Article ID: 1006-8775(2018) 03-0280-08

THE EVALUATION, DATA FUSION AND APPLICATION OF FY2E SST IN TROPICAL CYCLONES OVER NORTHWEST PACIFIC OCEAN

JIN Shuang-long (靳双龙)[1], HU Liang (胡 亮)[2, 3, 4], DENG Di-fei (邓涤菲)[4, 5], LIU Xiao-lin (刘晓琳)[1], SONG Zong-peng (宋宗朋)[1]

(1. State Key Laboratory of Operation and Control of Renewable Energy & Storage Systems, China Electric Power Research Institute, Beijing 100192 China; 2. State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081 China; 3. National Satellite Meteorological Center, Beijing 100081 China; 4. School of Physical, Environmental and Mathematical Sciences, University of New South Wales, Canberra ATC 2600 Australia; 5. Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029 China)

Abstract: The daily FY2E Sea Surface Temperature (SST) data from China National Satellite Meteorological Center (NSMC) was evaluated and compared with the Optimum Interpolation Sea Surface Temperature (OISST) data from US National Oceanic and Atmospheric Administration (NOAA) over Northwest Pacific Ocean (NPO) in this study. The results show that the distribution of FY2E SST is close to OISST in tropical region over NPO, especially in typhoon active season, but the value of FY2E SST is a little lower than that of OISST in tropical ocean, with the absolute deviation 1℃ lower and the relative deviation about 6% lower. The correlation coefficient between monthly FY2E SST and monthly OISST is as high as 0.7, which passes the *t*-test at a significance level of 0.01. Based on the evaluation result, the merged SST_{FY} over NPO is calculated using a weighting function. Besides, Tropical Cyclone Heat Potential ($TCHP_{FY}$) is calculated and combined with the simulated sea temperature profile. From three years operational tests in NSMC, the merged SST_{FY} and $TCHP_{FY}$ are shown to be good indexes in monitoring and predicting the intensity of tropical cyclones (TCs) over NPO.

Key words: SST; data fusion; TCHP; tropical cyclone

CLC number: P405 **Document code:** A

doi: 10.16555/j.1006-8775.2018.03.002

1 INTRODUCTION

In China, an average of 9.09 tropical cyclones (TCs) make landfall every year, in which 3.17 can reach the intensity of typhoon [1]. Wind, rain, waves, storm surge and other weather disaster associated with the TC are serious threats to the life and property safety of people living in coastal China. Taking super typhoon Damrey (0518) for example, it caused the collapse of Hainan Power Grid and the first black-out in a major Chinese power grid [2].

With the development of numerical models, the prediction of TC track has improved a lot, but it has made little progress in the forecasting of TC strength and rainfall[3]. Much work needs to be done. In addition to numerical models, some metrices are also useful and can help predict TC strength. For example, tropical cyclones are usually formed over warm tropical oceans with high sea surface temperature (SST), a deep mixed layer, a moist middle-lower troposphere, and a weak vertical wind shear [4]. TCs obtain energy from the underlying ocean in the form of surface entropy flux, which is largely determined by SST. Therefore, SST is a key factor to the formation and intensification of TCs [5].

The relationship between TC intensity and SST has been discussed over several decades. In 1958, Miller[6] developed the first relationship between SST and TC maximum intensity from the aspect of minimum sea level pressure. Emanual [7, 8] found that the maximum potential intensity in terms of the minimum sea level pressure or the maximum near-surface wind speed is a function of the underlying SST, the ambient near-surface air temperature and relative humidity, and the outflow-layer temperature in the upper troposphere. Nevertheless, from the first approximation, the maximum potential intensity of TC can be considered as a function of SST only. Both Miller and Emanuel predicted the maximum potential intensity increases with the increasing SST[6-8]. Therefore, the monitoring of SST plays an important role in the operational forecast of tropical cyclone intensity.

Fengyun 2E (FY2E) is the fifth satellite of China's

Received 2017-12-12; **Revised** 2018-06-22; **Accepted** 2018-08-15

Foundation item: Science and Technology Foundation of State Grid Corporation of China, National Natural Science Foundation of China (41575045, 41205030, 41175046); Basic Research Fund of the Chinese Academy of Meteorological Sciences (2017Z013)

Biography: HU Liang, Ph. D., associate researcher, primarily undertaking research on satellite meteorology.

Corresponding author: HU Liang, email: hul@cma.gov.cn

geostationary meteorological satellites and located at 105°E over the equator, with the perfect zenith angle to scan over Northwest Pacific Ocean (NPO, 100°–140°E, 0°–40°N). Due to the limitation of algorithm, however, FY2E can only detect the SST under clear-sky conditions, and the value is unavailable under cloudy condition. Optimum Interpolation Sea Surface Temperature (OISST) has been widely used in TC research in recent years, which is blended with in situ data and satellite data produced by National Oceanic and Atmospheric Administration (NOAA), and provides gridded SST in both cloudy and clear-sky condition[9, 10]. Unfortunately, we always cannot obtain the real-time OISST data but with delay of 2 or 3 days. Therefore, it is necessary to produce a new SST product including the advantage of FY2E SST and OISST. Accordingly, this study is designed to calculate the merged SST_{FY} and Tropical Cyclone Heat Potential ($TCHP_{FY}$) products over NPO using FY2E SST and OISST.

