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To cite this article: Jingdong Liu *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **300** 032093

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Improvement of the air-sea flux parameterization scheme in the ocean circulation model

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Abstract. COARE (Coupled Ocean-Atmosphere Response Experiment) algorithm is the more advanced algorithm, calculating the air-sea flux. COARE 3.0 is the latest version. In this paper, the COARE 3.0 bulk sea-air flux parameterization scheme is introduced into the SBPOM model. Compared the simulated sea surface temperature (SST) of the SBPOM ocean model with COARE 3.0 and without COARE 3.0 in the areas near equator, and analysed the reasons for the differences in the simulated SST. The results showed that the COARE 3.0 bulk air-sea flux parameterization scheme is good in the SBPOM ocean model. The simulation accuracy of the SBPOM ocean model in the areas near equator has been improved after the COARE 3.0 bulk sea-air flux parameterization scheme was introduced, and the simulation error of most areas was within 1°C, which was mainly due to the accuracy of the calculation of momentum flux improved by COARE 3.0 bulk sea-air flux parameterization scheme.

1. Introduction

Due to the influence of nature and mankind, the weather and climate of the earth are gradually changing in the 21st century, such as "global warming". These weather and climate anomalies affect the energy transport between the ocean and the atmosphere, such as momentum flux and heat flux between the sea and the air. They not only affect the distribution of temperature-salinity and ocean circulation in the ocean, but also play a driving role in the numerical simulation [3, 8, 9].

At present, there are four main parameterization schemes for obtaining air-sea flux in the world, namely bulk parameterization scheme, flux profile scheme, inertial dissipation scheme and vortex correlation scheme. Each scheme has its merits or defects [2, 6, 20, 25]. The advantages of the bulk parameterization scheme are that the algorithm structure is clear, the exchange coefficient can be obtained by iteration, and the operation speed is fast. It is widely used in various ocean models. The main disadvantage of this scheme is that the parameterization scheme is difficult to determine, and each parameterization scheme has its own unique exchange coefficient [20]. Besides, exchange coefficient needs to be supported by a large amount of observations and can be only used in areas with enough data. The final disadvantage is that the scheme has higher accuracy of air-sea flux calculated at a certain wind speed (middle-low wind speed) and poor applicability under high wind speed conditions [2]. The advantage of the flux profile scheme is that the requirements of the measuring instrument are low, and



the low-frequency measuring instrument can complete the measurement of the average variables profile of the atmospheric boundary layer. The disadvantages are that the atmospheric boundary layer variable profile is affected by many factors, and the use of a large number of empirical formulas makes the calculated air-sea flux error larger [6]. The advantages of the inertial dissipation scheme are that the required air-sea flux data can be directly measured by the instrument, and the result is intuitive and easy to operate. Since this scheme is based on the similarity theory, one disadvantage is that the calculated air-sea flux is the absolute value of the flux, and other data is needed to determine the sign of the flux. The advantage of the vortex correlation scheme is that the calculation method is direct, the air-sea flux obtained is highly accurate, and the flux at different heights can also be obtained; the disadvantage is the high requirement of the measuring devices and high cost in equipment purchase and maintenance, and it is not suitable for large-scale use. In addition, it has higher requirements for hydro-meteorological conditions during observation, and the error of data obtained is large when the observation environment is poor. Through the discussion of the advantages and disadvantages of these four kinds of air-sea flux parameterization schemes, this paper chooses the bulk parameterization scheme to improve the model air-sea flux. Because the bulk parameterization scheme is simple and only needs several elements such as wind speed, temperature and specific humidity, furthermore the calculation speed is fast and the calculation accuracy is high, and it has been applied in other models [12].

