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The Relationship Between Indian Ocean SST and Tropical Cyclone Genesis Frequency over North Indian Ocean in May

CHEN Yan (陈 艳)[1,2], YAN Hong-ming (晏红明)[3], TAO Yun (陶 云)[1,2], YANG Kun-lin (杨坤琳)[4], WANG Meng-qiu (王梦秋)[5]

(1. Yunnan Institute of Meteorological Sciences, Kunming 650034 China; 2. Research Centre for Disastrous Weather in Hengduan Mountains & Low-latitude Plateau, CMA, Kunming 650034 China; 3. Yunnan Climate Centre, Kunming 650034 China; 4. Meteorological Bureau of Dali, Dali, Yunnan 671000 China; 5. Meteorological Observatory of Chengjiang County, Yuxi, Yunnan 652599 China)

Abstract: Tropical cyclone (TC) activities in the North Indian Ocean (NIO) peak in May during the pre-monsoon period, but the TC frequency shows obvious inter-annual variations. By conducting statistical analysis and dynamic diagnosis of long-term data from 1948 to 2016, the relationship between the inter-annual variations of Indian Ocean SST and NIO TC genesis frequency in May is analyzed in this paper. Furthermore, the potential mechanism concerning the effect of SST anomaly on TC frequency is also investigated. The findings are as follows: 1) there is a broadly consistent negative correlation between NIO TC frequency in May and SST in the Indian Ocean from March to May, with the key influencing area located in the southwestern Indian Ocean (SWIO); 2) the anomalies of SST in SWIO (SWIO-SST) are closely related to a teleconnection pattern surrounding the Indian Ocean, which can significantly modulate the high-level divergence, mid-level vertical motion and other related environmental factors and ultimately influence the formation of TCs over the NIO; 3) the increasing trend of SWIO-SST may play an essential role in the downward trend of NIO TC frequency over the past 69 years.

Key words: North Indian Ocean; frequency of tropical cyclone genesis; SST; teleconnection

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1 INTRODUCTION

The main part of the north Indian Ocean (NIO) is located in the south of the Tropic of Cancer, including the Bay of Bengal (BoB) and the Arabian Sea (AS). It is one of the most active cyclonic oceans in the world (Gray [1]; Yuan et al. [2]; Fan et al. [3]), with tropical cyclones (TCs) accounting for about 7% of the world's TCs (Gray [1]; Sahoo and Bhaskaran [4]). Compared with other ocean basins, such as the Western Pacific, eastern Pacific, South Indian Ocean (SIO) and Northern Atlantic, the seasonal variation of NIO TC frequency features a unique bimodal distribution (Fig. 1a), which occurs in spring and autumn, respectively (Li et al. [5]; Felton et al. [6]; Balaji et al. [7]; Bhardwaj et al. [8]) and is most obvious especially in May and November (Singh [9]; Duan et al. [10]; Hoarau et al. [11]). Despite relatively low NIO TC frequency, the inter-annual variations are quite remarkable, and the proportion of super TCs developing from NIO TCs during the pre-monsoon period is the highest in the world (Li et al. [5]; Li et al. [12]; Neetu et al. [13]). NIO TCs can not only bring destructive weathers such as strong gales, torrential rain and storm surge to littoral counties in South Asia (Webster [14]) but also function as an important weather system causing heavy precipitation in Southwest China (Xu et al. [15]; Xiao and Duan [16]; Duan et al. [17]; Lü [18,19]; Yuan et al. [20]). In addition, TC activities over NIO in late spring and early summer are closely associated with the summer monsoon onset (Evan and Camargo [21]; Wu et al. [22]; Ren et al. [23]; Yan et al. [24]) and the beginning of the rainy season in Southwest China (Liang et al. [24]). Moreover, TCs formed in the pre-monsoon season are likely to produce remote heavy rainfall over China's low-latitude highlands (Yuan et al. [20]). According to the statistical results of (Xu et al. [15]), 56% of heavy-rain days and 71% of torrential-rain days in May in Yunnan province of China are connected with the cyclonic storm activities over the BoB. Therefore, the research into the laws of NIO TC activities and its causes in May is of great scientific significance to improve the forecast ability of TCs related to heavy precipitation weather.

Sea surface temperature (SST) is a major environmental parameter influencing TC activities. Scientists have long realized that TCs can be only

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Biography: CHEN Yan, Professor-level Senior Engineer, primarily undertaking extreme weather and climate research.

Corresponding author: YAN Hong-ming, e-mail: yanhongming2013@163.com

generated over the warm sea surface above a certain threshold temperature (Gray[1]; Dare et al.[26]; Defforge et al.[27]), and the variation of SST has a noticeable effect on TC frequency, intensity, duration and track (Emanuel[28]; Kotal et al.[29]; Balaji et al.[7]). As to the effect of SST on TC frequency, local SST anomaly can directly affect TC formation through the sea-surface evaporation/condensation and the change of wind-field convergence in the lower troposphere (Li[30]; Wu[31]). In respect of NIO, the consistency of the first peak for intense cyclones and the warmest month of NIO SST in May right signify the important role of SST in cyclogenesis (Hoarau et al.[11]). The analysis of Sahoo and Bhaskaran[4] showed that cyclogenesis locations in the BoB correlate with higher SST. On the other hand, the variation of SST in a particular area can also affect the tropical disturbances in other sea areas through the anomaly response of atmospheric circulation (Chen et al.[32]; Felton et al.[6]). Among them, the effects of El Niño-Southern Oscillation (ENSO) events have attracted wide attention. Hoarau et al.[11] noticed that intense cyclones in the northern Indian Ocean tend to form more frequently during La Nina events or under neutral conditions though the correlation is not robust. However, Felton et al.[6] examined the effects of ENSO on the modulation of TCs over the BoB for 1979-2011, and the results show that Nino-3.4 SST anomalies are negatively correlated with the BoB TCs by a lead time of 5 months significantly.

Singh[9] found a significant negative correlation between the Indian Ocean Dipole Mode Index (IODMI) from September to October and the BoB TC frequency in November. Yuan et al.[2] also pointed out that NIO TC activities are closely associated with the anomaly of the Indian Ocean Dipole (IOD). When IOD remains at the negative phase, the frequency of NIO TC activities is relatively high. Otherwise, it will be relatively low. Considering that they utilized the data about TC tracks updated every 6 hours as the basis for TC frequency statistics, the TC frequencies in their study include both the number and duration of TCs generated. However, due to the relatively low TC frequency, there is limited attention to and understanding of the laws regarding TC formation and development over NIO.