The paper is organized as follows: data and methodology are in section 2; section 3 presents the evaluation and comparison of horizontal distribution between OISST and FY2E SST; section 4 provides the statistical characteristics of OISST and FY2E SST over NPO; the data fusion and application of SST_{FY} and $TCHP_{FY}$ in TCs are given in section 5 and section 6, respectively; The last section discusses key points and draws conclusions.

2 DATA AND METHODOLOGY

The high-resolution SST product of the OISST [11] version 2 is obtained from ftp://eclipse.ncdc.noaa.gov/pub/OI-daily-v2/climatology/. The high temporal and spatial resolution OISST product has been blended with in situ data and satellite data since 1988 (e.g., Chen et al. [9]; Murakami et al. [10]). The SST product of FY2E satellite was obtained from http://satellite.nsmc.org.cn/portalsite/default.aspx. A brief introduction of these two SST datasets is given in Table 1.

Table 1. A comparison of the parameters of FY2E SST and OISST.

	FY2E SST	OISST	Note
Resolution	0.1°	0.25°	FY2E SST is unavailable under cloudy area.
Precision	0.1℃	0.01℃	
Effective range	0 to 40℃	–3 to 45℃	
MSD	1.07℃	2.05℃	The MSD of the difference between OISST and FY2E SST is 1.41 ℃

The resolution and precision are 0.1° × 0.1° and 0.1℃ for FY2E SST data, and 0.25°× 0.25° and 0.01℃ for OISST, respectively. The effective data range is 0 to 40℃ for FY2E SST, and –3 to 45℃ for OISST. To study the seasonal variation of SST over NPO, the mean square deviation (MSD) of FY2E SST, OISST and the difference between them are calculated based on monthly data. The MSD is 1.07℃ for FY2E SST but 2.05℃ for OISST, indicating the seasonal fluctuation is smaller in FY2E SST. The MSD of the difference between FY2E SST and OISST is 1.41℃, reflecting the deviation of these two datasets is within 1.5℃. It is noticeable again that FY2E SST is undefined under cloudy area, while OISST is available under both cloudy and clear sky.

3 A COMPARISON OF HORIZONTAL DISTRIBUTION BETWEEN FY2E SST AND OISST

To compare these two kinds of datasets, the annual average of FY2E SST and OISST, the absolute deviation and relative deviation between them are shown in Fig.1. The values are very close to each other to the south of 20° N and in the equator, the annual average distribution of these two data is similar. The absolute deviation is within 1℃, relative deviation is less than 6% over lower-latitudes. However, the deviation becomes larger over higher-latitudes, the maximum absolute deviation is up to 10℃, and relative deviation is up to 20 % over the Bohai Sea.

The absolute deviation between FY2E SST and OISST in the four seasons are shown in Fig.2. Like annual average deviation, the absolute deviation between FY2E SST and OISST is generally consistent for the four seasons. The absolute deviation is within 1℃ over most tropical ocean in the four seasons, especially in JJA (Fig.2b) and SON (Fig.2c).

The MSD distribution of FY2E SST (Fig.3a) is also close to the one in OISST (Fig.3b), with large values at mid-to-higher latitudes (>3℃) and small values at lower-latitudes (<2℃), which indicates that the seasonal variance of SST is active at mid-higher latitudes while it keeps relatively stable at lower-latitudes and equatorial regions.

The MSD of the difference between FY2E SST and OISST (Fig.3c) shows that large differences are located at mid-higher latitudes, but small values are located at lower-latitudes and equatorial regions. It suggests that not only the seasonal variation of FY2E

SST and OISST is active at mid-higher latitudes, but also their difference is more vigorous compared with the one in the tropics and equator.