The earliest bulk algorithm Liu-Katsaros-Businger (LKB) [22] was developed in 1979, and this algorithm works well in calculating sea surface air-sea flux. In the early 1990s, based on COARE experimental mapping data as well as other experimental data of voyage and the development of air-sea interaction theory, the LKB bulk algorithm empirical formula and the air-sea exchange coefficient in the formula were further improved. The improved LKB algorithm was renamed to the COARE 1.0 bulk algorithm. After the generation of COARE 1.0 algorithm, with the increase of the amount of observed data and the deepening of theoretical research, the COARE algorithm is gradually improving, and there are improved versions such as COARE 2.0 and COARE 2.5. The main difference between these versions is the improvement of the empirical exchange coefficient and the expansion of the application of the model. Based on the analysis of the early versions of COARE and the combination of new theoretical research results, the COARE 3.0 bulk algorithm was in use in 2003. Some Studies [5, 11, 12, 23] show that the current COARE 3.0 bulk algorithm is an internationally recognized optimal parameterization scheme for calculating momentum flux and heat flux between sea and air.

The POM is a three-dimensional bar clinic ocean circulation model based on the original equations developed at Princeton University [4]. The Stony Brook Parallel Ocean Model (SBPOM) used in this paper is a parallel version based on the POM model developed by Antoni and Wang [18]. The SBPOM model does not contain a parameterization scheme for calculating air-sea flux, and its air-sea flux needs to be provided by reanalysis data. In order to realize the coupling operation between SBPOM model and atmospheric model, the parameterization scheme of air-sea flux calculation is needed to be integrated into SBPOM model.

This paper improved the SBPOM ocean model based on COARE 3.0 bulk parameterization scheme. The improved SBPOM ocean model is used to simulate the sea surface temperature (SST) in the sea near the equator. Then, the simulated SST of improved SBPOM ocean model was compared with the ECMWF data, and the differences between the air-sea flux calculated by the COARE 3.0 bulk parameterization scheme and the NCEP reanalysis data was analysed. And the main reasons for the changes in the simulated SST before and after the improvement.

2. Materials and methods

2.1. Scheme

The COARE 3.0 bulk parameterization scheme is based on the MOST similarity theory, which expresses the air-sea flux as a function of the mean value of the atmospheric or oceanological elements near the sea surface [1, 5, 13, 24]:

$$\overline{w'x'} = c_x^{1/2} c_d^{1/2} S \Delta X \quad (1)$$

Where x is the wind speed component of the direction u , v , θ is the potential temperature, q is the atmospheric or oceanological elements near the sea surface; c_x is the corresponding bulk exchange coefficient of x , c_d is the bulk exchange coefficient of wind speed; $c_x^{1/2} c_d^{1/2}$ is the total bulk experience exchange coefficient; ΔX is the difference between the sea surface variable and the mean value of the sea surface atmospheric variable; S represents the relative average wind speed of the sea surface, which is the vector sum of the average wind speed of the sea surface and the gust (U_g) of the sea surface. The profile of ΔX and S is:

$$\Delta X = X_{sea} = X(z) \quad (2)$$

$$S = (U^2 + V^2 + U_g^2)^{1/2} \quad (3)$$

The empirical exchange coefficient in the MOST similarity theory is related to the sea surface stability of the air-sea interface:

$$c_x^{1/2}(\zeta) = \frac{c_{xn}^{1/2}}{1 - \frac{c_{xn}^{1/2}}{k} \psi_x(\zeta)} \quad (4)$$

Where n means that the profile is applicable to neutral stability conditions ($\zeta=0$) based on MOST similarity theory, z refers to the distance of the observation instrument from the sea surface when measuring the variable $X(z)$, ψ_x represents the empirical formula of the mean stability of the variable, k is the Karman constant, z_{0x} describes the roughness length of the surface neutral transfer characteristics of the variable x . The profile of the stability parameter ζ in the MOST similarity theory is:

$$\zeta = -\frac{kgz}{T} \frac{(\overline{w'\theta'} + 0.61T\overline{w'q'})}{(-\overline{w'u'})^{3/2}} \quad (5)$$

Where T represents the temperature, g is the acceleration of gravity, $\overline{w'z'}$ represents the component of the different variables along the streamline direction.

The COARE 3.0 bulk parameterization scheme integrates a variety of modules such as sea surface roughness and skin cooling of the warm water layer, and the influence of various factors on the calculation of air-sea flux was taken into account. This makes the calculated air-sea flux more accurate and can meet the needs of model simulation.

