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Evaluation of HYCOM sea surface salinity and temperature using buoy measurements

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ABSTRACT

The Sea Surface Temperature and Salinity (SST/S) are influential climatic parameters that play an essential role in determining the state of the ocean and the relationship between the sea surface and the atmosphere. Access to accurate data sources with an appropriate spatial and temporal resolution of these variables is of interest to researchers in various fields, such as climatology and monitoring the growth and reproduction of different animals in the aquatic environments. This research evaluates the quality of SST/S data obtained from the Hybrid Coordinate Ocean Model (HYCOM) global reanalysis using local observations obtained from buoys. To assess the daily values of HYCOM reanalysis with a spatial resolution of 0.08 degrees, the time series of SST/S data measured in 14 buoys from 2012 to 2022 was considered as reliable values. Based on the data used in this study, there was a high correlation between HYCOM SST data and corresponding local values up to 0.99. In addition, the agreement between the HYCOM data and the buoy observations was lower for salinity than the water temperature. Statistical assessments showed that the bias of HYCOM SST values has a different sign at distinct locations, while HYCOM estimated SSS more than the corresponding buoy observation. In most stations, the absolute bias value of the HYCOM reanalysis in the SST and SSS products was less than 0.38 C and 0.5 psu, respectively. Also, the average RMSE of the differences between HYCOM reanalysis and local observations at all stations for temperature and salinity was estimated to be 0.58 Celsius and 0.57 psu.

KEYWORDS

HYCOM reanalysis
Sea Surface Salinity
Sea surface Temperature
Buoy observation

1. Introduction

Sea Surface Temperature and Salinity (SST and SSS) have been introduced as essential and affecting climate variables by the World Meteorological Organization (WMO) (GCOS, 2011). These variables play an important role in the relationship between the ocean and the atmosphere and are effective in determining the state of the ocean.

For example, SSS is an important parameter in the interaction between the atmosphere and the ocean, and thus will affect climate and weather patterns. This parameter adjusts vertical mixing and water surface temperature (Foltz et al., 2019). Also, salinity data can provide valuable information about ocean dynamics, ocean cycles and air-sea fluxes. Consequently, this essential variable can be taken into account when studying changes in the atmospheric boundary layer and the Earth's climate (Lagerloef, 2002). In addition, monitoring the vertical movement of water between surface and subsurface layers requires the study of water salinity (Durock et al., 2012).

On the other hand, SST is one of the important climatic parameters which is of interest to many researchers in climate, ocean and fisheries fields (Trenberth et al., 2014; Ban et al., 2015; Koylu & Geymen 2016). The change in these parameters has a significant effect on the climate components and changes in the life of different species in marine environments (Gobler et al., 2017; Androulakis et al., 2020). Moreover, geophysical parameters such as SST and SSS control the responses of the atmosphere to the ocean, and their monitoring is useful for studying water vapor changes and sea surface warming (Ji et al., 2018).

Among the parameters that affect the physical and biochemical processes in aquatic ecosystems, we can mention the temperature and salinity of the sea (Maynard et *al., 2016). Investigation of these important parameters between the ocean and the atmosphere is important to monitor the health and reproduction of wild and farmed fish (Thakur et al., 2018).*

There are various methods for measuring the temperature and salinity of the sea surface which have their own advantages and disadvantages. Among these methods, we can mention Argo floats and buoys, which prepare in situ measurements of SST/S data. While this local data is used as a reference to compare with the satellite data, it is still limited and unavailable in all aquatic areas. Satellite data with appropriate spatial coverage provide SST and SSS products that require calibration and are unable to provide reliable data under certain atmospheric conditions.

In areas where there are no changes in salinity at small-scale, satellite data and salinity values obtained from models are suitable (Hall et al., 2022). Also, global reanalysis data can be useful in areas that suffer from a lack of direct in situ observation. Global ocean reanalysis estimates long-term changes in ocean conditions because these products are able to provide long-term biochemical and physical characteristics of the ocean (Verezemskaya et al., 2021).