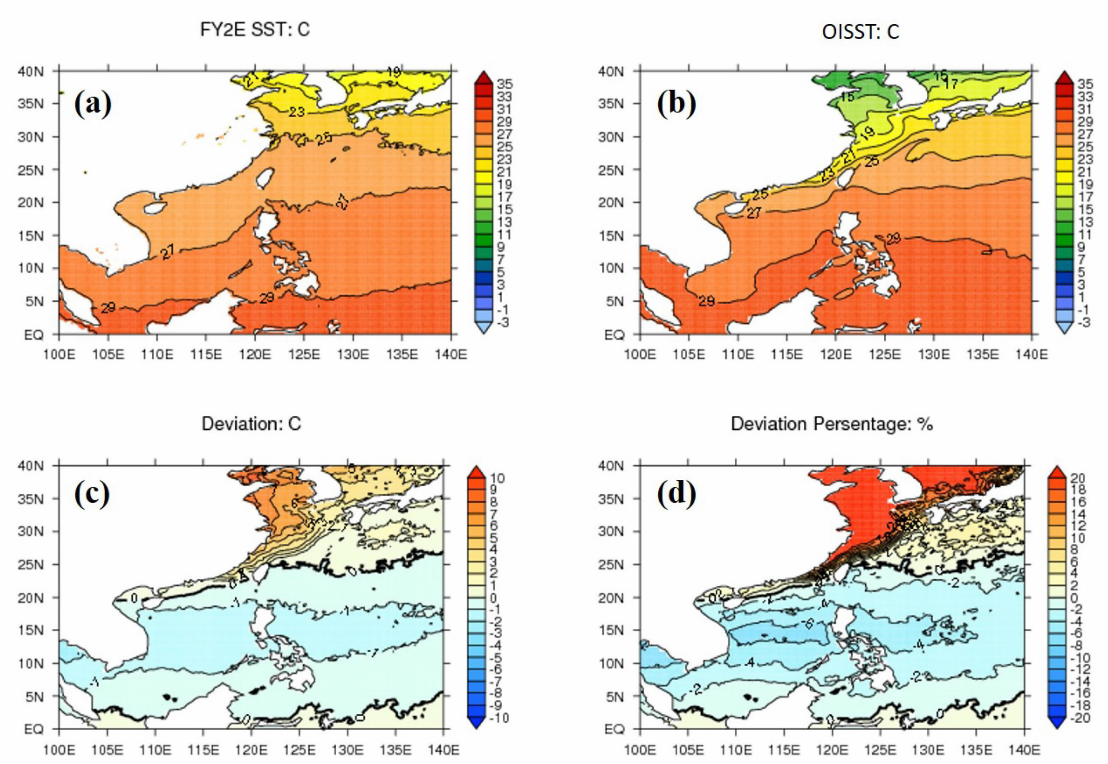

Figure 1. The annual average of FY2E SST (a) and OISST (b). The absolute deviation (c) and relative deviation (d) between FY2E SST and OISST.

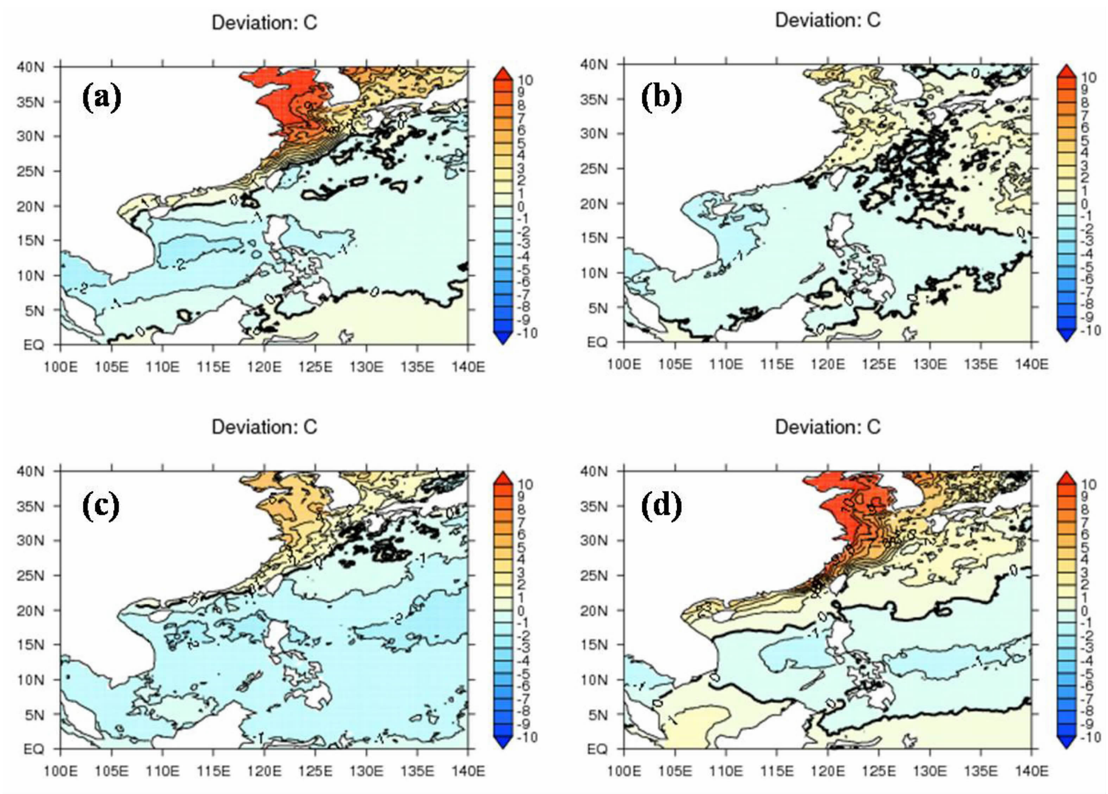

Figure 2. The absolute deviation between FY2E SST and OISST in MAM (March, April and May; a), JJA (June, July and August; b), SON (September, October and November; c) and DJF (December, January and February; d).