2.2. Materials

NECP reanalysis data contains ocean and sea surface atmospheric data, using a Gaussian grid with coverage of 88°S-88°N, 0°-360°, with the spatial resolution of $1.9^\circ \times 1.875^\circ$ and the time resolution of 6h[17]. The SODA data is a monthly average reanalysis data provided by the Global Ocean Data Assimilation Analysis System with a spatial resolution of 0.5° and σ coordinate [7]. The spatial

resolution of the ETOPO5 topographic data is $5' \times 5'$. The ECMWF reanalysis data is the reanalysis data provided by the European Medium-Range Weather Forecast Centre [14]. It contains information on global atmosphere, ocean and air-sea flux. It used T55 grid and σ coordinate. This data assimilate a large number of high-precision observatory data and satellite data. This paper uses this data as verification data for simulated results. The Argo buoy data was derived from the international Argo project proposed in 1998, and 181 Argo were used as the observed data to compare with the simulated results [26].

2.3. Models and settings

Compared with the POM model, the Computational efficiency of the SBPOM is greatly improved. The simulated area is $5^{\circ}\text{S} \sim 15^{\circ}\text{N}$, $0^{\circ} \sim 360^{\circ}$, with the spatial resolution of 0.5° , and divided into 40 layers with σ coordinate. The terrain data is provided by ETOPO5 the initial field and boundary are provided by the SODA data. The initial SBPOM model was driven by the momentum flux and heat flux from NECP. The improved SBPOM model was driven by the momentum flux and heat flux calculated by the COARE 3.0 bulk parameterization scheme. The simulated time of the model is January 2014.

3. Result

Fig. 1 shows that the difference of the SST simulated by the improved SBPOM model and the ECMWF reanalysis data is mostly in the range of $\pm 1.5^{\circ}\text{C}$, and the simulated error is large in the local area. The areas with large error are mainly distributed along the equator and on the west coast of Mexico and North Africa, and the simulated error in the coast of the Somali Peninsula is largest, reaching 3°C . Combined with *Fig. 2* and *Fig. 3*, it can be seen that the improved SBPOM model simulated results have a large improvement, and the simulation error is in the range of $\pm 1^{\circ}\text{C}$, especially in the area where the simulated error is large in *Fig. 1*, and the simulation accuracy is greatly improved.

In order to further compare the difference between the simulated SST of the improved SBPOM mode and the measured SST, the simulated results are interpolated to the Argo buoy point. And the scatter plot of the simulated results and the Argo measured data is shown in *Fig. 4*. Comparing the fitted line with the line $y = x$, the red line in *Fig. 4 (A)* shows that the red line is below the black line, indicating that the SST of the initial SBPOM model is generally high and the error is large. It can be seen from *Fig. 4 (B)* that the red line and the black line are basically coincident, indicating that the simulated result has small error, which is greatly improved compared with A.

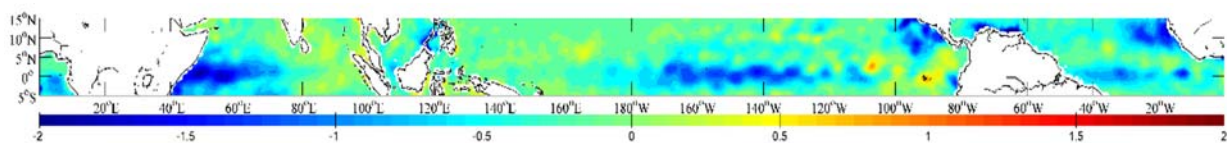


Figure 1. Differences between SST simulated without COARE 3.0 and ECMWF data ($^{\circ}\text{C}$)