In recent years, a growing number of scientists have noticed that the SST anomaly in the Indian Ocean has significant effects on TCs generated over many sea areas (Ramsay et al.[33]; Magge et al.[34]). Du et al.[35] pointed out, due to the Kelvin wave excited by the warming of the tropical Indian Ocean (TIO), the abnormal anti-cyclonic circulation generated in the lower troposphere over the Northwestern Pacific (NWP) in summer will inhibit the TC genesis in this area, thus decreasing the frequency of NWP TCs. As shown by the study conducted by Wang et al.[36], the negative correlation between southern TIO SST and TC frequency in the South China Sea from May to November is significant at the 99% significance level. Zhan et al.[37,38] found that the SST anomaly in the eastern Indian Ocean can affect the NWP TC frequency by modulating the NWP summer monsoon and equatorial Kelvin wave activities. Hence, it can be seen as an important factor which can be used to predict NWP TC frequency.

Due to the small number of observation stations in the NIO, the previous studies on TC mainly focused on NWP, and the understanding of the causes of NIO TCs is still limited. However, upgrading marine observation networks and satellite observations provide us with more available data to survey the NIO TCs. In this paper, we choose the number of NIO TCs generated in May with a long time series as the research object to analyze the laws about inter-annual variations and their relationship with the Indian Ocean SST. In addition, the effect of SST change on the circulation genesis of NIO TCs is also discussed, which may shed light on the diagnosis and prediction of NIO TC frequency in pre-monsoon season.

This paper is organized as follows. The second part introduces the research data and methodology. The third part will give the characteristics of the spatial-temporal distribution of NIO TC frequency in May. The fourth part is devoted to analyzing the relationship between NIO TC frequency and Indian Ocean SST and identifying the key influencing area. The fifth part discusses the potential mechanism concerning the influence of SST anomaly in the key area on the formation of NIO TCs. The sixth part presents a summary and discussion.

2 DATA AND METHODOLOGY

The data about NIO TCs used in this paper are collected from the Joint Typhoon Warning Center (JTWC) of the US. The research period is May in the years from 1948 to 2016. For the TC-related data from 1948 to 1971, TCs are not graded according to intensity. For the data released from 1972 to 2016, TCs are classified into seven grades according to the grading standard of Saffir-Simpson (Simpson[39]). To ensure the consistency between the data, TCs generated after 1972 in this paper include TS (tropical storm) and TC above TS (maximum average wind speed on the ground near the center$\geqslant$34knots, including TS and H1-H5). TC time is defined as the date of TC formation without considering the time of duration and decline. In other words, TC frequency in May means the number of TCs generated in May.

SST data in this paper are the monthly average reanalysis SST (Hadley SST) collected by Hadley Centre for Climate Prediction and Research from 1948 to 2016. The data resolution is 1°×1°. The circulation data in this paper are the monthly average reanalysis data from NCEP/NCAR (2.5°× 2.5°) at the same period. Moreover, we also use the subtropical southern Indian Ocean dipole (SIOD) index from 1950 to 2016 provided by the National Climate Center of China Meteorological Administration.

To quantify the effect of SST on the NIO TC genesis, a genesis potential parameter (GPP) proposed by Kotal et al.[29] is used in this paper, which includes both dynamic and thermodynamic variables and appropriates for the NIO

TC genesis (Li et al. [12]). The equation for the GPP is as follows:

$$\mathrm{GPP}=\begin{pmatrix}\varsigma_{850}\times M\times I\times S, & \text{if } \varsigma_{850}>0, M>0, \text{and } I>0,\\ 0, & \text{if } \varsigma_{850}\le 0, M\le 0, \text{or } I\le 0,\end{pmatrix} \tag{1}$$

where ζ_{850} =low level relative vorticity (at 850 hPa), $S=u_{850}-u_{200}$=vertical zonal wind shear between 850 and 200 hPa, $I=(t_{850}-t_{500})$=middle tropospheric instability (temperature difference between 850 and 500 hPa), and M=(RH-40)/30=middle troposphere relative humidity. RH is the mean humidity between 700 and 500 hPa.

Correlation analysis and composite analysis are employed in this paper. For composite analysis, student's *t*-test is used to conduct the significance test. The significance of correlation coefficients between time and variable is also tested to analyze the linear trend.

3 SPATIAL-TEMPORAL DISTRIBUTION CHARACTERISTICS OF NIO TCS IN MAY

NIO TC activities display clear seasonal characteristics. Fig. 1a shows the monthly NIO TC numbers from 1975 to 2016. It can be seen that early summer and autumn are two periods with more TC numbers. TC numbers show prominent double peak characteristics. Two peaks occur in May and November, of which TC numbers are the most in November, followed by October and May. TC numbers are minimal in March and August. A total of 70 NIO TCs were generated in May from 1948 to 2016. Fig. 1 shows the locations of the originating points of various TCs. Obviously, NIO TCs are mainly generated in most parts of the BoB and central-eastern parts of the AS. Among them are 49 BoB TCs, accounting for 70 percent of the total number. There are 21 AS TCs, making up 30 percent of the total number, consistent with previous literature (Li et al. [5]; Fan et al. [3]) because the SST of AS is relatively colder than that of the BoB (Bhatla et al. [40]). As seen in Fig. 2, TC frequency in May changes yearly. Although the frequency of NIO TCs is relatively low as a whole, the

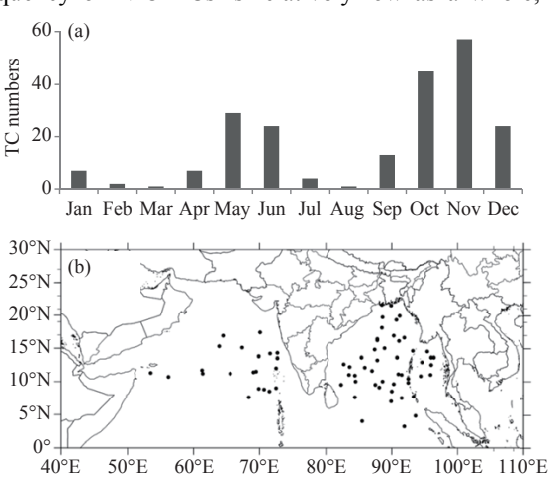


Figure 1. (a) Monthly TC numbers in the NIO during 1975–2016 and (b) the locations of the originating points of NIO TCs in May from 1948 to 2016.