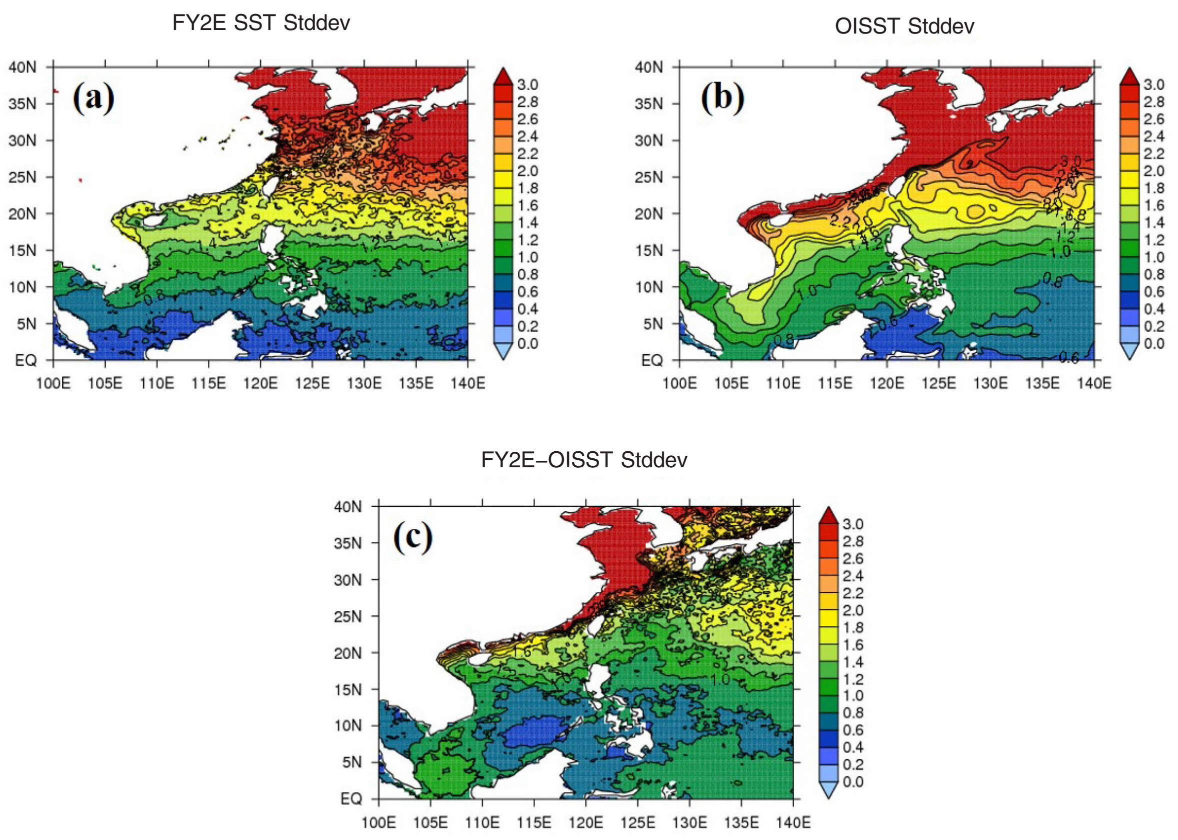

Figure 3. The mean square deviation of FY2E SST (a), OISST (b) and the difference between FY2E SST and OISST (c).

4 STATISTICAL CHARACTERISTICS OF OISST AND FY2E SST OVER NPO

To further evaluate the SST product of FY2E, we calculate the statistical characteristics of FY2E SST and OISST over NPO (Fig.4). The Probability Density Function (PDF) of FY2E SST and OISST (Fig.4a) shows that OISST is more concentrated from 23℃ to 31℃, and the peak value (28%) is larger than that in FY2E SST (20%). The PDF of OISST is larger than that of FY2E SST in the region where SST is lower than 23℃, suggesting that FY2E SST is not sensitive enough on low SST. It is consistent with the abnormal higher SST happening at the mid-high latitude region in each season in FY2E (Fig.2).

Figure 4b shows that the regional average between FY2E SST and OISST are very close from May to December, but differs a lot from January to April, when FY2E SST is significantly higher than OISST. The seasonal variation of mean and minimum SST is obvious in OISST whereas the value is less significant in FY2E SST. The maximum value of FY2E SST is higher than that of OISST, and the deviation of them is close to 10℃, which means the algorithm of FY2E SST is too coarse to resolve the high SST (>30℃).

Figure 4c is the absolute deviation and relative deviation between FY2E SST and OISST. It shows that the largest difference occurs from January to April. The absolute deviation is 3℃ and the relative deviation is 14%. The absolute deviation between FY2E SST and OISST is about 2℃ in the typhoon season (June to October).