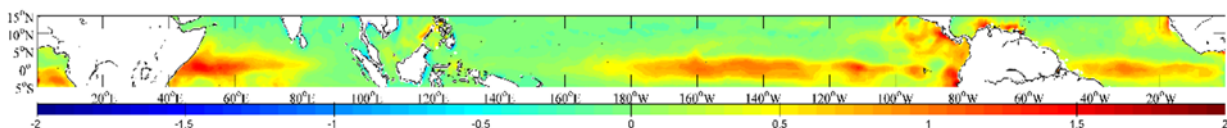


Figure 2. Differences between SST simulated with COARE 3.0 and without COARE 3.0 ($^{\circ}\text{C}$)

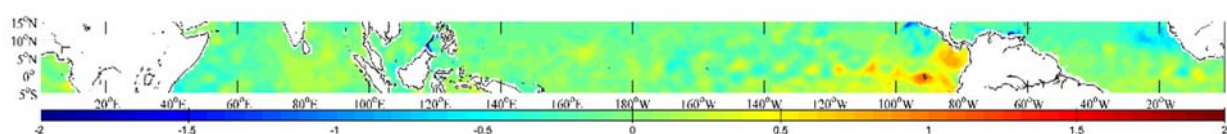


Figure 3. Differences between SST simulated with COARE 3.0 and ECMWF data ($^{\circ}\text{C}$)

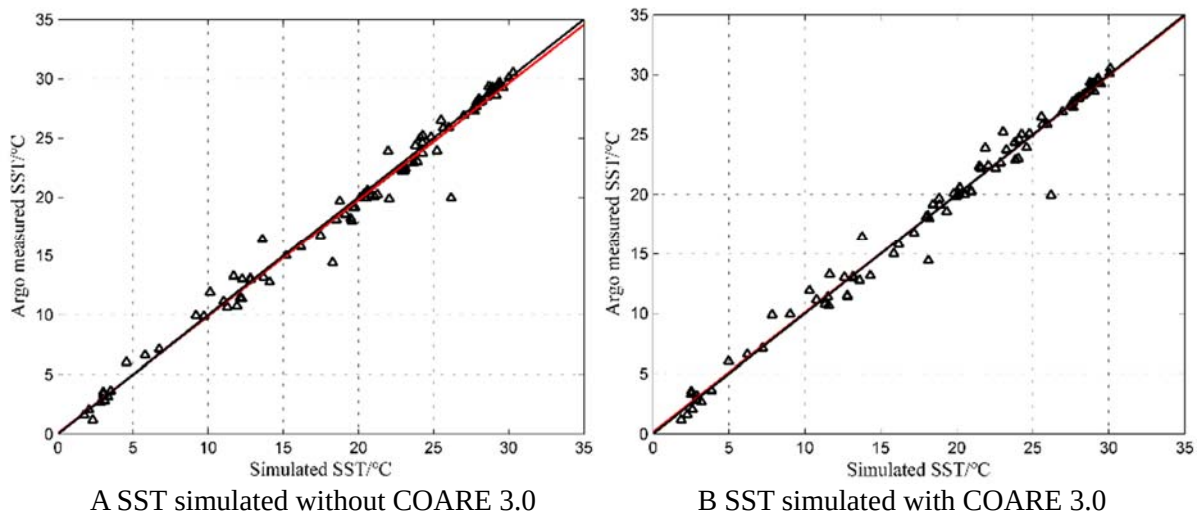


Figure 4. Comparison of SST simulation results with Argo buoy data (black line: $y = x$, red line: fitted line)

4. Discussion

The simulated SST after the introduction of the COARE 3.0 bulk parameterization scheme causes the improvement of the simulation compared to the simulated SST with NCEP reanalysis data. According to the setting of the mode, the heat flux and the momentum flux are respectively divided into the sensible heat flux term, the other heat flux term, the zonal momentum flux term, and the meridional momentum flux term to discuss the reason [10, 15, 16, 19, 21].

