in the water is sea currents, and the wind does not have a direct effect on the movement of the drifter. Based on the GPS system installed on it, as the drifter moved, its geographical coordinates were sent by the mobile telecommunication system. The location data sent by the floating drifter can be adjusted in any desired period, which was used in this research in a period of 5 minutes. A GPS device recorded the speed and direction of the drifter. To build the device, it was inspired by the ideas of international companies and it was decided to build the Davis drift device by making changes to facilitate the project (FIgure 4).

RESULTS AND DISCUSSION

The purpose of this research was to use the data assimilation method to optimize the results of FVCOM's numerical model in forecasting the movement of surface debris in the Strait of Hormuz. For this purpose, the spatial data of a drifter's movement were used as real measurements and to optimize the model results. In this regard, to show the ability of the data assimilation method in optimizing the results of the numerical model, the available tidal gauge data in the Strait of Hormuz area have been used.. For this purpose, On January 1, 2008, at 113:30, a surface drifter was released in the northern part of the Strait of Hormuz. The locations data sent from drifter with 5-minute interval time for 3 days were collected. Then the CR and AR outputs were compared with real location data of drifter using the statistical parameters of the correlation coefficient (CC) and bias based on the following formulas:

$$CC = \frac{\sum_{i=1}^{n}((x_i-\bar{x})\times(y_i-\bar{y}))}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad (9)$$

$$Bias = \bar{x} - \bar{y} \quad (10)$$

In which in these relations x and y are the positions sent by the surface drifter and the values calculated by the model, respectively.

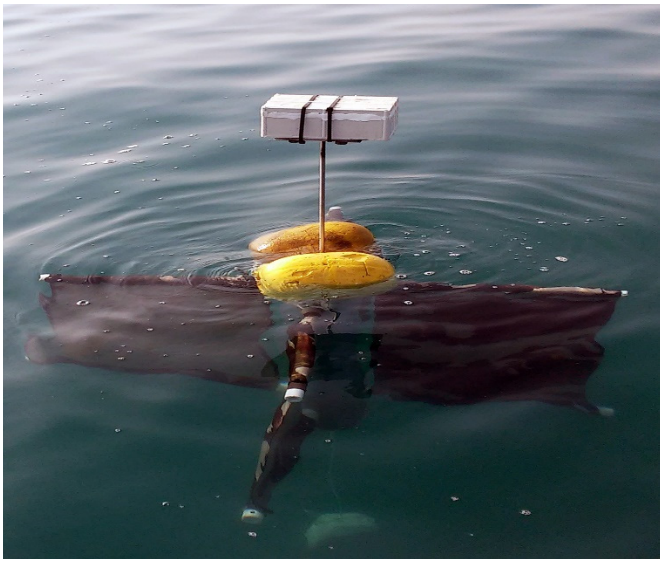

Fig. 4. Surface drifter

Since the tide gauges data has been selected as the input data for data assimilation, it is expected that the assimilation of these data will have a direct effect on optimizing the sea surface level of the AR results and thus optimize surface tidal currents. Figure 5 shows the water level results in both models and a comparison with the water level of the nearest local tide gauge for the two days of simulation (Figure 6). Due to the good agreement of the water level results in both the implementation of the numerical model with the field data of tide gauge, both in terms of the amplitude of water level and terms of phase, shows the correct settings of the model that can be used in various applications such as prediction of particle tracking. In addition, according to Table 1, it can be seen that the bias in water level from the CR outputs compared to field data is of the order of 2.5 centimeters. However, the assimilation of tidal level data to the model in the AR model has reduced the level difference by 0.3 centimeters and as can be seen, the accuracy of the water level outputs has increased. Also, the maximum distance between of water level from the tide gauge data and model's results has reduced from 48 cm in the CR model to 16 cm in the AR model.

In figure 6 the scatter plot of tide gauge data versus CR and AR run outputs, the correlation coefficient, and the trend line between them has presented. As can be seen in figure 6, the slope of the trend line in the AR model is closer to 1, which indicates that the results of the AR model are optimized due to the assimilation of tide gauge data to the model.