5 DATA FUSION OF FY2E SST

From the above analysis, FY2E SST is close to OISST over NPO, especially in JJA and SON, when TCs are active. It provides good potential for the use of FY2E SST to monitor the strength of TC in our operational forecasting. Due to the limitation of algorithm, FY2E can only detect SST under clear sky, and the value is unavailable under cloudy condition. TC is a strongly rotating vortex system with active convective cloud. FY2E SST data is not available during cloudy areas (Fig.6a), but the data of clear sky regions still can be obtained from the gap between TC convective cloud bands within the circulation of rotating TC. Thus, we can get the FY2E SST at different regions of TC when it is rotating. To ensure the reliability of data, the temporal and spatial resolution of FY2E SST in our operational platform are chosen to be 1 h and 5 km, respectively.

The data fusion algorithm is as follows: First, once a TC is detected, data from the past 12 h to the current time are downloaded automatically. Second, the clear sky SST in the past 12 h in the FY2E SST product are used to get the average SST (SSTmean) for every grid point over NPO under the assumption that SST varies little over the past 12 h (it is feasible in practice). Third, for the case that the areas are covered by cloud continuously during the past 12 h, SST data can be interpolated using SST_{mean} based on the Delaunay triangulation interpolation method. Fourth, the systematic error is finally corrected for FY2E SST based on equation (1)

$$SST^{*}=SST_{mean}+D \tag{1}$$

where SST^{*} is the error corrected SST, D is the climate deviation between FY2E SST and OISST shown in Fig.2.

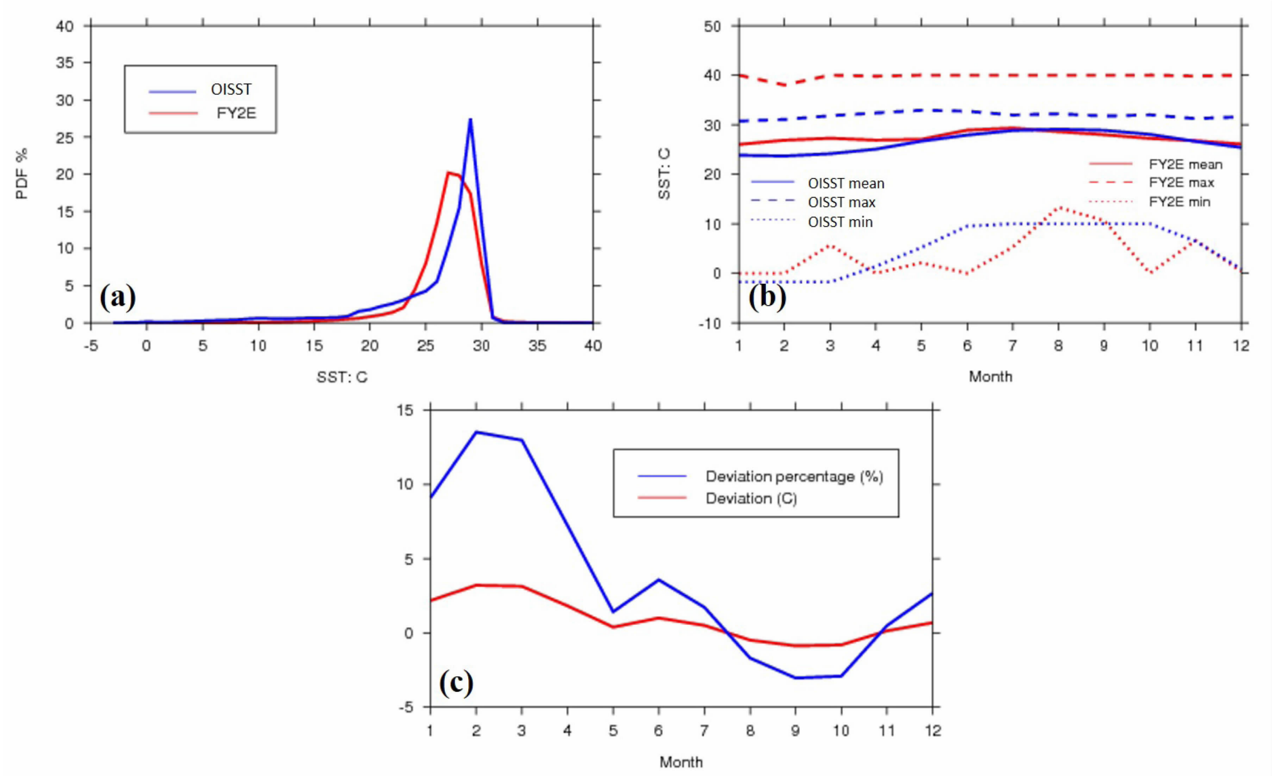

Figure 4. The probability density function (a), mean, maximum and minimum (b), absolute deviation and relative deviation (c) of FY2E SST and OISST over Northwest Pacific Ocean.