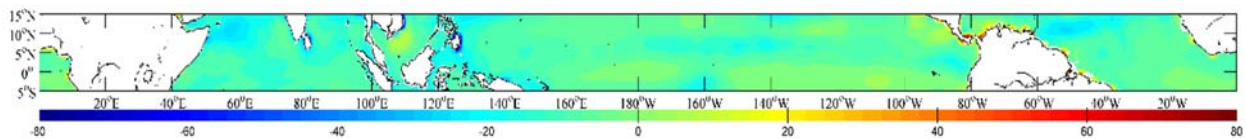


Figure 5. Sensible heat flux calculated by COARE 3.0 bulk parameterization scheme (W/m²)

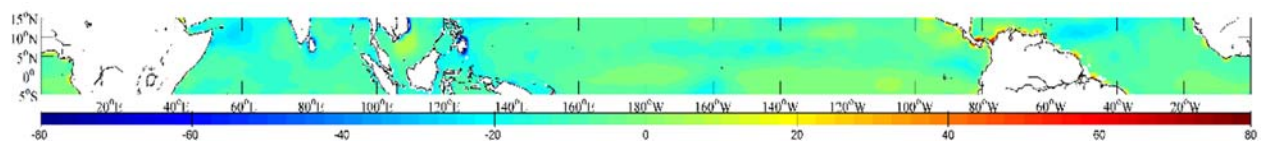


Figure 6. Sensible heat flux provided by NCEP (W/m²)

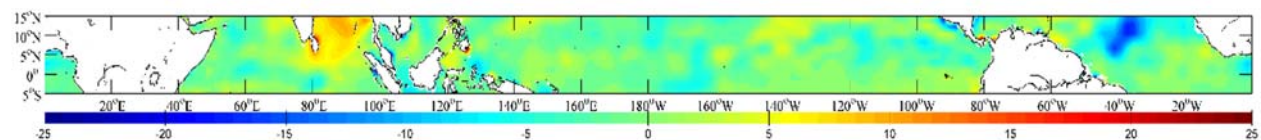


Figure 7. Difference between sensible heat flux with NCEP and that calculated by COARE 3.0 bulk parameterization scheme (W/m²)

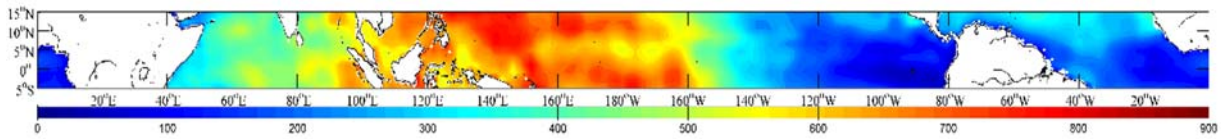


Figure 8. Q calculated by CORAE 3.0 bulk parameterization scheme (W/m²)

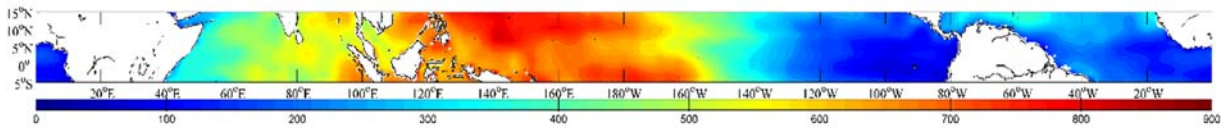


Figure 9. Q provided by NCEP (W/m²)

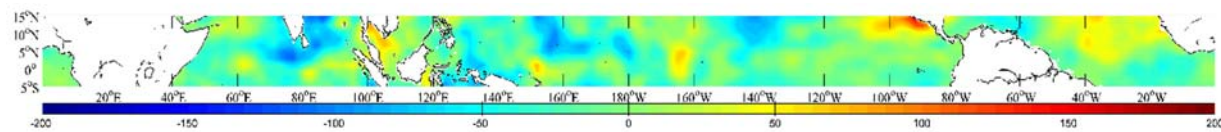


Figure 10. Difference between Q with NCEP and that calculated by CORAE 3.0 bulk parameterization scheme (W/m²)

From *Fig. 5* and *Fig. 6*, it can be seen that the sensible heat flux in the near-equatorial sea is small, and the distribution of the sensible heat flux of the NCEP reanalysis data is almost the same with the distribution of that calculated by COARE 3.0 bulk parameterization scheme. Combined with *Fig. 7*, the sensible heat flux calculated by the COARE 3.0 bulk parameterization scheme is slightly higher than that of the NCEP reanalysis data, and the difference is about 20 W/m².