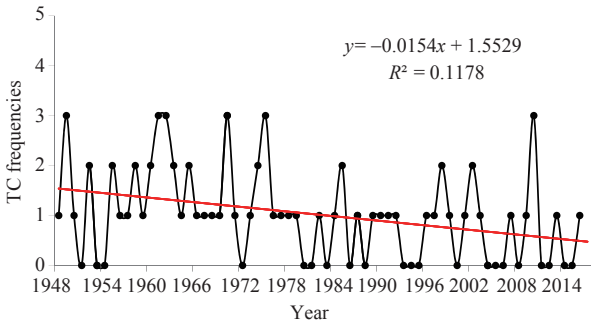


Figure 2. The interannual variation of the frequency of NIO TCs in May from 1948-2016. The red solid line represents the linear trend.

inter-annual variations are noticeable. The proportion of the years with one TC is the highest, standing at 45.2%. The proportion of the years with two TCs stands at 15.1%. That of the years with three TCs is 8.2%. The proportion of the years with zero TC is also high and stands at 31.5%. Regarding the long-term trend, the frequency of NIO TCs shows a downward trend and decreases at a rate of 0.154 TCs/10 years, which is statistically significant at the 95% level. This is consistent with the analysis carried out by Duan et al. [10] on the frequency of BoB TCs from 1945 to 2006. They thought the decrease in TCs might be attributed to global warming and improved TC detection techniques. Numerical simulations conducted by Patwardhan et al. [41] partly supported this conjecture. Recently, some scientists (Balaji et al. [7]; Bhatla et al. [40]) pointed out that a decreasing trend is observed in the total TC frequency in NIO, while the frequency and duration of intense TCs with a wind speed higher than 64 knots is notably increasing in recent years.

4 CORRELATION BETWEEN NIO TC FREQUENCY IN MAY AND SST

NIO SST in May is the highest throughout the year (Hoarau et al. [11]). The average SST distributions with different numbers of TCs generated in May from 1948 to 2016 are presented in Fig. 3. It is clear that, no matter how many NIO TCs are generated, the SST of all NIO sea areas is higher than 26.5°C, exceeding the threshold temperature for TC formation (Gray [1]; Defforge et al. [27]; Dare et al. [26]). The SST in the vast sea areas with a latitudinal distribution from the east of Somalia to the Andaman Sea reaches or exceeds 29.5°C, topping the whole Indian Ocean, while it is relatively low in the northern AS. On the sea surface south of 15°S, the isotherm shows a dense latitudinal distribution, and SST decreases rapidly as it moves toward the south. However, it is difficult to identify the relationship between TC frequency change and SST anomaly merely based on Fig. 3. After calculating the correlation coefficients between NIO TC frequency and SST in May from 1948 to 2016 (Fig. 4c), we can find that there is a relatively consistent negative correlation between them in most sea areas and the areas with a significant correlation are located in the SWIO and the equatorial Indian Ocean (EIO). These two areas with a significant

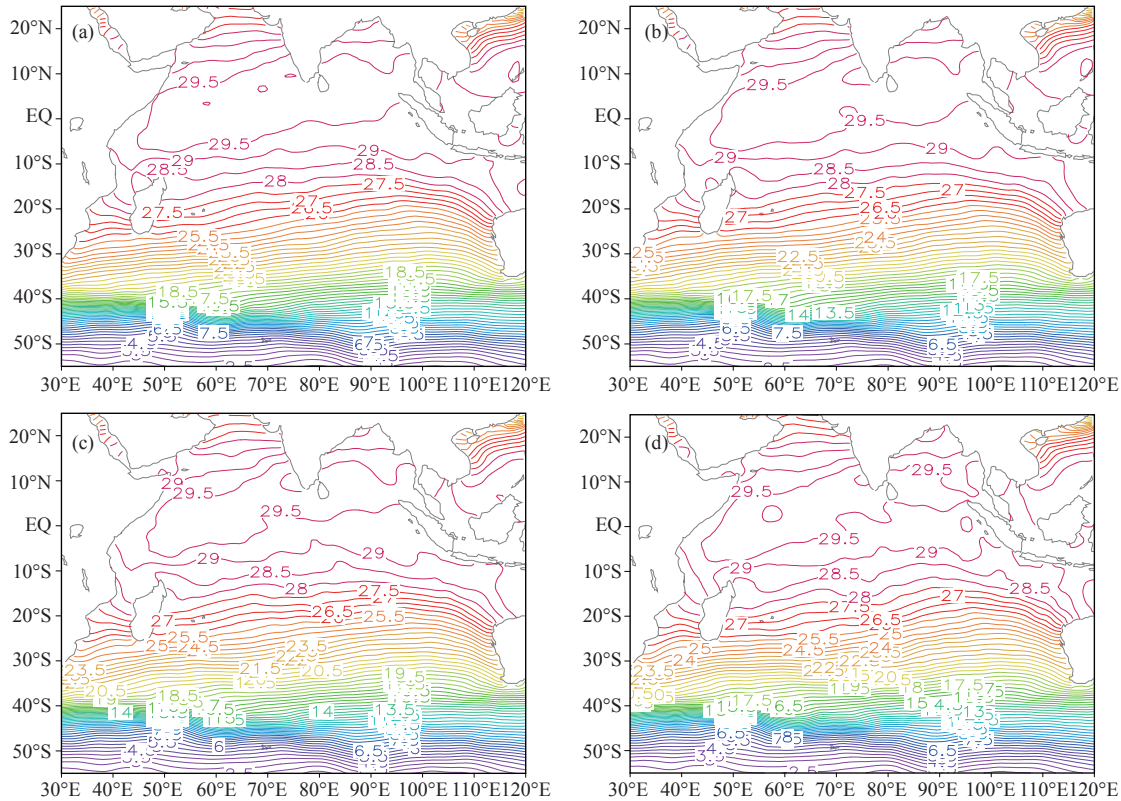


Figure 3. (a) The composite monthly SST distribution during the years with zero NIO TC in May; (b) same as (a), but for the years with one NIO TC; (c) same as (a), but for the years with two NIO TCs; (d) same as (a), but for the years with three NIO TCs (units: °C)

negative correlation are also the sea areas with the greatest SST inter-annual variations in the Indian Ocean in May (Fig. 5). Especially, the significant negative correlation in the SWIO nearly matches the area with a high standard deviation of SST in SIO. This sea area roughly covers the southwestern pole of SIOD (Swadhin et al.[42]; Yan et al.[43]). It suggests that the principal mode of the variation of SIO SST may be related to the formation of NIO TCs.