As mentioned above, we always cannot receive the real-time OISST but with a delay of 2 or 3 days in the actual TC monitoring operational system. To obtain the best SST data, we use a weight merging method to integrate OISST into SST^{*}. The weight formulas and data fusion method are shown in equation (2) and (3), respectively.

$$W=\alpha+(\frac{\beta-\alpha}{2})\times\{1+\arctan[\gamma(dT-1.5)]\} \tag{2}$$

$$SST_{FY}=W\times SST^{*}+(1-W)\times OISST \tag{3}$$

where SST^{*} is the error corrected SST in equation (1), OISST is the NOAA SST product from 2 or 3 days ago; W is the weight, dT is the difference between SST^{*} and OISST; α, β and γ are three constants, where α is the weight when SST^{*} equals to OISST, β is the weight when the difference between SST^{*} and OISST equals to or is larger than 3℃. Here α is 0.9, β is 0.1, and γ is 0.8, respectively in this study.

Using equation (1)–(3), the merged SST_{FY} is calculated, which is shown to be a better indicator for TC strength prediction over NPO. Fig.5 shows that when the difference between SST^{*} and OISST is within 1.5℃, SST_{FY} basically depends on SST^{*}; otherwise it mainly depends on OISST.

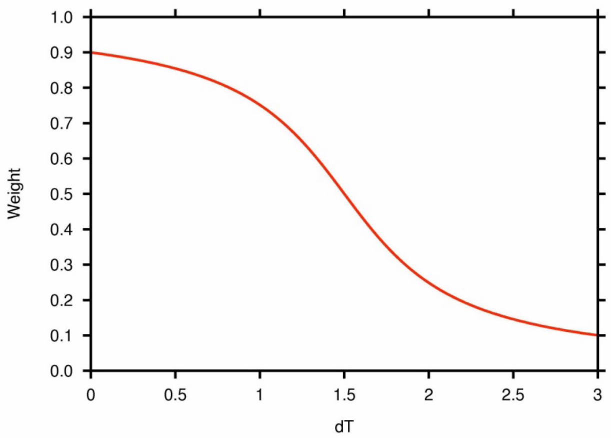

Figure 5. The distribution of weight versus the difference (dT) between FY2E SST and OISST.