Additionally, global reanalysis is usually used to provide an estimate of ocean currents in regions where there are no suitable regional models with the ability to display local processes. Global ocean reanalysis estimates optimal conditions of the ocean state by assimilating data from various observations in the numerical models (de Souza et al., 2020).

Data assimilation of various local and satellite observations in general ocean circulation models estimates more accurate results of the ocean state and its changes than utilizing only observations or models without data insertion into the model. However, before using reanalysis data in scientific and industrial studies or adaption these data sources as boundary conditions on a regional scale, it is important to evaluate their accuracy (Verezemskaya et al., 2021).

The Hybrid Coordinate Ocean Model (HYCOM) is one of the global ocean reanalysis developed by Fleet Numerical Meteorology and Oceanography. To produce HYCOM reanalysis, various observational data such as satellite altimetry observations, local and satellite SST data as well as vertical profiles of temperature and salinity obtained from Argo floats, buoy measurements and XBT recordings were used in the data assimilation process. Several studies have evaluated HYCOM reanalysis in different regions (Hong et al., 2016; Chen et al., 2018; de Souza et al., 2020; Russo et al., 2022; Hall et al., 2022). For example, Hong et al. (2016) evaluated salinity and temperature variables of HYCOM reanalysis in the East Sea. According to their study, temporal correlation of SST changes obtained from HYCOM with the corresponding GHRSST data was obtained more in summers than in winters. Their research showed that HYCOM products represent well the mesoscale circulations and phenomena in the Ulleung region.

In 2018, another study evaluated HYCOM reanalysis data from 1993 to 2014 with field observations. Their results showed that the SST data obtained from HYCOM is 0.29 degrees warmer than the values observed in the global ocean. Also, they found that the structure of the HYCOM salinity and temperature profiles of below the water surface is consistent with the observations made (Chen et al., 2018).

In 2020, a study conducted in waters around New Zealand compared four global ocean reanalysis products. The results of this research showed that all reanalysis temperature and salinity products had significant biases in the studied region, especially in coastal areas where these products were not able to display coastal processes and currents (de Souza et al., 2020). In addition, Hall et al. (2022) used 45-day Saildrone data, which is one of the latest marine data collection technologies, to validate the SSS data of SMAP satellite products and the HYCOM model in the western tropical Atlantic. They observed that HYCOM salinity products were unable to detect the presence of fresh tongue in the study area. Based on the data from January 17 to March 2, 2020, the standard deviation and bias between the Saildrone data and the corresponding salinity values obtained from HYCOM were up to 0.56 psu and -0.183 psu, respectively.

Due to the importance of SST and SSS parameters, as well as the crucial need to evaluate the data obtained from global ocean reanalysis before use, this study led to assess the HYCOM reanalysis products with the help of long-term time series of buoy observations. For this purpose, oceanographic measurements of 14 buoys from the National Buoy Data Center (NDBC) will be used from 2012 to 2022. Also, the statistical quality of water surface temperature and salinity provided by HYCOM reanalysis in different seasons is compared. The study area, the characteristics of the buoy stations and the reanalysis data used are given in section 2. In the following, spatio-temporal matching process between the HYCOM and buoy data is explained in section 3. The results of the statistical evaluation of the HYCOM reanalysis data quality are presented in section 4, and finally, the conclusions are drawn in section 5.

2. Data and study area

Local observations measured by 14 buoys were used in the present work. Figure 1 shows the spatial distribution of the selected stations. To evaluate the quality of HYCOM data in estimating ocean surface salinity and temperature, buoy measurements have been used as reliable values. In Table 1, the location of the selected buoy stations in terms *of latitude and longitude, as well as the number and temporal period of the available data, are presented. As seen in Table 1, the stations considered in this study are scattered between latitudes 14.825° to 46.851°N and longitudes 51.017° to 124.972° W.*

2.1. Buoy measurements

Buoys are floats anchored in fixed places and regularly and accurately collect observations from many different atmospheric and oceanographic sensors. The height and width of these floats vary from a few meters to 12 meters. In this study, the buoy measurements collected from NDBC were used to examine the accuracy of the SST/S data values of the global HYCOM ocean reanalysis. NDBC buoys are located in coastal and offshore waters from the western Atlantic Ocean to the Pacific Ocean around Hawaii and from the Bering Sea to the South Pacific Ocean.