Due to the large amount of data sent from the GPS's drifter, the drifter travel path was plotted in a time interval of 2 hours during in the 3-day. Figure 7 shows the travel path of the drifter

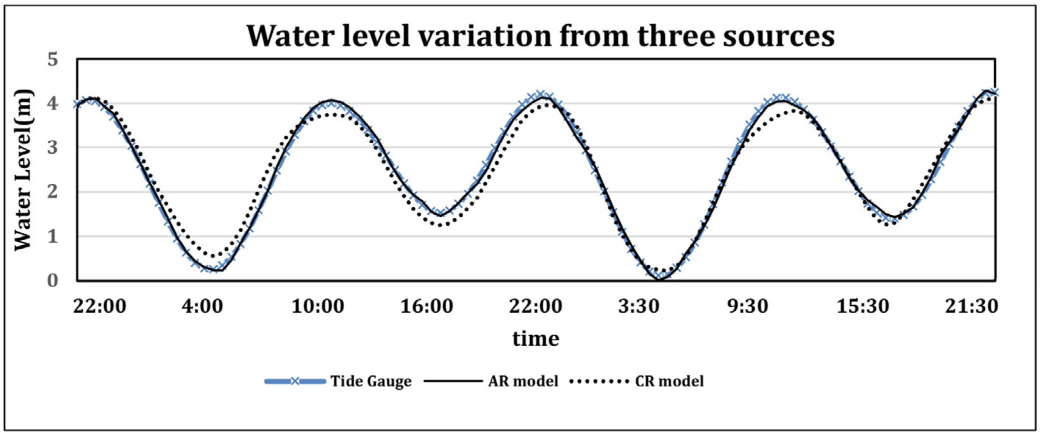

Fig. 5. Water level variation of tide gauge and two model results

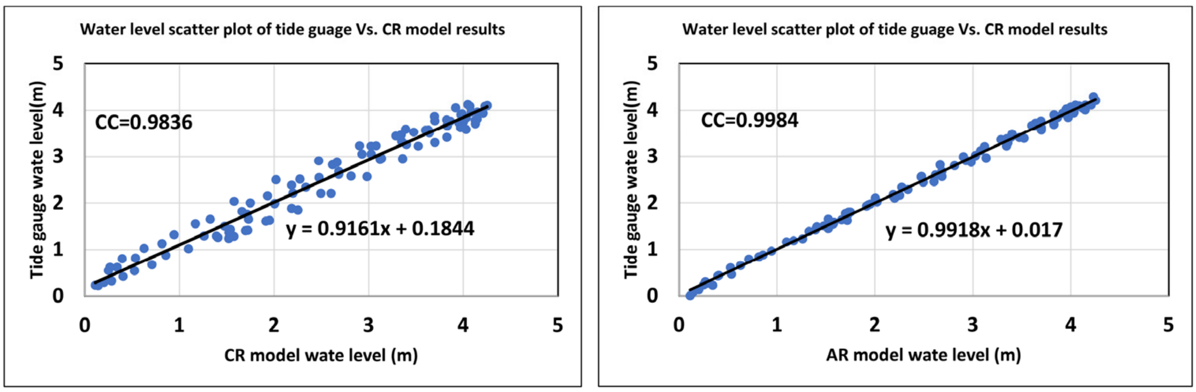

Fig. 6. Water level scatter plot of tide gauge Vs. CR (left) and AR (right) model

Table 1. Statistical comparison of water level field data with two-run results

	correlation coefficient (CC)	Bias(cm)
CR vs. field data	0.9836	2.4852
AR vs. field data	0.9934	0.3379

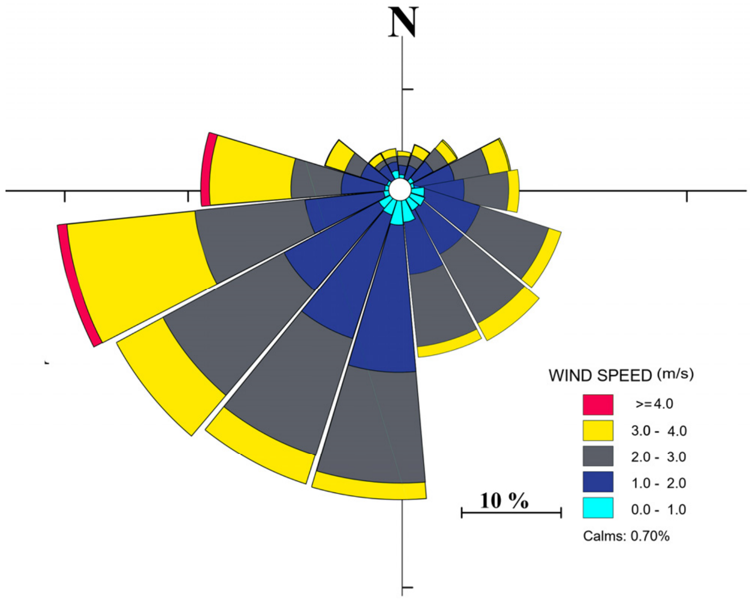

Fig. 7. Wind rose of drifter location

as well as the output results of both models in 8 frames. In addition, in the figure, the velocity vectors' magnitude and direction in the region are shown.