After examining the distributions of correlation coefficients between NIO TC frequency in May and the Indian Ocean SST at an earlier time (Figs. 4 a, b), we can also find that there is a significantly negative correlation between TC frequency in May and SWIO SST from March to April except that the statistically significant areas in fig.4a shrink slightly. Nevertheless, the correlation between TC frequency and EIO SST noticeably weakens in Fig. 4a and b, with only a few small patches of statistical significance distributed in eastern EIO. By contrast, great differences in the correlations between TC frequency in May and the SST before March exist, and the areas of significant correlation in SWIO contract obviously (figs. omitted). The above results suggest a significant and stable negative correlation between NIO TC frequency in May and the SWIO SST from March to May. That is, when SWIO SST is relatively high from March to May, the frequency of NIO TCs in May will be relatively low and vice versa. On the other hand, the negative correlation with EIO is relatively weak without salient continuity.

Considering that the sample of NIO TCs in May is relatively small, it is necessary to further examine the composite differences in SST distribution between the years with one to three TCs and the years with zero TC. As seen in Fig. 3, during the years with zero TC (Fig. 3a), a large sea area slightly stretches from southwest to northeast with a high SST above 29.5°C in the central and northern parts of the TIO. During the years with one TC (Fig. 3b), the area with a high SST shrinks slightly. By comparing the difference between the two (Fig. 6a), it is clear that SWIO SST decreases remarkably, and the maximum temperature drop exceeds –0.5°C during the years with one TC. During the years with two TCs, the SWIO SST decreases more conspicuously (Fig. 6b). The maximum temperature drop in SWIO exceeds –0.9°C. The area with a significant temperature drop overlaps that in Fig. 4a but covers a wider range. During the years with three TCs, there is a sea area with a much lower temperature drop in SWIO with the maximum SST anomaly up to –1.2°C, while the area with a significant temperature drop moves about 10 degrees southward (Fig. 6c). It confirms that the lower SWIO-SST, the more NIO TCs in May. With regard to EIO, there is no significant change in SST, no matter how many TCs are formed.

The analysis results above demonstrate that the SST in most sea areas of NIO in May reaches or exceeds the critical temperature for TC formation. However, a negative correlation exists between NIO TC frequency in May and Indian Ocean SST during the same and previous periods. The area with a significant and stable negative correlation

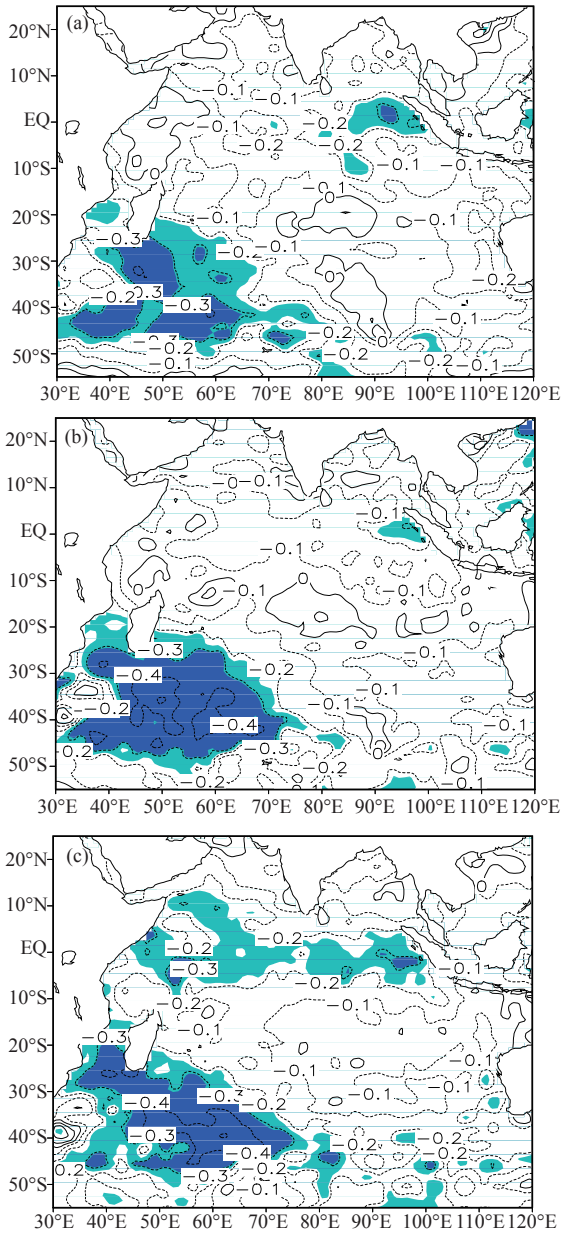


Figure 4. (a) The distribution of correlation coefficients between NIO TC frequency in May and the monthly SST of March, (b) April and (c) May. The light and dark shadings represent 95% and 99% significance, respectively.

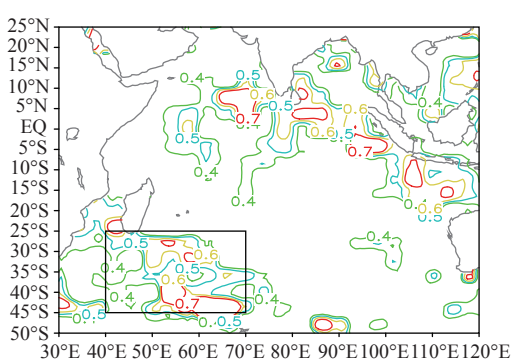


Figure 5. The distribution of standard deviation of SST in May from 1948 to 2016 (units: °C). The black rectangle shows the key areas of SWIO (40°–70°E, 45°–25°S).