Other heat flux terms (Q) are composed of long-wave radiation (Q_L), latent heat flux (Q_E) and short-wave radiation (Q_S). The profile is:

$$Q = Q_L + Q_E - Q_S \quad (6)$$

Fig. 8 and *Fig. 9* show that high value of the other heat flux was distributed in the area between the Indian Ocean and the Pacific Ocean and the mid-western Pacific Ocean, with a maximum of about 900 W/m²; in the Atlantic and the mid-eastern Pacific, the value is lower than 400 W/m². *Fig. 10* shows that in most areas, the calculated result of the CORAE 3.0 bulk parameterization scheme is slightly higher than that of the NCEP reanalysis data. The absolute value of difference is greater than 50 W/m² in the central Indian Ocean, the Gulf of Thailand, the west coast of Mexico, and the eastern Atlantic.

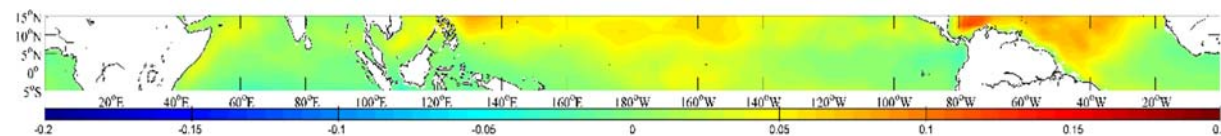


Figure 11. The zonal momentum flux calculated by the CORAE 3.0 bulk parameterization scheme (N/m²)

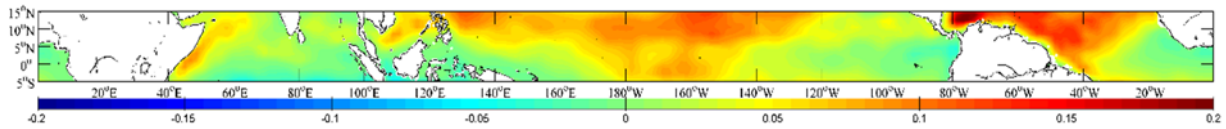


Figure 12. The zonal momentum flux provided by NCEP (N/m²)

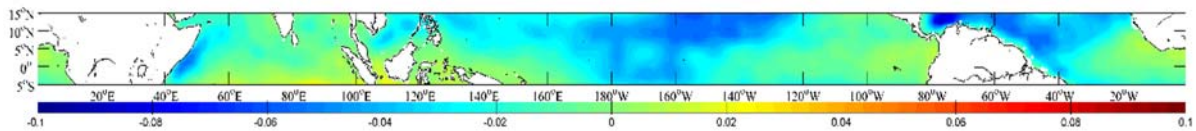


Figure 13. Difference between the zonal momentum flux with NCEP and that calculated by the CORAE 3.0 bulk parameterization scheme (N/m²)

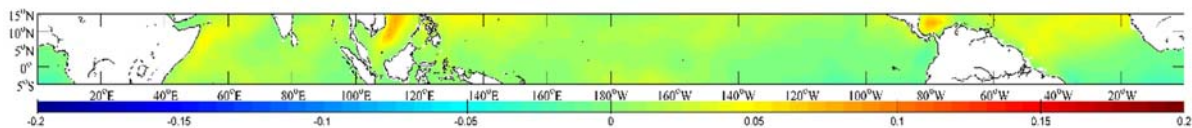


Figure 14. The meridional momentum flux calculated by the CORAE 3.0 bulk parameterization scheme (N/m²)

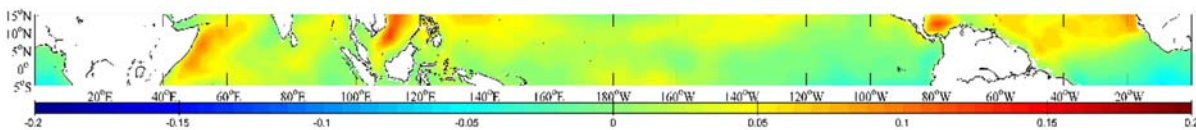


Figure 15. The meridional momentum flux provided by NCEP (N/m²)

