

Optimization of the modeled surface temperature by assimilation of SST data over the Persian Gulf

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Present study is the impact of sea surface temperature(SST) data assimilation on the results of FVCOM by using Nudging scheme. Results of statistical assessments showed the capabilities of the SST assimilation. The SST bias decreases from -0.57°C in control run to -0.49 °C in assimilation run. Mean RMS difference of modeled and observations SST is significantly reduced and approaching to 0.69°C. Surface temperatures of shallow parts were optimized specially near the Hormuz Strait.

[Keywords:Data assimilation; SST; Nudging; OISST; FVCOM]

Introduction

SST is one of the most important variables in studying the ocean and the atmosphere and their interactions and the accuracy of SST can help the better understanding these interactions. Although recently coastal models thanks to their improvements can simulate many of the characteristic parameters of the ocean systems, but the model outputs have some errors due to uncertainty in some factors such as initial and boundary conditions and the intrinsic numerical and input data errors. Data assimilation is one of the latest efforts to overcoming on this problem. Data assimilation is the combining of observational measurements with model information in order to reduce and, if possible, correct errors with observations. So remotely observed data have been combined with the models using data assimilation methods in order to decrease the simulation errors.

The most commonly techniques in data assimilation are nudging, 3D and 4D variational methods, optimal interpolation (OI) and Kalman filter (KF). Manda et al.¹ recognized the skill and feasibility of nudging method compare to sophisticated assimilation methods such as the EnKF for estimating the upper mixed layer.

In this study, we used nudging scheme to assess the ability of this assimilation scheme to improve the structure of the temperature field in a high-resolution setup of a FVCOM (Finite Volume Coastal Ocean

Modeling) model. After the SST assimilation process, the modeled oceanic state variables were compared with the observed data to evaluate the improvement yielded by the assimilation procedure.

Materials and Methods

The model used for this study is FVCOM, an unstructured grid, three-dimensional primitive equations fully current-wave-ice coupled finite volume community ocean model. This model was developed originally by Chen et al.² and modified and upgraded by a joint effort of the University of Massachusetts-Dartmouth (UMASS-D) and Woods Hole Oceanographic Institution³. FVCOM is governed by seven primitive equations of momentums, continuity, temperature, salinity, and density in the spherical coordinate, with turbulent mixing parameterized by the general ocean turbulence model in the vertical and Smagorinsky⁴ turbulent closure scheme in the horizontal. Flux forms of the governing equations are discretized in the unstructured triangular mesh in the horizontal and in the generalized terrain-following coordinate in the vertical⁵. FVCOM is integrated with options of various mode split and semi-implicit schemes in time and the second-order accurate advection schemes in space. The unstructured grid finite volume methods combine the best attributes of the finite difference method for simple discrete computational efficiency

and the finite element methods for geometric flexibility. Flux computational approach provides an accurate representation of mass, heat, and salt conservation.

We used the unstructured mesh and the domain was built with the triangular grid (Figure 1).

Horizontal resolution of the model grid varies from ~5km near the coast to ~25km in the offshore region of the Persian Gulf. Total numbers of triangular cells and nodes are 30552 and 15779, respectively. As the Gulf is a shallow water system with a mean depth of ~38m, the sigma coordinate is used in the vertical, with a total of 10 uniform layers. ArvandRoud is the main freshwater inflow into the Persian Gulf which formed by combining the Euphrates, Tigris and Karun Rivers⁶. Climatological monthly mean of the river inflow is used with an annual mean transport of 1,576 m³/s and high-flow seasons between March-May. For vertical mixing and horizontal diffusion we used the Mellor-Yamada level 2.5 turbulence closure⁷ and Smagorinskyschemes, respectively. The external and internal mode time steps are 6.0 and 60.0 s, respectively.

The study period is from 1998 to 2003 based on the in situ data availability. Surface forcing including daily surface wind, precipitation, evaporation, shortwave, longwave radiation, latent and sensible heat fluxes, was prepared from ECMWF (European Centre for Medium-Range Weather Forecasts) data with 0.5° spatial and 6 h temporal resolutions available from 1998 to 2003, containing reanalysis product. To modify and localize the wind data set in the domain, the results of Abbaspour and et al.⁸ were used.

Five years of SST data collected between 1998 and 2003, were selected for assimilation. These data were selected due to their low-spatial and high-temporal resolutions. Ahmadabadi et al.⁹ showed the maximum, minimum and mean of error for SST in the Persian Gulf is 0.77, -0.09 and ±0.43, respectively, which are acceptable amounts.