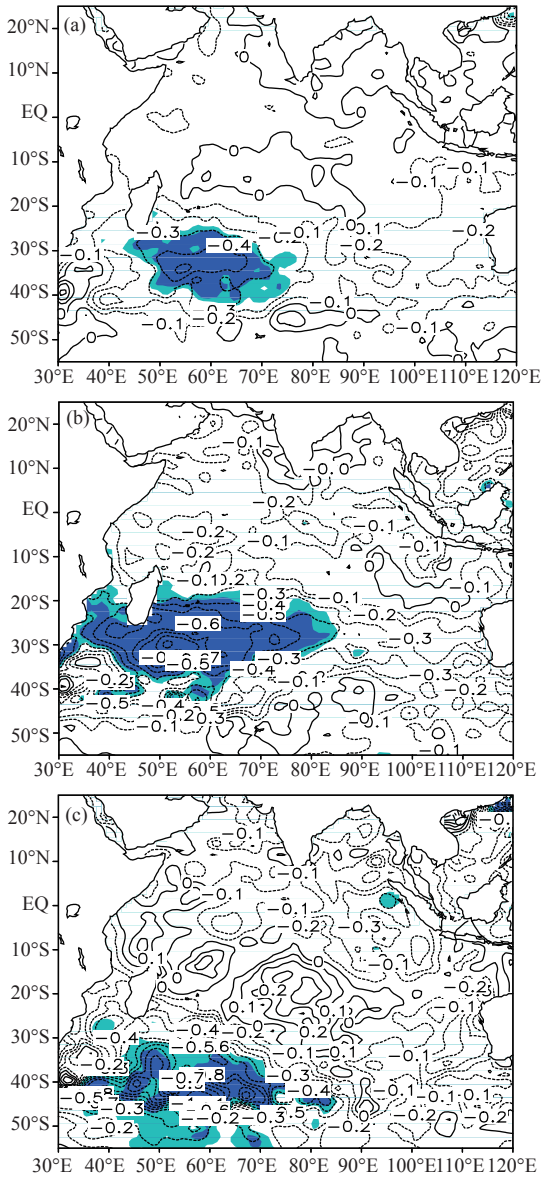


Figure 6. (a) The composite differences in SST between the years with one TC and the years with zero TC in May (isoline interval is 0.1°C, similarly hereinafter); (b) same as (a), but for the years with two TCs; (c) same as (a), but for the years with three TCs. The light and dark shadings represent 95% and 99% significance levels, respectively.

is not the place of TC formation. SWIO is right about the key area affecting TC frequency. In other words, SWIO SST during the same and previous periods significantly affects NIO TC frequency in May. Therefore, we define SWIO (40°–70°E, 45°–25°S) as the key area of Indian Ocean SST affecting NIO TC frequency in May (see the rectangle in Fig. 5). In the following parts of this paper, the SST in the key area will be represented as SWIO-SST. On the ground that the indication of EIO SST change is weak, it will not be discussed in this paper.

5 EFFECT OF SWIO-SST ANOMALY ON LARGE-SCALE CIRCULATION

The analysis above and previous literature indicate

that a warm sea surface is a necessary condition for TC formation, and the genesis and development of TCs are also dependent on the atmospheric environment. To explore the possible mechanism concerning the effect of SWIO-SST change on NIO TC frequency, we calculate the distribution of correlation coefficients between SWIO-SST in May and some environmental factors which may affect TC formation.

First, we investigate the relationship between GPP and SWIO-SST. Fig. 7a shows the distribution of climatological mean GPP. It can be seen that there are two high GPP areas located in the Southwest of AS and BoB, respectively. The GPP anomalies in these two high-value areas are closely related to SWIO-SST (Fig. 7b-d), especially in May. When SWIO-SST is high, the GPP of these two regions is low, which is unfavorable for the formation of NIO TCs; On the contrary, when SWIO-SST is low, GPP in these two regions is high, which is favorable for the formation of NIO TCs. Compared with Fig. 1b, the region where more NIO TCs generate is mainly concentrated in the southern BoB, which is roughly consistent with the negative-value area of GPP regression in Fig. 7b-d, further indicating the important impact of SWIO-SST on TC generation over the BoB basin. In addition, it can be seen in Fig. 7b-d that the regression coefficients are also very significant in the North border area of Bob and AS, suggesting that when SWIO-SST is high, the GPP in these two regions is high, which is conducive to TC generation, and vice versa. However, the TC frequency is very low in these two regions (Fig. 1b), which may be related to the relatively low SST there (Fig. 3).

As is well known, a weak vertical wind shear is an important circulation condition for TC formation (e.g. Merrill [44]; Yanase et al. [45]; Li et al. [5]). The formation and development of TCs require that the vertical wind shear be lower than a certain critical value (Goldenberg et al. [46]). To investigate the influence of vertical wind shear on the frequency of NIO TC, an index of vertical wind shear (VWS) is defined in formula (2). Fig. 8a shows the monthly variation of VWS in AS (5°–10°N, 50°–75°E) and BoB (5°–10°N, 80°–100°E) basins. It can be seen that VWS in two conversion seasons (April and May, as well as October and November) are very weak, less than 12m/s, while the VWS in July and August is significantly strengthened and exceeds 27m/s. The VWS anomalies are closely related to the seasonal variation of zonal winds in the upper and lower troposphere. Both the easterly wind at 200hPa and the westerly wind at 850hPa are significantly strengthened (figure omitted) during the southwest monsoon activity from July to August, significantly strengthening VWS in AS and BoB basins in summer. Although easterly at 850hPa is weak, the westerly at 200hPa is strong in winter, which results in the strong VWS from December to February. Only in the two transition seasons, because it is in the key season of the East-West wind transition, the zonal winds at 200hPa and 850hPa are very weak, which will correspondingly weaken the VWS, resulting in increasing frequency of TC generation. Comparing Fig. 8a and Fig. 1a, the seasonal variation of NIO TCs frequency is consistent with that of VWS, indicating the important impact of VWS on NIO TCs.

Fig. 8b shows the distribution of the VWS over the Indian Ocean in May. It can be seen that the strength of the VWS in the southern and northern of the Indian Ocean is quite different. In the north of 10°S, the VWS is weak, except that in the eastern equatorial Indian Ocean is greater than 15m/s. Note the VWS in most areas of AS and BoB basin are very weak, less than 10m/s, which is conducive to the formation of TC. In the subtropical region of the SIO, the VWS is strong and the areas of VWS exceeding 40m/s are located in the southeastern Indian Ocean near Australia. To investigate the relationship between SWIO-SST and NIO TCS, we calculated the correlation between SWIO-SST and the VWS (Fig. 8c). It can be seen negative correlation over the latitudes roughly from 10°S to 15°N. It implies that when SWIO-SST increases, the VWS in most areas over the central Indian Ocean will decrease,