The NDBC website provides real-time, high-resolution ocean data in NetCDF format (https://dods.ndbc.noaa.gov). The oceanographic data of the buoys in the NDBC archives include the geodetic longitude and latitude of the station, the depth of the buoy measurement, the measurement time, the water surface temperature in Celsius, the sea water salinity in practical salinity unit (psu) and other variables (Sun et al. et al. 2018). We used buoys with more than two years of measured data to perform statistical evaluation.

2.2. HYCOM

HYCOM is a data-assimilative ocean model supported by the National Ocean Partnership Program (NOPP). Satellite observations, Argo floats, CTD and XBT measurements are included in the model with the help of the Navy Coupled Ocean Data Assimilation (NCODA) 3D system to predict variables such as temperature, salinity and currents for the ocean. HYCOM reanalysis is used daily by the Global Ocean Forecast System (GOFS) of the US Army and also by the National Center for Environmental Prediction (NCEP) (Metzger et al., 2014).

A subset of HYCOM data used in Google Earth Engine (GEE) includes water temperature, salinity, velocity and depth variables. These parameters are interpolated in a regular grid of 0.08 degrees between latitudes 80.48 ° S to 80.48 ° N in 40 standard height levels (Cummings & Smedstad, 2013). In this research, surface and near-surface temperature and salinity variables were extracted from HYCOM reanalysis through GEE at the position of buoy stations. HYCOM temperature and salinity products in GEE are available from 2 October 1992 onwards.

3. Evaluation process

To make a correct comparison between SST/S data obtained from HYCOM reanalysis and the corresponding values measured in buoys, the data must match spatially and temporally. In other words, the spatial and temporal difference between the HYCOM products and buoy observations must be considered.

The buoys used in this work measure salinity and water temperature at a depth of one meter. On the other hand, the daily water salinity and temperature data from HYCOM have been extracted at depths of 0 and 2 meters through GEE. Therefore, the corresponding values obtained from the HYCOM reanalysis were interpolated into the depth of one meter before comparing with the buoy observations.

Oceanographic observations in the NDBC buoys are conducted with a 1-hour temporal resolution and based on the number of seconds (UTC) that have passed since January 1, 1970. Therefore, to achieve temporal matching between two data sets of SST/S, buoy observations were averaged every day and converted to a daily scale. Here, the data of the days when the buoys measured less than 16 hours have been removed.

Finally, after spatio-temporal matching between available data of Buoy and HYCOM, pairs of corresponding values from both data sets were provided in 14 stations for an observation period ranging between 2 and 11 years. The statistical quality of HYCOM data is evaluated using Mean Bias Error (MBE), Root Mean Squares Error (RMSE) and correlation coefficient (R) for HYCOM SST/S data compared to the buoy observations.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(\mathrm{HYCOM}_i - \mathrm{Buoy}_i) \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{HYCOM}_i - \mathrm{Buoy}_i)^2} \quad (2)$$

$$R = \frac{\sum_{i=1}^{n}(\mathrm{Buoy}_i - \mathrm{Buoy}_m)\sum_{i=1}^{n}(\mathrm{HYCOM}_i - \mathrm{HYCOM}_m)}{\sqrt{\sum_{i=1}^{n}(\mathrm{Buoy} - \mathrm{Buoy}_m)^2}\sqrt{\sum_{i=1}^{n}(\mathrm{HYCOM}_i - \mathrm{HYCOM}_m)^2}} \quad (3)$$

n is the number of pairs of SST/S values obtained from HYCOM reanalysis and buoy measurements. Also, Buoy_i *and* HYCOM_i *are the ith values of the SST/S time series resulting from the in-situ buoy observation and the corresponding HYCOM data, respectively. In Equation (3), the subscript m expresses the average of the time series of SST/S for each buoy station.*