As can be seen in figure 7, the predominant path of the drifter is an almost reciprocating path that indicates the dominant effect on drifter movement was tide and the wind was secondary effect. This confirms the results of previous research that the tide is the first dominant effect in the Persian Gulf circulation and wind-driven and density-driven currents are the second and third effects, respectively (Reynolds, 1993). In addition, the gentle movement of the drifter from northeast to southwest is due to the local wind. The direction of this wind is from northeast to southwest (Figure 7).

As can be seen in figure 8, up to the first 5 steps, which take about 10 hours, the drifter movement and both model results are the same trajectories and they have very little difference. Gradually, however, the effects of wind on the sea surface currents have led to the separation of the paths. According to the current arrows in each frame, it can be seen that the movement of the drifter is completely dependent on the surface currents so that the location of the drifter in each period is completely in line with the direction of the current in the previous period.

Figure 9 shows the relative distance between the location of the drifter and the prediction results of both models.

It can be seen from the figure that over time, the distance forecasted by the CR model with its actual value has a faster rate of change than the results of the AR model, which is due to the steeper slope of the CR model line than its corresponding value in the AR model. Accordingly, it can be seen that in the CR model, the slope of the line is about 0.1 and according to the figure, it can be seen that the maximum distance has increased to about 4 km. But in the AR model, the growth trend of the distance is about 30 meters per time step, which according to the figure, during the run of the model in 3 days, the maximum distance is about 1 km compared to the actual value.