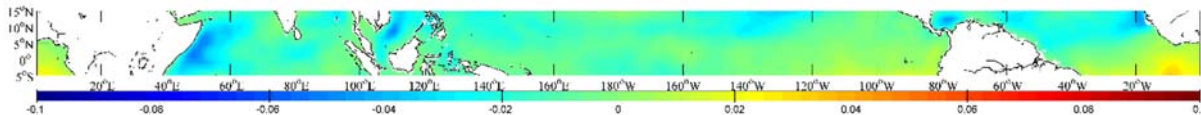


Figure 16. Difference between the meridional momentum flux with NCEP and that calculated by the CORAE 3.0 bulk parameterization scheme (N/m²)

In the sea near the equator, the wind speed is small. *Fig. 11, Fig. 12, Fig. 14 and Fig. 15* show that the momentum flux is relatively small, the distribution of momentum flux of NCEP and that of the momentum flux calculated by CORAE 3.0 bulk parameterization scheme are basically the same, and the difference is in the range of -0.08 N/m^2 – 0.02 N/m^2 . Compared with the NCEP reanalysis data, for the zonal momentum flux, the calculated result of the CORAE 3.0 bulk parameterization scheme is small in the north of the equator in the Pacific and Atlantic, and is large in the south of the equator in Indian Ocean and the eastern part of the Pacific and Atlantic; for the meridional momentum flux, the calculated result of the CORAE 3.0 bulk parameterization scheme is small in the western Indian Ocean, the South China Sea, the Gulf of Mexico, and the north of the equator in the Pacific and Atlantic; while in the eastern Pacific and the southern Atlantic, that is large.

By analysing the distribution of heat flux and momentum flux of NCEP and that calculated by CORAE 3.0 bulk parameterization scheme and simulated SST improvement portion, it is suspected that the main reason for the difference of simulated SST between the initial SBPOM and the improved SBPOM is the improvements in momentum flux due to CORAE 3.0 bulk parameterization scheme. In order to verify this hypothesis, only the heat flux term is improved for the SBPOM, and the momentum flux term is not changed. The simulated result was compared with the ECMWF. Comparing the *Fig. 1*

with Fig. 17, it is found that the improvement of heat flux has little effect on the SST simulation. We can conclude that the improvement of the momentum flux by the CORAE 3.0 bulk parameterization scheme is the main reason for the improvement in SST.

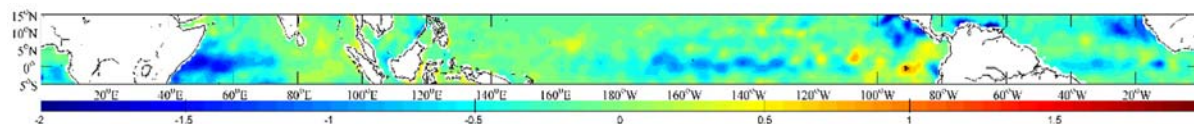


Figure 17. Difference between simulated SST of the heat flux term improved with the ECMWF (°C)

5. Conclusion

The CORAE 3.0 bulk parameterization scheme can be applied not only in other models, but also be good in the SBPOM model. The introduction of the CORAE 3.0 bulk parameterization scheme simplifies the model preparation process, and is helpful to the coupling between SBPOM ocean model and the atmosphere model in the future. In the numerical simulation of SST in the areas near equator, compared with the use of NCEP reanalysis data, the CORAE 3.0 bulk parameterization scheme can improve the SST simulation accuracy. And the simulation error of most areas was within $\pm 1^\circ\text{C}$. The main reason is that the accuracy of the calculation of momentum flux improved by COARE 3.0 bulk sea-air flux parameterization scheme.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (Grant No. 41676014). For this paper, the corresponding author is Jian Shi.

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