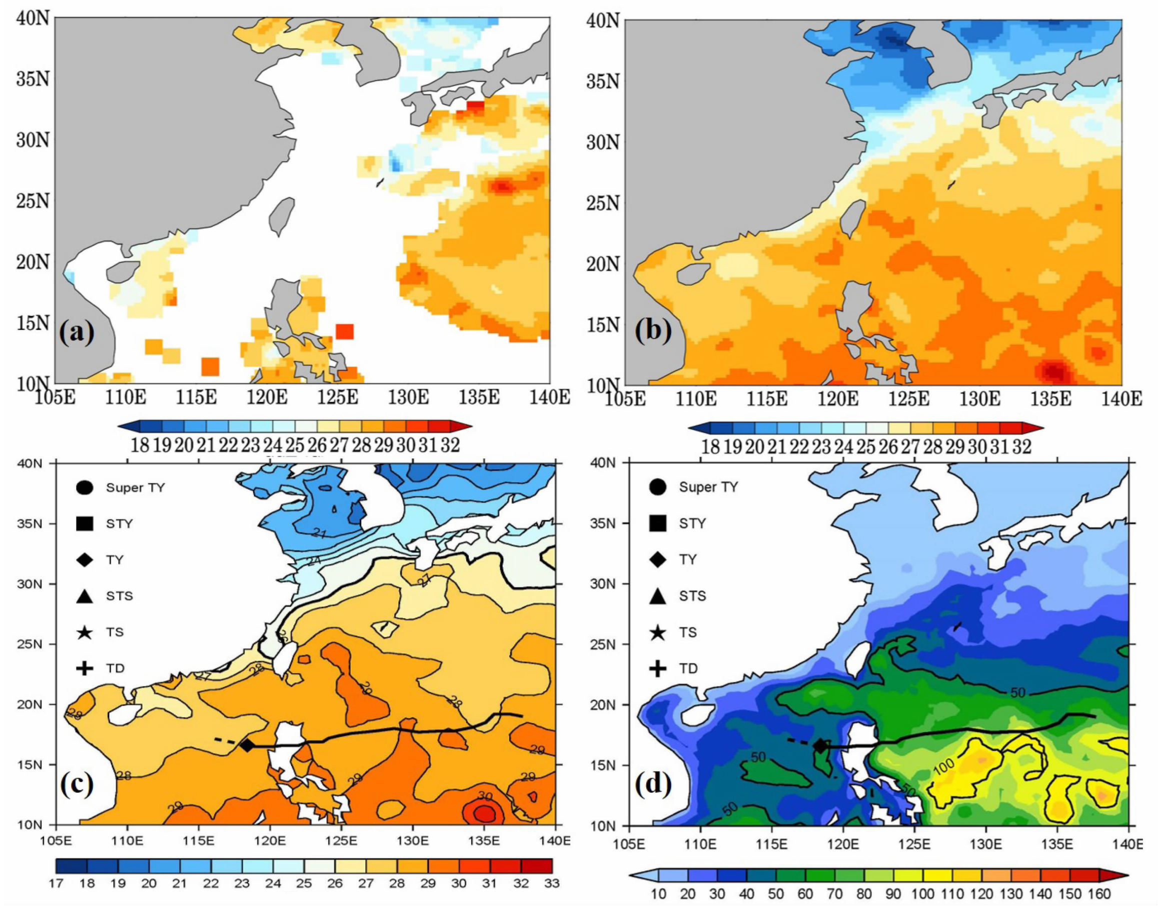

Figure 6. The distribution of FY2E SST (a), OISST (b), SST_{FY} (c) and $TCHP_{FY}$ (d) at 0000 UTC 2nd October, 2011. The black lines in (c) and (d) are the track of TC Nalgae (1119), the dashed lines are 24 h track prediction.

6 PRODUCTION AND APPLICATION OF $TCHP_{FY}$

Tropical Cyclone Heat Potential (TCHP)[12], defined as the ocean heat content between the sea surface and the depth of the 26 ℃ isotherm, has been shown to be more closely linked to intensity changes of tropical cyclones than SST alone [13, 14]. Areas with high TCHP values can be an important factor in the rapid intensification of tropical cyclones[15, 16].

Based on the merged SST_{FY} and the statistical sea temperature profile, we can get $TCHP_{FY}$ using equation (4).

$$TCHP_{FY}=C\cdot\rho\cdot\int_{H_{26}}^{surface}(SST_{FY}-26)dH \quad (4)$$

where C is the specific heat capacity of sea water; ρ is the density of sea water; H_{26} is the depth of the 26℃ isotherm; it is the product of an ocean model from National Meteorological Center (NMC) in this study.

Figure 6 shows the distribution of FY2E SST, OISST, SST_{FY} and $TCHP_{FY}$ at 0000 UTC 2nd October, 2011. As we can see in Fig.6a, FY2E SST data over large areas are unavailable due to the effect of cloud over TC. Although SST_{FY} is different from OISST, it captures the main characteristics of SST (Figs. 6b and 6c). According to the prediction of NMC, if TC Nalgae (1119) enters the South China Sea (SCS) after landing on Philippine islands, it would enhance in the next 24 to 48 h. But as we can see from Fig.6d, the $TCHP_{FY}$ is low although the SST is higher than 26℃ over SCS, which means not enough energy is available for the development of TC. The truth is that the strength of Nalgae downgraded to strong tropical storm 24 h later (Figure omitted). The case study means the new products are good indicators in predicting the strength of TC in NPO, and $TCHP_{FY}$ is better than SST_{FY}.

Figure 7 shows the other application of SST_{FY} and $TCHP_{FY}$ in super typhoon Ma-on (1106) from 0000 UTC 15th July to 0000 UTC 21st July, 2011. Before 0000 UTC 17th July, 2011, TC Ma-on is over warm sea surface with SST_{FY}>26℃ and $TCHP_{FY}$>50 kJ/cm^2, which provides favorable condition for the development of Ma-on, so the maximum wind speed increases gradually from 0000 UTC 15th July to 0000 UTC 17th July, 2011. From 0000 UTC 17th July to 0000 UTC 21st July, 2011, the SST_{FY} maintains at 26–27℃, but the $TCHP_{FY}$ is lower than 50 kJ/cm^2, unfavorable for the development of Ma-on. The best track data of TC also demonstrates that the intensity of Ma-on weakened gradually after 0000 UTC 17th July, 2011.

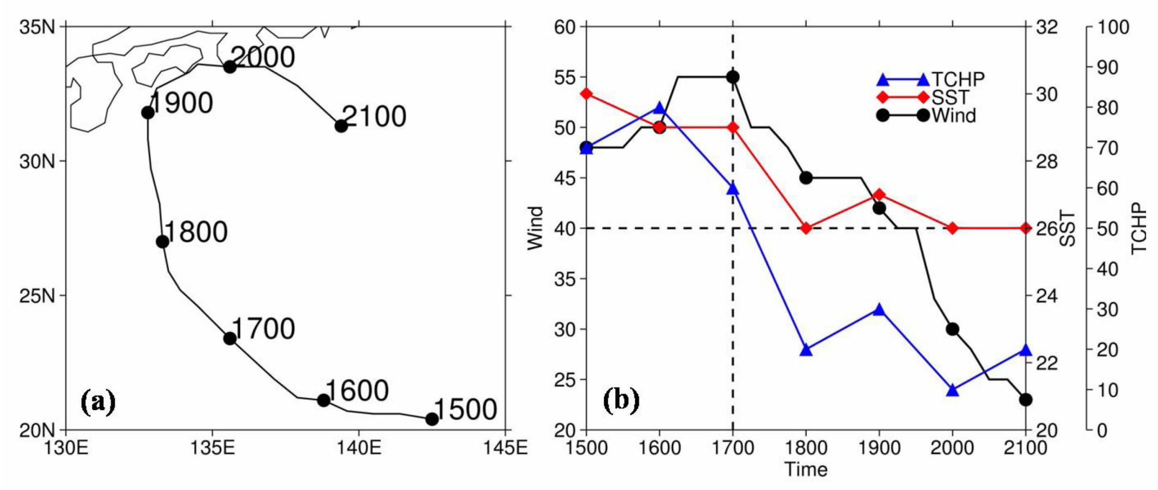

Figure 7. The track (a), strength, SST_{FY} and $TCHP_{FY}$ (b) of TC Ma-on (1106) from 0000 UTC 15th July to 0000 UTC 21st July, 2011.