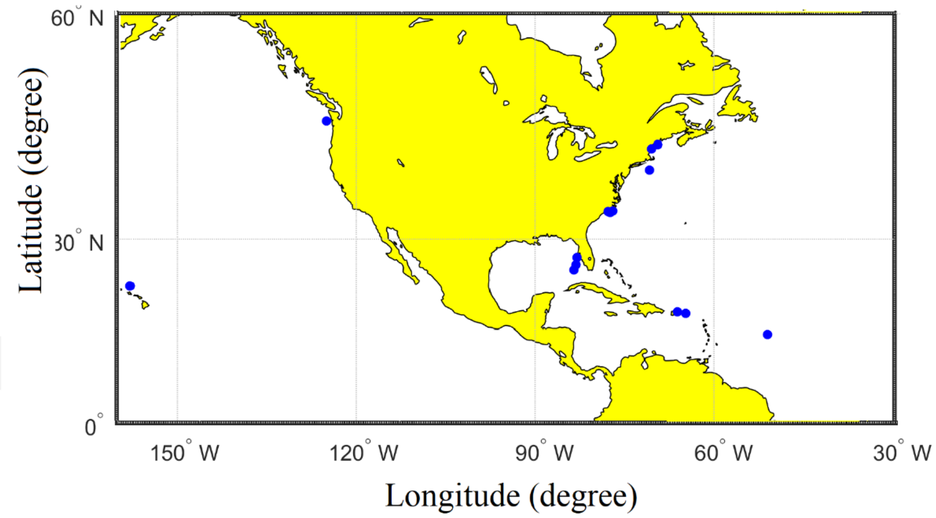

*Figure **1**. Spatial distribution of buoy stations (blue points) in the study area*

*Table **1**. Geodetic coordinates of buoy stations in this study*

Station name	Latitude (deg)	Longitude (deg)	N	Data history
41nt0	14.825	-51.017	2933	2012_2022
51wh0	22.667	-157.95	2879	2012_2022
41037	33.991	-77.36	2909	2012_2022
41038	34.141	-77.715	3151	2012_2022
41052	18.251	-64.763	1306	2018_2022
41053	18.476	-66.099	2711	2012_2022
41064	34.207	-76.949	1426	2017_2022
42013	27.173	-82.924	1343	2018_2022
42023	26.01	-83.086	1318	2018_2022
42026	25.171	-83.475	1007	2019_2022
44030	43.179	-70.426	314	2020_2022
44032	43.715	-69.358	2944	2012_2022
44076	40.137	-70.775	565	2020_2022
46100	46.851	-124.972	1973	2016_2022

4. Results

After collecting the buoy data and extracting the corresponding proper SST/S data from HYCOM reanalysis, the values of the two data sets were matched with each other in terms of temporal scale and depth. In this section, the statistical quality of SST and SSS obtained from HYCOM will be examined separately in each of the buoy stations.

4.1. HYCOM SST evaluation

The time series of daily SST values at the position of stations 51Wh0, 42023, 44032 and 46100, which are randomly selected in different places, are graphically compared with the corresponding data extracted from HYCOM in Figure 2. There is a high agreement between the HYCOM data and the SST measured at the location of the buoys, as shown in Figure 2. However, the amount of this agreement varies in different stations. For example, the *negative bias of SST values obtained from HYCOM is evident at station 42023, while the value and sign of the bias may differ at other stations.*

In addition to the graphical comparison of HYCOM SST data with the corresponding observations measured at the position of four arbitrary buoys, the average values of bias and RMSE of the HYCOM-Buoy SST differences in all stations are calculated and listed in Table 2. Also, the amount of correlation between two SST data sets and the number of data pairs, is shown in Table 2. According to the results presented in Table 2, the absolute value of the average bias of the SST differences in 14 studied stations varies between 0.1 C and 0.86 C.

Based on the data used in this study, the sign of HYCOM SST bias in different buoys is not the same. It should be noted that, except for station 42023, the HYCOM SST bias is estimated to be less than 0.38 C at the location of the rest of the buoys. Also, the RMSE of the SST differences between two data sets was between 0.23°C and 0.81 °C, except at station 42023, where the error value was estimated to be 1.39 °C. The comparison between the SST measured by the buoys with the corresponding values of HYCOM reanalysis shows the high correlation of the behavior of the time series obtained from both sets. As can be seen in Table 2, the correlation coefficient (R) for the SST variable is estimated at 99% in most stations.