For assimilation, the daily OISST gridded data (Optimum Interpolation SST) with spatial resolution 0.25 x 0.25-degree¹⁰ were used and for verification of the assimilation procedure, ROPME (Regional Organization for the Protection of the Marine Environment) CTD data collected in the 2001 summer were used. It should be mentioned that a large amount of in situ observations was collected during the ROPME cruise in 2001 (Figure 2).

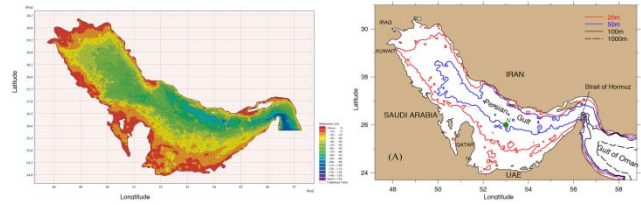


Fig. 1 — (right) The computational mesh of the Persian Gulf, (left) The model domain

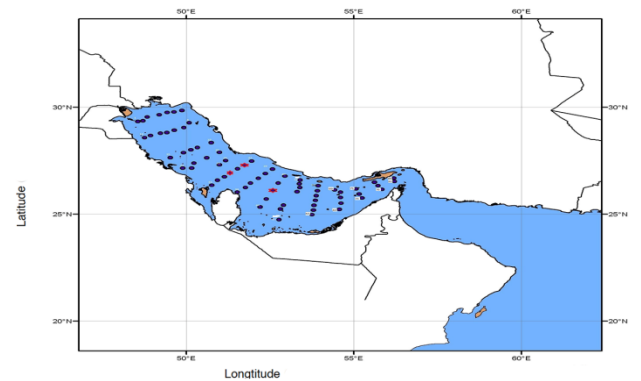


Fig. 2 — Locations of the in situ CTD stations for ROPME-2001 cruise

To compare the results of assimilation procedure with the In situ measurements, three points separated due to their higher depths relative to other stations at some locations. The bias and root mean square error (RMSE) were used for representation of the results quantitatively as follow:

$$\text{Bias} = \bar{x} - \bar{y}$$

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

In which, x_i and y_i denote the measured and modeled values, respectively. Moreover $\bar{x}$ and $\bar{y}$ are their average values, respectively.

Although the nudging method is the easiest and first of data assimilation schemes, but for many important applications such as forecast applications and operational assimilation systems because of low computational cost is very useful and is known as a fast and practical method. In this method, the model is slowly nudged (relaxed) towards observations at each time step in the model via a Newtonian relaxation term in the prognostic equation of the variable. Nudging method has been used in ocean data assimilation by Holland and Malanotte-Rizzoli¹¹ and by Malanotte-Rizzoli and Young¹².

Manda et al.¹ studied the sea surface temperature mixing process and used nudging and ENKF methods and by comparing the results they showed the skill of

the nudging method against the sophisticated nonlinear ENKF assimilation method. The feasibility of this method has suitable it for the assimilation of satellite SST data into many oceanic models.

The nudging scheme adds a nudging term to the prognostic equations would look something like

$$\frac{\partial u}{\partial t} = M(u) + \frac{u_{obs} - u}{\tau_r}$$

Where τ_r and M are the relaxation time and the model equations respectively.

Results and Discussion

The results of a five -year integration, starting first January 1998 is presented. Simulated SST are averaged over the integration period and are compared to results of survey carried out in this region. To study the effect of SST assimilation, the model was run in two stages with the same design: the control run (without assimilation) and assimilation run. Results were compared with databases. Figure 3 presents the daily averaged SST of control and assimilated run compared with OISST in the whole domain.

The time is given as the number of years from the start of assimilation. As can be seen the the assimilated run results have a close neighboring with the OISST data and both have an equilibrium mean

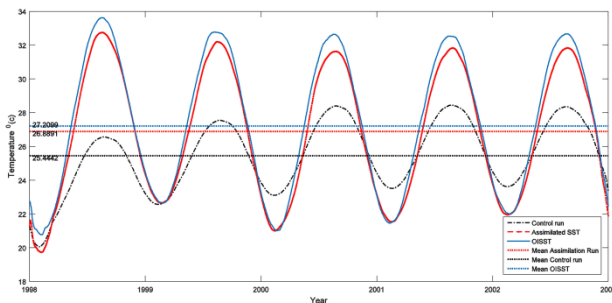


Fig. 3 — Time series of daily mean SST with and without assimilation compared with OISST