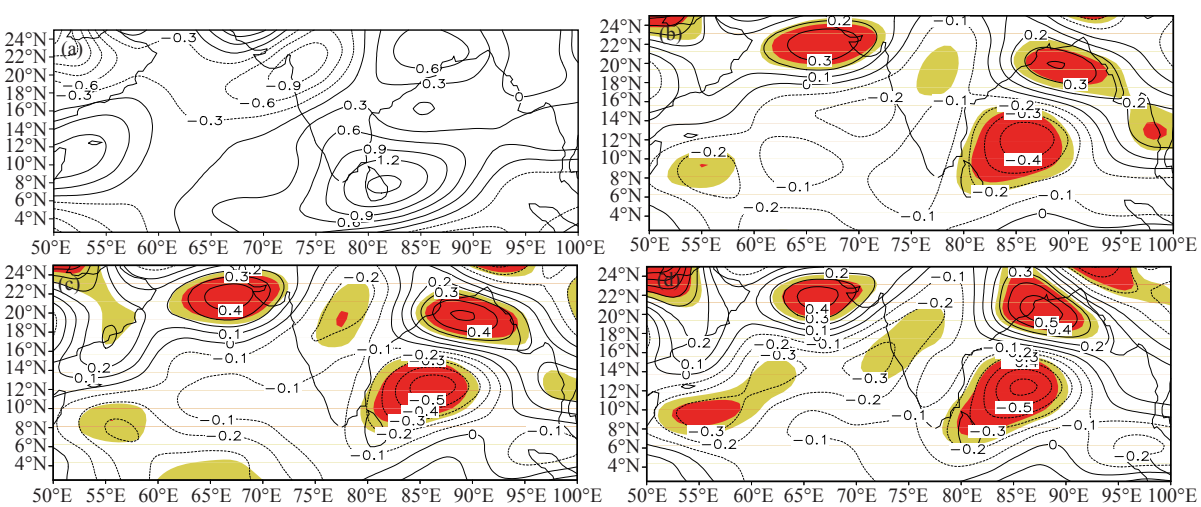


Figure 7. Distribution of the climatological mean GPP (GPP×10^{-5}) in May (a), regressions of GPP in May with SWIO-SST of March (b), April (c), and May (d). Yellow and red shadings show the areas that are significant at 90% and 95% confidence levels, respectively.

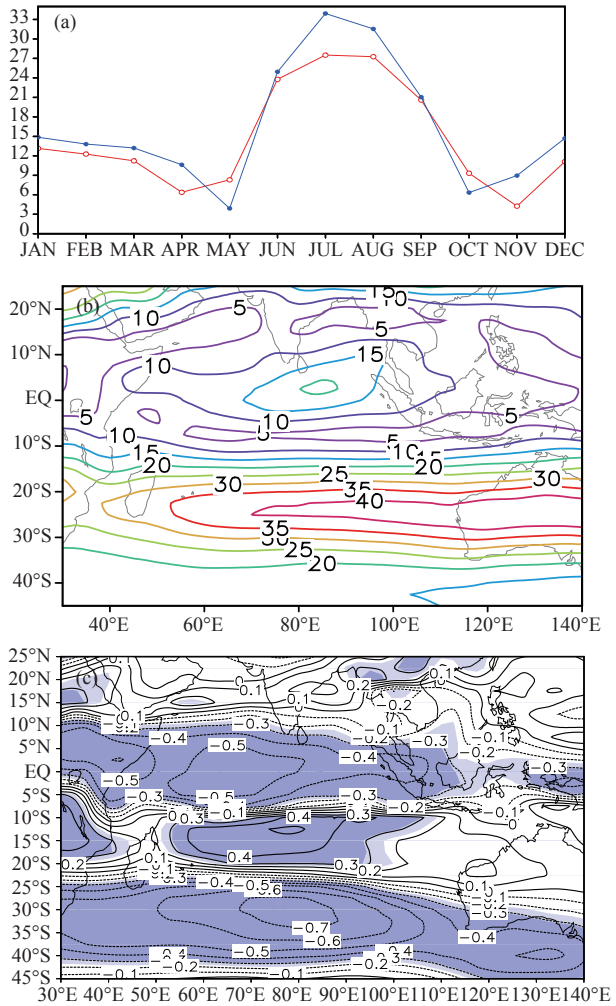


Figure 8. (a) The monthly variation of VWS (units: m/s) over the AS (10°–20°N, 50°–75°E, blue line) and BoB (10°–20°N, 80°–100°E, red line) basin from 1981 to 2010; (b) the distribution of VWS in May; (c) the correlation coefficients between SWIO-SST and VWS. The light and dark shaded areas represent 95% and 99% significance levels, respectively.

associated with a weak pre-monsoon circulation (Webster et al.[47]). Nevertheless, it must be noted that some areas in the BoB and AS appear to have a weak positive correlation. It suggests that when SWIO-SST has a positive anomaly, the VWS over those sea areas has a potentially increasing tendency. But the positive correlation between them is not statistically significant.

$$\mathrm{VWS} = \sqrt{(u_{850}-u_{200})^2+(v_{850}-v_{200})^2} \quad (2)$$

Quite a few studies have revealed that upper-level environmental flow has an important impact on the formation and development of TCs (Merril[44]; Shi et al.[48]; Qian et al.[49]; Komaromi et al.[50]; Li et al.[12]). Generally speaking, upper-level divergence/convergence can enhance/suppress the outflow and ultimately change the strength or structure of the TC below. As is seen in Fig. 9a, the areas with a significant correlation between SWIO-SST and high-level divergence at 200hPa are mainly distributed over the Indian Ocean in an annular manner. The positive or negative distribution alternates in the correlation area, forming a teleconnection wave train roughly surrounding the Indian Ocean. Noticeably, the upper troposphere over SWIO is the area with a positive correlation, while the main part of NIO is the area with a significantly negative correlation. It implies that when SWIO-SST increases, the air at the upper troposphere over SWIO tends to outflow. Contrastingly, convergence may occur in most parts of NIO, which may hinder the TC formation.

According to the continuity equation, ascending airflow will emerge in the middle and lower troposphere in the case of upper-level divergence. On the contrary, when the airflow in the upper troposphere converges, downward movement may occur or ascending flow will be depressed, which is detrimental to the convection and the formation of TCs. To verify this inference, we further calculate the correlation between SWIO-SST and vertical velocity (ω) at 500hPa and divergent wind at 200hPa, as seen in Fig. 9b. Apparently, the area with a significant negative correlation of the vertical velocity in the middle troposphere over the Indian Ocean indeed corresponds to the high-level divergence. And the area with a significantly positive correlation of the vertical velocity over the Indian Ocean corresponds to the high-level convergence. With respect to NIO, most parts of it have a significantly positive correlation, which is also consistent with the divergence field. In an attempt to examine the three-dimensional correlation features along the wave train, Fig. 10 further displays the vertical cross section of correlation coefficients between SWIO-SST and divergent wind, vertical velocity along the black solid line shown in Fig. 9b. The wave-train structure is ascertainable in Fig. 10. Especially, it is conspicuous that there is a significantly negative correlation between SWIO-SST and the vertical velocity over SWIO below 200hPa, and there is a much more noticeable positive correlation between SWIO-SST and the vertical velocity below 150hPa over NIO. As SWIO-SST increases, the airflow in the lower troposphere converges, and the airflow in the upper troposphere diverges over SWIO. In contrast, the upper-level airflow convergence over NIO leads deep descending below, detrimental to the development of convection and TCs. This process may lead to a negative correlation between SWIO-SST and NIO TC frequency.