To examine the effect of seasonal changes on the efficiency of SST data, the HYCOM SST statistics were calculated for each station in the winter (DJF) and summer (JJA) seasons. The seasonal values of the statistics and the average SST values obtained from the buoy for different stations, are given in Figure 3.

According to Figure 3, except for station 42023, the size of HYCOM SST bias values for all stations has no seasonal variation. For station 42023, the HYCOM estimates of the SST values in the winter season are more than 2C lower than the buoy, while the bias value at this station is close to zero for the summer season. The cause of this result may be the local winter changes in the station location, which were not considered in the global scale HYCOM reanalysis.

As expected, the average summer SST measurements in all stations were higher than the winter time data (Figure 3). According to the correlation coefficient and RMSE obtained for the SST values in the studied stations, it is generally not possible to make a definite opinion about the higher quality of HYCOM SST data in one season compared to another. The wintertime RMSE values of HYCOM SST are close to the corresponding summertime values in most stations.

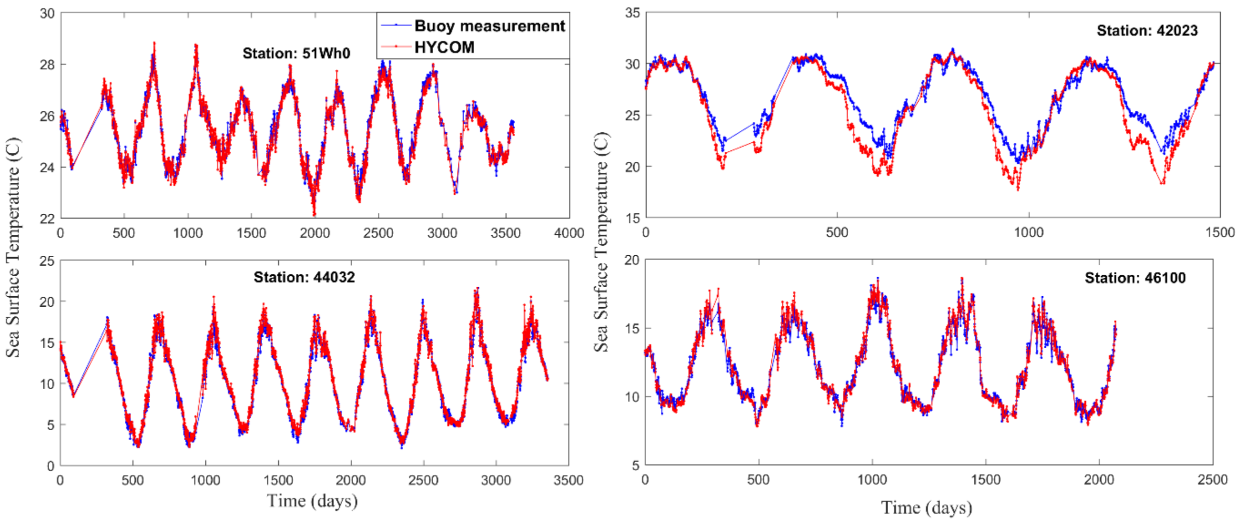

Figure 2. Comparison between HYCOM SST products and buoy measurements at 4 stations

Table 2. Statistics of HYCOM SST products in comparison with in situ buoy measurements

Station name	MBE (C)	RMSE (C)	R	N
41nt0	-0.22	0.30	0.98	2933
51wh0	-0.03	0.23	0.98	2879
41037	-0.13	0.73	0.99	2909
41038	0.09	0.55	0.99	3151
41052	-0.26	0.31	0.99	1306

41053	-0.38	0.45	0.97	2711
41064	-0.10	0.81	0.98	1426
42013	0.10	0.45	0.99	1343
42023	-0.86	1.39	0.97	1318
42026	-0.04	0.28	0.99	1007
44030	0.15	0.69	0.99	314
44032	0.26	0.70	0.99	2944
44076	0.21	0.83	0.99	565
46100	0.03	0.41	0.99	1973