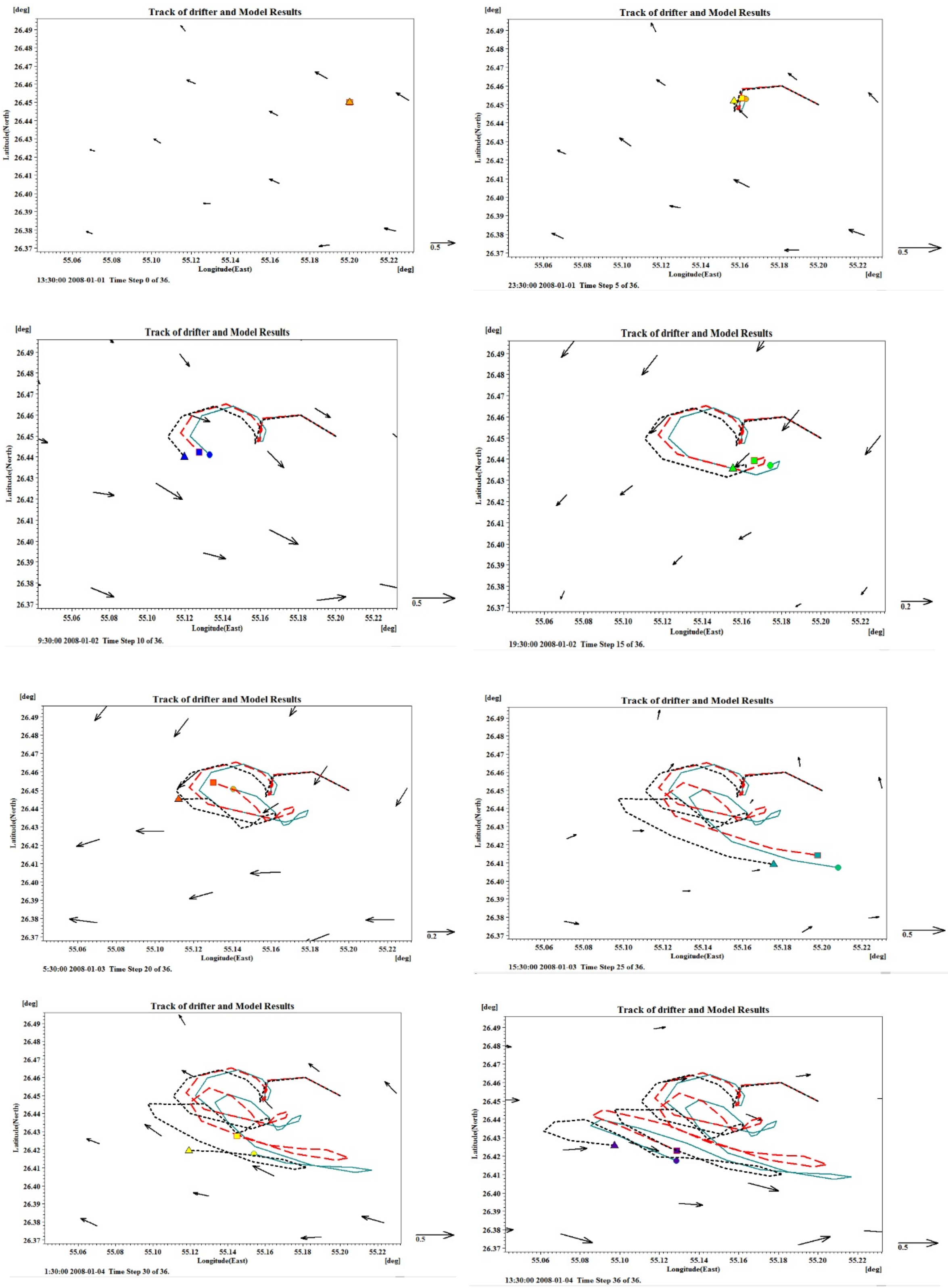

Fig. 8. Timeline trajectory of field drifter (blue line) and AR (red dashes) and CR (black dots) results

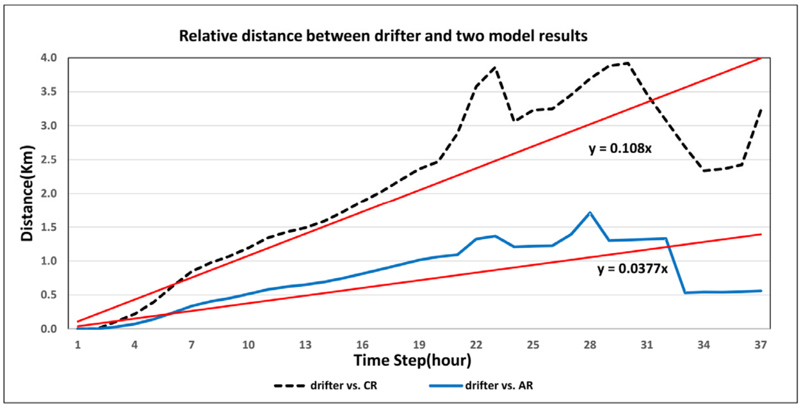

Fig. 9. Distance of drifter with CR&AR model forecasting results

CONCLUSION

In this study, the capabilities of the data assimilation method in optimizing the forecasting of the trajectory of a surface drift using the FVCOM numerical model in the Strait of Hormuz in the Persian Gulf have been evaluated. In the data assimilation method, the Nudging scheme was used. In this scheme, water level data were assimilated to the numerical model and the model was run in two stages. One uses the data assimilation method and the other without using this method. Then, the results of both models in forecasting the trajectory of the drifter were compared with the field data collected from the GPS installed on the drifter.

Small bias values obtained from the results of the two models show that the model in both CR and AR modes has good accuracy in forecasting the water level by comparing the results with water level data obtained from the nearest local tide gauge and there is little difference between them. It depicts the good configuration of the model and its ability for future marine research. In addition, the data assimilation decreased the maximum difference of water level between observation data and model results. According to the shape of the drifter's trajectory, it can be concluded that the first and dominant factor in drifter motion in this region is tide and tidal currents, so that drift motion during the early simulation time is completely a function of tidal ellipses and the results of both CR and AR models have slightly different. Then by affecting the Nashei local wind on the drifter movement, gradually the distance between the results of the model and the motion of the drifter increases. Since the predominant direction of this wind is from northeast to southwest, the drifter movement is affected by this wind, and its path shifts to the southwest.

Figure 8 shows that the results of the AR model have less error in predicting the path of the drifter compared to the actual motion of the drifter compared to the results of the CR model Figure 8 shows that the results of the IR model have less error in predicting the travel path of the drifter than the actual movement of the drifter compared to the results of the CR model so that the maximum distance between the results of the AR model with the field value is about 1.7 km but this value is about 4.5 km in the CR model. The projected distance of the IR model is about 500 meters from the drift station, but this distance is about 3.2 km for the CR model. So that at the end of the simulation time, the distance between the IR model output and actual drifter location is about 500 meters, but this distance is about 3.2 km for the CR model which shows that data assimilation has reduced the model error by about 90%. By considering the slope of the trend line of variation in the spatial distance between the drifter and two models, it can be seen that the use of the data assimilation method has been able to decrease the growth of this distance from 0.1 km / h to 0.037 km / h. This underscores the importance and applicability of this method for performing long-term predictions of particle motion in seawater

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The author declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the author.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

REFERENCES

Abbasi, R., Chegini, V., Sadrinasab, M., & Siadatmousavi, S. M. (2018). Correcting the Sea Surface Temperature by Data Assimilation over the Persian Gulf. Iranian Journal of Science & Technology, Transactions A: Science. 43:143-149. 10.1007/s40995-017-0357-z.