In addition, many researchers have pointed out that the lower cyclonic circulation is beneficial to TC formation (Gray[1]; Li et al.[12]). After investigating the correlation between SWIO-SST and wind field at 850hPa (Fig. 9c), we find that the wave train structure around the Indian Ocean is also discoverable in the lower circulation, although it is not as clear as that of the high-level divergence over Southeast Asia. It mainly takes the form of anti-cyclonic circulation in NIO. More specifically, when SWIO-SST rises, the abnormal anti-cyclone may be stimulated in the lower troposphere over most parts of

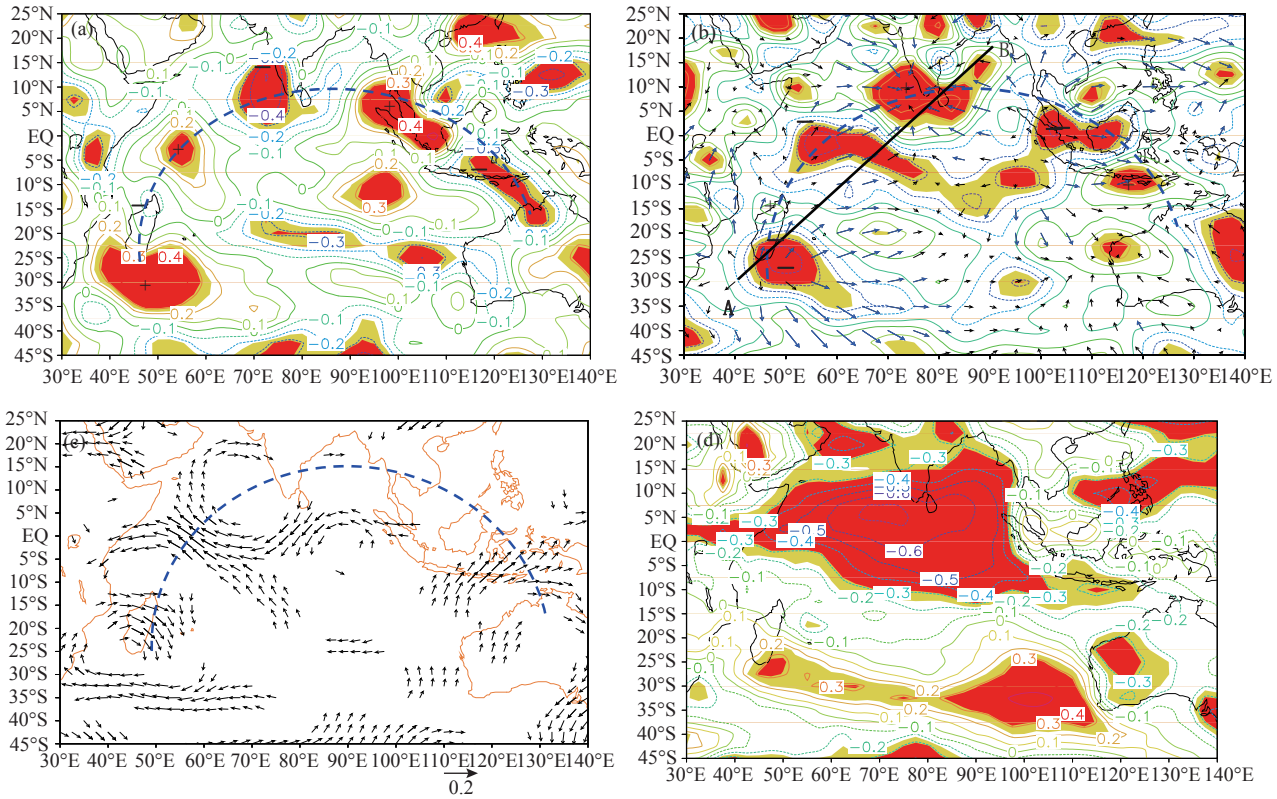


Figure 9. (a) The distribution of correlation coefficients between SWIO-SST and divergence at 200hPa in May; (b) same as (a), but for divergent wind (vectors) at 200hPa and vertical velocity at 500hPa (isolines); (c) same as (a), but for wind field at 850 hPa (only statistically significant vectors at 95% level are displayed); (d) same as (a), but for relative humidity at 500 hPa. The yellow and red areas represent 95% and 99% significance levels, respectively. The dashed curve in Fig. a-c indicates the wave train path.

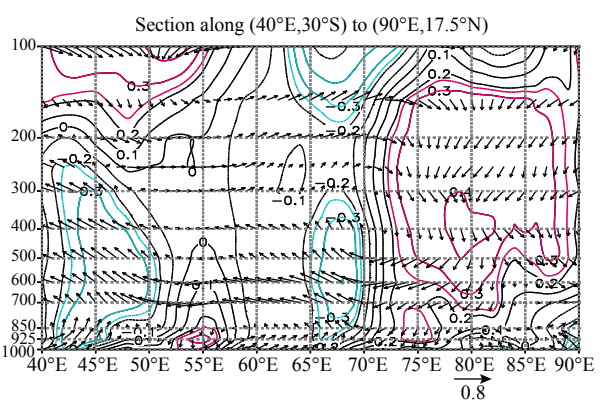


Figure 10. The vertical section of correlation coefficients between SWIO-SST, divergent wind (vector), and the vertical velocity in May (isoline, red and green isolines show positive and negative correlation coefficients at 95% significance level respectively) along the black solid line (40°E, 30°S–90°E, 17.5°N) shown in Fig. 9b.