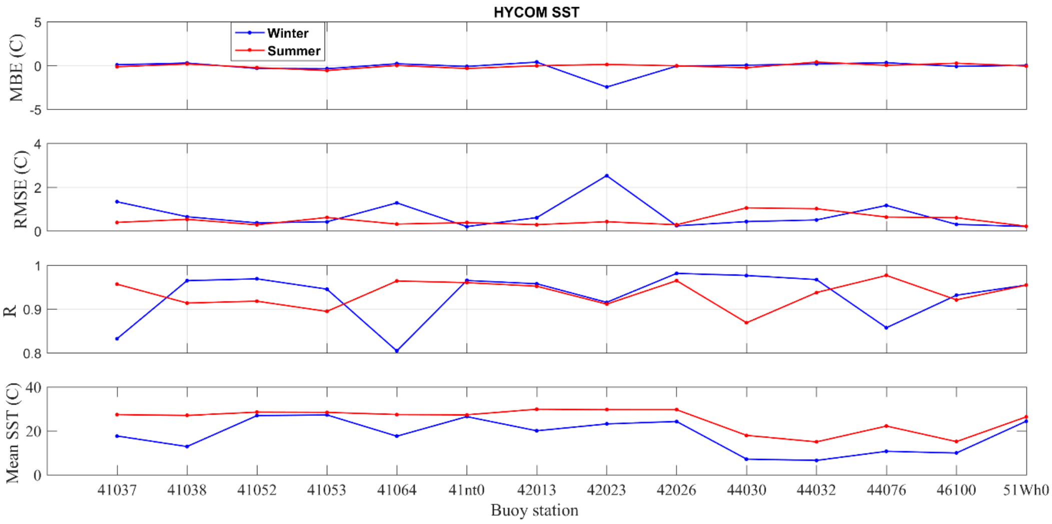

Figure 3. Seasonal variation of the HYCOM SST statistics for all stations.

4.2. HYCOM SSS evaluation

As in Figure 2, the time series of daily SSS values at the location of buoys 51Wh0, 42023, 44032 and 46100 are graphically compared with salinity data extracted from the HYCOM reanalysis in Figure 4. By comparing Figures 2 and 4, it can be seen that the consistency of HYCOM SST data in the studied stations is better than the salinity values extracted from the HYCOM reanalysis. As seen in Figure 4, the seasonal behavior of the HYCOM SSS time series is almost similar to the buoy measurements, although it is associated with a significant bias.

After extracting and conducting the initial graphical comparison of the SSS time series obtained from buoys and HYCOM reanalysis in some stations, the mean bias and RMSE of the HYCOM-Buoy SSS difference values in all stations were calculated and, together with the correlation coefficient are given in Table 3.

A pairwise comparison of SSS values obtained from in-situ measurements and reanalysis data shows that in almost all stations, HYCOM estimates SSS values more than local data. The average bias values of HYCOM SSS in the study stations vary from close to zero to 0.62 psu. Some researchers have attributed the overestimation of salinity by HYCOM in certain areas to the deficiencies in the climatological forcing of the model (Wilson & Riser, 2016; Castellanos et al., 2019).

Furthermore, the RMSE of the difference between HYCOM and buoy observations in 14 stations was obtained in the range of 0.25 to 0.86 psu. Comparing the results presented in Tables 2 and 3, indicates that the correlation of HYCOM SSS data with local observations is lower than the correlation values for HYCOM SST. Correlation between Buoy salinity observations and HYCOM data was estimated to vary from 30% to 86% from one point to *another.*

[Hall et al. (2022)](#) compared 45-day water salinity observations obtained from saildrone measurements with corresponding HYCOM values. The values of the statistics obtained for HYCOM SSS in the present research are consistent with the results obtained in their study.