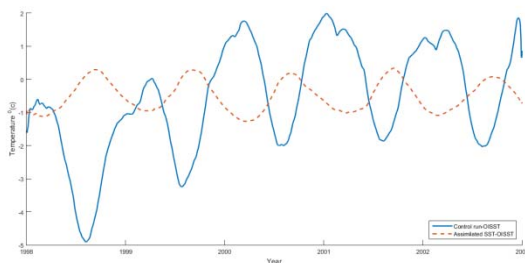


Fig. 4 —Control and assimilation run SST differences with respect to OISST for 1998-2003

state of $\sim 27^{\circ}\text{C}$. In contrast, the SST of the control run shows a cold drift for the first year and reaches significantly colder equilibrium state of $\sim 26^{\circ}\text{C}$ (Figure 3). As can be seen in the control run SSTs, although its coverage is low at the beginning of the time series, but gradually increases to almost 26°C . The first comparison showed that the assimilation SSTs is almost closer to OISST than the control run in all years.

To examine overall SST biases, Figure 4 shows the differences of the control and assimilation run with respect to OISST as time series. It should be mentioned that the OISST was selected as the standard of comparison in this study.

As can be seen from this figure, the assimilation SSTs matches better with OISST in comparison to control run SSTs. Adversely, the control run SSTs differ considerably with OISST during the whole run time. Moreover, this figure demonstrates the good performance of the application of data assimilation procedure over the whole years. The SST variations trend can also be extracted from this figure.

The assimilated simulation demonstrates significant capabilities in reproducing general spatial pattern of the SST, with larger variations in the northwest coast of the region and smaller in the southeast part near the Strait of Hormuz (Figure 5).

As was mentioned, the comparison of the model and the OISST data confirms the improvement of the results due to the assimilation procedure. Specially the improvement of the results at three regions consisting of the northwest, the strait and at the southern parts of the domain is quite obvious.

The RMS differences of the control run SSTs and assimilation run SSTs relative to the OISST during the modeling time are shown in Figure 6. As can be observed from this figure, the Assimilation has also increased the accuracy of SSTs. This figure also shows that the model accuracy in both runs in deep water regions is better than the results in shallow

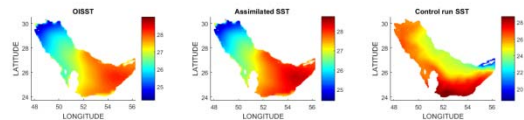


Fig. 5 — Spatial distributions of 5-years averaged SST from Assimilated run, OISST and Control run

water regions. This fact is due to the lack of much less calibrated satellite data in the latter regions and probably the shallowness of these regions.

The yearly averaged root mean square error (RMSE) of the SST in the assimilative model decreased below 1.5°C after the assimilation run, and the mean RMSE was 0.69°C over the years (green dot line in Figure 7). The RMSE of the SST in the assimilative model displayed seasonal variation, such that it was below 0.69°C from July to November and above 0.69°C from December to June.

To show the quality of the performance of the assimilation procedure, more detailed results were provided by calculating the main statistical parameters for showing the performance of the models for totally four months as representatives of four months in years (i.e. one month in each season). of course this gives a better insight into the model and the assimilation results in different seasons. Figure 8 shows the difference maps of the simulated SST and OISST results for the above mentioned months during a year for both control run (left panel) and assimilation run (right panel). As can be observed from this figure, the systematic error after assimilation yields to zero, that confirms the previous findings on the effectiveness of the assimilation algorithm. Specially a significant improvement can be

seen in the northern part of the domain near the Hormuz Strait, showing the differences of about less than 1°C .

The model SST in control run shows a significant difference with the OISST during all seasons. This indicates that the SSTs difference specified in the control run model can result in uncorrected heat flux components (i.e. shortwave, longwave, latent and sensible radiations) and therefore the net surface heat in the Persian Gulf. It seems that the summer thermocline increase the errors in the shallow water. These errors can be generated during periods with strong heating and small mixing and that cause enhanced variability and increasing the differences and during winter increasing these differences are probably an effect of the satellite noise.