Abbasi, R., Chegini, V., Sadrinasab, M., & Siadatmousavi, S. M. (2017). Capabilities of data assimilation in correcting sea surface temperature in the Persian Gulf. Pollution. 3(2): 273-283.

Abbasi,R., Chegini,V., Sadrinasab, M., & Siadatmousavi, S. M. (2018). Optimization of the modeled surface temperature by assimilation of SST data over the Persian Gulf. Indian Journal of Geo-Marine Sciences. 47: 1803-1808.

Agamuthu, P., Mehran, S., Norkhairah A., & Norkhairiyah, A. (2019). Marine debris: A review of impacts & global initiatives. Waste Management & Research. 37(10):987-1002.

Antil, H., Lohner, R., & Price, R. (2021). Data Assimilation with Deep Neural Nets Informed by Nudging.

Chen, C., Liu, H. & Beardsley, R.C. (2003). An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: application to coastal ocean & estuaries. Journal of Atmospheric & Oceanic Technology, 20(1): 159-186.

Darvishi, M., & Ahmadi, G. (2014). Data assimilation techniques & modelling uncertainty in geosciences. The International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences. XL-2/W3: 85-90.

Galgani, F., Brien, A. S., Weis, J., Ioakeimidis, C., Schuyler, Q., & Makarenko, I. (2021). Are litter, plastic & microplastic quantities increasing in the ocean? Micropl. Nanopl. 1. doi: 10.1186/s43591-020-00002-8.

Chassignet, E. P., Xu, X., & Zavala-Romero, O. (2021). Tracking Marine Litter with a Global Ocean Model: Where Does It Go? Where Does It Come From?. Frontiers in Marine Science. 8: 2296-7745.

Gorman, D., Gutiérrez, A., Turra, A., Manzano, A., Balthazar-Silva, D., Oliveira, N., & Harari, J. (2020). Predicting the Dispersal & Accumulation of Microplastic Pellets Within the Estuarine & Coastal Waters of South-Eastern Brazil Using Integrated Rainfall Data & Lagrangian Particle Tracking Models. Frontiers in Environmental Science. 8.

Handyman, D ., Purba, N. P., Pranowo, W ., Harahap, S ., Dante, I ., Yuliadi, L ., & Faizal, I. (2019). Microplastics Patch Based on Hydrodynamic Modeling in The North Indramayu, Java Sea. Polish Journal of Environmental Studies. 28: 1-8.

Moazzami, H ., Siadatmousavi, S.M., & Mazaheri, S. (2016). Data Assimilation for Wave Data in Persian Gulf Using WAVEWATCH- III Spectral Model. International Journal of Maritime Technology. 12: 115-125.

Nearing, G., Yatheendradas, S., Crow, W., Zhan, X., Liu, J., & Chen, F. (2018). The Efficiency of Data Assimilation. Water Resources Research. 54. 10.1029/2017WR020991.

Ondara, K., Wisha, U., & Panjaitan, S. (2021). Particle Tracking Model Approach for Analyzing Crude Oil Spill (Palm Fatty Acid Distillate) in Bayur Bay Based on Navier Stokes Discrete. Buletin

Oseanografi Marina. 10: 67-74.
Reynolds, R. M. (1993). Physical Oceanography of the Persian Gulf, Strait of Hormuz, & the Gulf of Oman—Results from the Mt Mitchell expedition, Marine Pollution Bulletin. 27: 35– 59.
Serpoushan, N., Zeinoddini, M., & Golestani, M. (2013). An Ensemble Kalman Filter Data Assimilation Scheme for Modeling the Wave Climate in Persian Gulf. Proceedings of the International Conference on Offshore Mechanics & Arctic Engineering - OMAE. 5. 10.1115/OMAE2013-10399.
Swiatek, D. (2010). Application of the Newtonian nudging data assimilation method for the Biebrza River flow model.
Van Sebille, E., Aliani, S., Law, K. L., Maximenko, N., Alsina, J. M., Bagaev, A., ... & Wichmann, D. (2020). The physical oceanography of the transport of floating marine debris. *Environmental Research Letters*, *15*(2), 023003. Wang, B., Zou, X., & Zhu, J. (2000). Data assimilation & its application. Proceedings of the National Academy of Sciences. 97: 11143-11144.
Zhao, E., Mu, L., Qu, K., Shi, B., & Yu, Y. (2018). Numerical investigation of pollution transport & environmental improvement measures in a tidal bay based on a Lagrangian particle-tracking model. Water Science & Engineering. 11: 23-38.