[Masud-Ul-Alam et al. (2022)](#) evaluated the accuracy of satellite and modeling products in the northern Bay of Bengal. Similar to the results of the present research, they reported a high agreement between model and buoy SST data, while the quality of model SSS values was estimated to be lower than the salinity. In their study, the model SST with bias values in the range of -0.5 °C to 0.5 °C were considered similar to the in-site measurements. Also, model SSS biases between −0.5 and 0.5 psu were considered small.

In addition to the statistical evaluation of the HYCOM SSS data (Table 3), mean bias, RMSE, correlation coefficient and average salinity values at the location of the buoys for the summer and winter seasons were calculated and shown in Figure 5. According to the results, HYCOM SSS bias is positive in almost all stations for both the summer and winter seasons. In most stations, the correlation of HYCOM SSS data with buoy observations was better in summer than in winter. However, no specific pattern was observed regarding the seasonal comparison of bias and RMSE of the reanalysis salinity data. In other words, in some stations (e.g., 41053, 41064, 42013), the amount of summertime bias and RMSE values are lower than in the winter, and in other stations, the opposite results are obtained.

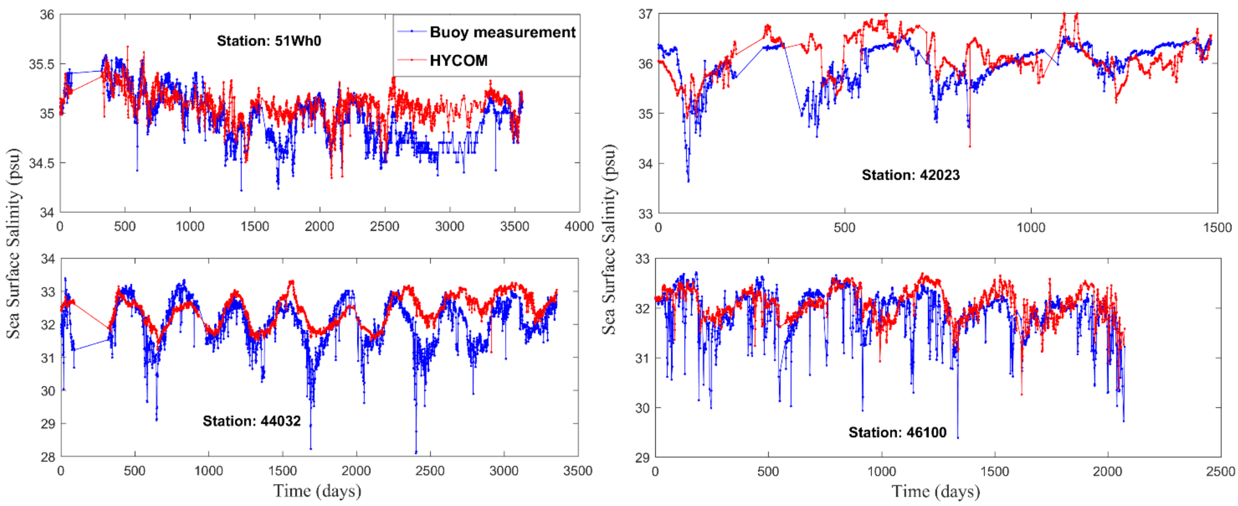

Figure 4. Comparison between HYCOM SSS products and buoy measurements at 4 stations

Table3. Statistics of HYCOM SSS products in comparison with in situ buoy measurements

Station name	MBE (psu)	RMSE (psu)	R	N
41nt0	0.05	0.35	0.55	2933
51wh0	0.12	0.23	0.63	2879
41037	0.09	0.41	0.52	2909
41038	0.45	0.80	0.37	3151
41052	0.36	0.47	0.86	1306
41053	0.51	0.66	0.65	2711
41064	0.23	0.52	0.38	1426
42013	0.53	0.67	0.42	1343
42023	0.15	0.48	0.42	1318

42026	0.38	0.81	0.28	1007
44030	0.62	0.80	0.65	314
44032	0.41	0.72	0.55	2944
44076	-0.13	0.63	0.75	565
46100	0.17	0.47	0.39	1973