The vertical structure of temperature under assimilation effect was studied by comparing vertical profiles of the model and the in situ data. Figure 9 presents the comparison of both control and assimilation SST run model vertical profiles against the corresponding in situ profiles, for three situations shown in Figure 2. The simulated temperature profiles by the assimilative model were more consistent with those observed. As can be seen from this figure, the

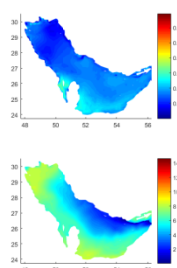


Fig. 6 — RMS differences of the assimilation run SSTs(top) and control run SSTs (bottom) relative to the OISST for all months for 1998-2003

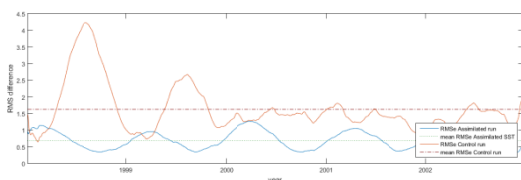


Fig. 7 —The yearly mean RMS difference of the SST for the data assimilative model (blue line) and non-assimilative control model (red line). The temporal means of the RMSE for the assimilative and control models are represented by green dot line and brown dash line, respectively

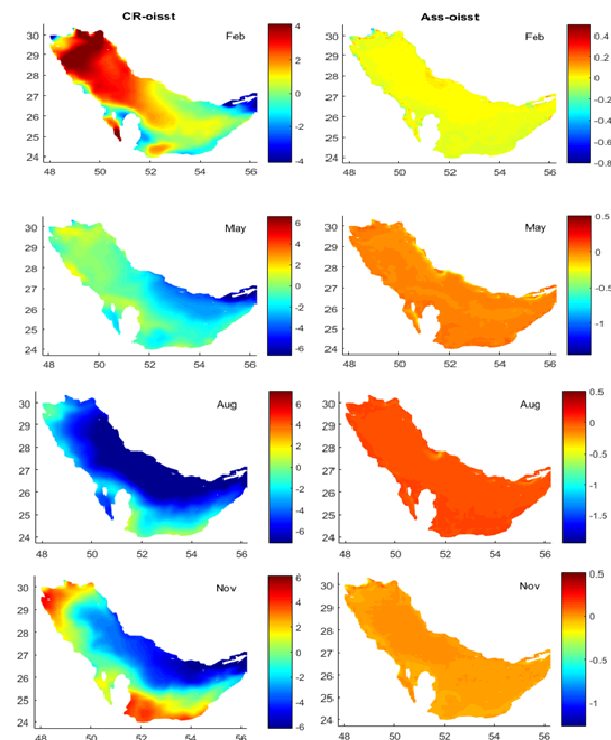


Fig. 8 —Difference ($^{\circ}\text{C}$) between monthly averaged OISST and CR (left panel) and Assimilation run (right panel) for different months during 1998-2003

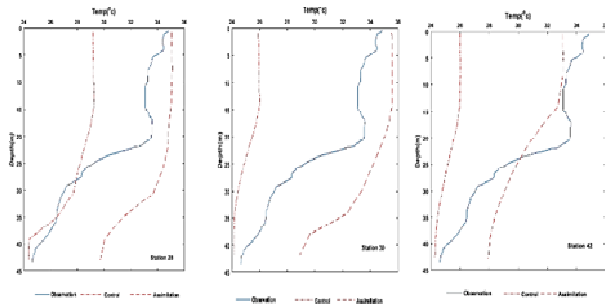


Fig.9 —Vertical temperature profiles at the three stations. See the station locations of each profile in Figure 2

temperature difference of stations, are negligible between the observed data and the assimilation experiment for the upper 10 m. Moreover, for both the upper 5 and 20m, there is about 1°C difference between the observed and the simulated temperatures.

The temperatures simulated by the model are warmer than those observed above a depth of 5 m in assimilation run in 28th and 30th stations. However, the subsurface temperature profile was brought close to that observed by the SST assimilation; the subsurface temperature from the assimilative model was still warmer than the observed one. The assimilation has essentially no effect at the sea bed of the stratified water because of the presence of strong stratification, the heat can't exchange between the upper part of the mixed layer with lower parts of it.

Conclusions

The results show that the assimilation can effectively improve the thermal structure of the domain not only in the surface but also in the subsurface. It was demonstrating that, over the period of modelling, the agreement of the assimilated SST with the satellite observation has been improved by $\sim 11\%$ in comparison with the regular SST without data assimilation. When the satellite-borne SST data were assimilated into the FVCOM ocean model through the nudging, the assimilated model state showed improvements compared to those in the non-assimilative model over all the simulation periods for most of the model domain. Regions with the largest errors were found to be the southern coasts and southwestern of the Persian Gulf. Northern regions have low SSTs errors in comparison with OISST.

work demonstrates that the prosobranch gastropod in shallow water of Edremit bay and Dardanelles is well represented by various habitats (sandy, rocky, muddy and epiflora etc.) in all the sites studied. Changes in both

physical and chemical properties of this coastal zone may soon have negative impacts in this region. Especially, the bottom structure of the Dardanelles coast constantly changes due to strong currents, which may affect the diversity of organisms living on the sediment.

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