7 CONCLUSIONS AND DISCUSSION

Taking OISST as a reference, the FY2E SST product is evaluated and integrated to get two new sets of data including the merged sea surface temperature (SST_{FY}) and tropical cyclone heat potential ($TCHP_{FY}$) over Northwest Pacific Ocean (NPO, 100–140°E, 0°–40°N) in this study.

The FY2E SST product has high accuracy on climate scale, and agrees well with OISST over tropical region, especially in the active season of typhoons. However, the deviation between FY2E SST and OISST increases with the increase of latitude. FY2E SST is systematically higher than OISST at higher latitudes.

The results show that the merged SST_{FY} and $TCHP_{FY}$ are good indexes in monitoring and predicting the intensity of TCs over NPO under several assumptions. They have been applied to the operational forecasting system in the National Satellite Meteorological Center.

At present, OISST data is used in our algorithm. The future goal is to replace the OISST with 3-day averaged SST from FY2E SST data, and further form an independent SST product based on FY2E SST only.

REFERENCES:

[1] HU Ya-min, SONG Li-li, LIU Ai-jun, et al. Analysis of the climatic features of landfall tropical cyclones in China during the past 58 years [J]. Acta Sci Nat Univ Sunyatseni, 2008, 47(5): 115-121.

[2] TANG Si-qing, ZHANG Mi, LI Jian-she, et al. A review of "9.26" blackout in Hainan Grid: Causes and recommendations [J]. Power Sys Auto, 2006, 30(1): 1-7.

[3] ZHANG Jin, MA Shu-hong, CHEN De-hui, et al. The improvements of GRAPES_TYM and its performance in northwest Pacific Ocean and South China Sea in 2013 [J]. J Trop Meteor, 2017, 33(1): 64-73.

[4] GRAY W M. Global view of the origin of tropical disturbances and storms [J]. Mon Wea Rev, 1968, 96(10): 669-700.

[5] MALKUS J S, RIEHL H. On the dynamics and energy transformations in steady-state hurricane [J]. Tellus, 1960, 12(1): 1-20.

[6] MILLER B I. On the maximum intensity of hurricanes [J]. J Meteor, 1958, 15(4): 184-195.

[7] EMANUEL K A. The maximum intensity of hurricanes [J]. J Atmos Sci, 1988, 45(4): 1143-1155.

[8] EMANUEL K A. The behavior of a simple hurricane model using a convective scheme based on subcloud-layer entropy equilibrium [J]. J Atmos Sci, 1995, 52 (11): 3960-3968.

[9] CHEN X, WANG Y, ZHAO K. Synoptic flow patterns and large-scale characteristics associated with rapidly intensifying tropical cyclones in the South China Sea [J]. Mon Wea Rev, 2015, 143(1): 64-87.

[10] MURAKAMI H, GABRIEL A V, SETH U, et al. Simulation and prediction of category 4 and 5 hurricanes in the high-resolution GFDL HiFLOR coupled climate model [J]. J Climate, 2015, 28(23): 9058-9079.

[11] REYNOLDS R W, SMITH T M, LIU C, et al. Daily high-resolution-blended analyses for sea surface temperature [J]. J Climate, 2007, 20(21): 5473-5496.

[12] LEIPPER D, VOLGENAU D. Hurricane heat potential of the Gulf of Mexico [J]. J Phys Oceanogr, 1972, 2(7): 218-224.

[13] SHAY L K, GONI G J, BLACK P G. Effects of a warm oceanic feature on hurricane Opal [J]. Mon Wea Rev, 2000, 128(5): 1366-1383.

[14] GONI G J, TRINANES J A. Ocean thermal structure monitoring could aid in the intensity forecast of tropical cyclones [J]. EOS Trans AGU, 2003, 84(51): 573-578.

[15] WILLIS J K, ROEMMICH D, CORNUELLE B. Interannual variability in upper-ocean heat content, temperature and thermosteric expansion on global scales [J]. J Geophys Res, 2004, 109: C12036.

[16] MAINELLI M, DEMARIA M, SHAY L K, et al. Application of oceanic heat content estimation to operational forecasting of recent Atlantic category 5 hurricanes [J]. Wea Forecast, 2008, 23(1): 3-16.

Citation: JIN Shuang-long, HU Liang, DENG Di-fei, et al. The evaluation, data fusion and application of FY2E SST in tropical cyclones over northwest Pacific Ocean [J]. J Trop Meteor, 2018, 24(3): 280-287.