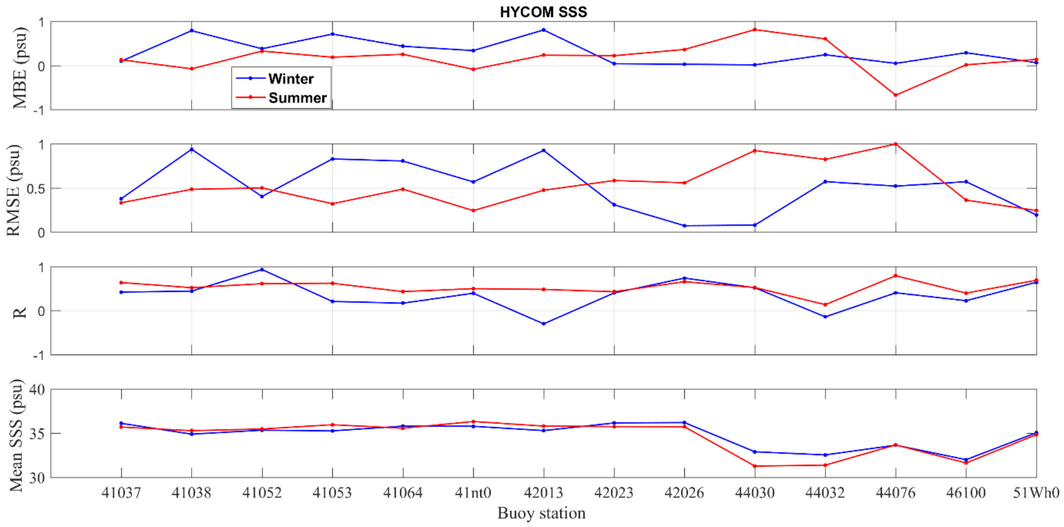

Figure 5. Seasonal variation of the HYCOM SSS statistics for all stations

5. Conclusion

The temperature and salinity of the sea surface as influential climatic parameters and connecting variables between the atmosphere and the ocean have always been of interest to researchers in the studies of weather changes, the life of marine animals, monitoring ocean cycles and the vertical movement of water in different layers. Global water salinity and temperature data are usually obtained by retrieving raw satellite observations, Argo floats and buoy measurements and other local measurements. In conjunction with the mentioned data sources, ocean reanalysis obtains different variables such as temperature and salinity with high spatial resolution through data assimilation of various observations in numerical models. In areas with significant local changes in the oceans, global ocean reanalysis is less accurate than direct observations. Therefore, before utilizing global ocean reanalysis SST/S products, evaluating the quality of these data sets in the considered region is necessary.

Based on the time series of oceanographic observations collected from 14 NDBC buoys, the statistical quality of SST/S data obtained from HYCOM reanalysis was evaluated in this research. HYCOM data with a spatial resolution of 0.08 degrees was used for at least five years in most stations. After averaging the hourly buoy data and interpolating the HYCOM products in the depth of the buoys, the corresponding temperature and salinity data pairs were prepared from both data sets.

Statistical comparison between SST data obtained from HYCOM reanalysis and corresponding local values measured in buoys showed a high correlation (more than 0.97) in all stations. Also, the results revealed that the bias sign of HYCOM SST varies in different stations. In most stations, the absolute value of SST bias obtained from HYCOM reanalysis was estimated to be less than 0.38 C. The RMSE of the HYCOM-Buoy SST differences at the location of the studied buoys ranged between 0.23 C and 0.81 C.

Moreover, the HYCOM SSS data were compared with the corresponding buoy observations. Statistical evaluation of the SSS data showed that HYCOM reanalysis estimates salinity more than actual observations in almost all stations. The results showed that the size of HYCOM SSS bias might reach 0.62 psu in some stations. According to the examination of correlation values, HYCOM reanalysis and in-situ observations have a higher correlation for SST than the SSS variable, and this difference reaches more *than 50% in some stations. Additionally, the statistics related to SST/S data obtained from HYCOM in the winter and summer seasons were compared. Based on the obtained seasonal values, there was no clear pattern in the increase or decrease of the quality of HYCOM SST/S data with the change of season in the studied stations.*

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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