NIO, which is unfavourable to TC formation. Moreover, we can also find that the obvious anomalous easterly wind occurs around the EIO under the influence of the wave train. It is an adverse factor in terms of the onset and intensification of the Asian summer monsoon in this region (Webster et al.[47]; Joseph et al.[51]). On the other hand, the wave-train-related easterly wind may be responsible, to a certain extent, for the negative relationship between SWIO-SST and vertical shear of monsoon in Fig. 7b. Since Asian summer monsoon is a planetary-scale circulation regime and the mechanism of its variation is highly complicated, it is beyond the research content of this paper and thus will not be discussed deeply.

Besides the factors associated with the wind field, the importance of relative humidity in the middle troposphere to TC formation is also recognized (DeMaria et al.[52]; Li et al.[5]; Li et al.[12]). As seen in the distribution of the correlation coefficient between SWIO-SST and relative humidity at 500hPa presented in Fig. 9d, a vast significant negative correlation area covers the northern part of the Indian Ocean. It suggests that when SWIO-SST increases, the middle-level relative humidity in the north of the Indian Ocean will decrease, which is detrimental to NIO TC formation, and vice versa. However, it shows that the response of relative humidity to SWIO-SST anomaly has no direct association with the teleconnection pattern surrounding the Indian Ocean. As Fig. 8 indicates that the monsoon circulation over TIO weakens when SWIO-SST rises, the variation of Asian monsoon associated with SWIO-SST anomaly can influence the humidity. Li et al.[12] have pointed out that the specific humidity budget anomaly associated with TC genesis can be primarily attributed to vertical advection. So, the exact physical process involving the interaction between SWIO-SST,

monsoon and middle-level moisture remains to be discussed deeper.

6 CONCLUSIONS AND DISCUSSION

NIO TC formation enters a peak period in May. During this peak, TC activities significantly influence the climate and weather in South Asia, Southeast Asia and Southwest China. To explore the laws regarding the change of NIO TC frequency and identify potential factors for diagnosis and prediction, we utilize the monthly average data, including the TC data from the JTWC of the US, the SST from the Hadley Centre for Climate Prediction and Research of the UK and NCEP / NCAR reanalysis. We analyze the correlation between NIO TC frequency in May and Indian Ocean SST and preliminarily investigate the possible mechanism concerning the effect of SWIO-SST anomaly on TC frequency. The results are as follows.

(1) Over the past 69 years, zero to three TCs are generated over the NIO in May every year. But in the long term, TC frequency shows a downward trend.

(2) A relatively consistent negative correlation exists between NIO TC frequency in May and Indian Ocean SST from March to April/in May. The significant key influencing areas are located in the SWIO. When SWIO-SST is low (high), NIO TC frequency tends to be high (low).

(3) SWIO-SST anomaly significantly affects the high-level divergence over the Indian Ocean through a teleconnection surrounding the Indian Ocean. Under the influence of the teleconnection pattern, when SWIO-SST is relatively low (high), abnormal divergence (convergence) will occur in the upper troposphere over most parts of NIO along with ascending (descending) airflow in the middle troposphere and abnormal cyclonic (anti-cyclonic) circulation emerging in the lower troposphere. These atmosphere responses are beneficial (detrimental) to NIO TC genesis, which may be an important physical mechanism concerning the effect of SWIO-SST on NIO TC formation.

In the past, many researchers found that the anomaly of the SST in SIO has an important modulatory effect on global circulation and climate change. As the second EOF mode of SIO SST, the climatic impact of the SIOD has attracted wide attention (Behera et al. [53]; Jia et al. [54]; Yan et al. [43]). It is not difficult to notice that SWIO defined in this paper almost overlaps the "southwestern pole" of SIOD. Therefore, it is necessary to briefly discuss their similarity and dissimilarity.

Figure 11a shows the SWIO-SST in May from 1948 to 2016 and the SIOD index from 1950 to 2016. It can be found that SWIO-SST shows an upward trend, which is statistically significant at the 99% level. However, SIOD tends to decrease slightly without passing the significance test at the 95% level. In terms of the relationship between SWIO-SST and the frequency of NIO TCs revealed in this study, the long-term trend of SWIO-SST is self-consistent

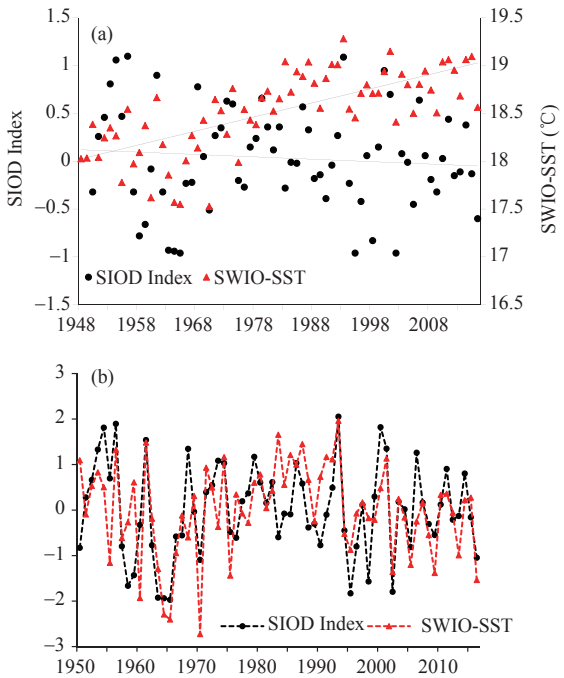


Figure 11. (a) SWIO-SST, SIOD index and their linear trend (straight line). (b) Normalized SWIO-SST and SIOD index with the linear trends removed.

with the trend of NIO TC frequency in May. Namely, the downward trend of NIO TC frequency in May may be associated with the constantly increasing SWIO-SST.

Although SWIO-SST and SIOD have different long-term trends, their correlation coefficient is 0.362, which is statistically significant at the 99% level. Fig. 11b shows the normalized SWIO-SST and SIOD with the linear trends removed. It can be seen that their inter-annual variations are highly similar after the linear trend is removed, and the correlation coefficient even reaches up to 0.586. Admitting that their inter-annual variations are highly similar, the analysis results indicate that SWIO-SST and SIOD have different long-term trends. Therefore, SWIO-SST can not be completely replaced by the SIOD index.

In conclusion, this paper preliminarily reveals the relationship between Indian Ocean SST and NIO TC frequency in May and the possible mechanism, which may shed light on the diagnosis and prediction of NIO TC frequency. However, in-depth research should be carried out in the future regarding theoretical analysis and numerical simulation. Furthermore, the collaborative effect of SWIO-SST and other forcing factors or atmospheric systems, such as ENSO and the Asian monsoon, remains to be further studied.

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