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IMPACT OF TROPICAL INTRASEASONAL OSCILLATION ON THE TRACKS OF TROPICAL CYCLONES IN THE WESTERN NORTH PACIFIC

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Abstract: In this work, an index of tropical 20-90 d oscillation (intra-seasonal oscillation; ISO) in the western North Pacific (WNP) was determined via the combined empirical orthogonal function (EOF) method using daily outgoing longwave radiation (OLR) field data from the National Oceanic and Atmospheric Administration (NOAA), daily wind field data (at 850 hPa) from the European Centre for Medium-Range Weather Forecasts (ECMWF) and referencing the Madden-Julian oscillation (MJO) index proposed by Wheeler and Hendon. An in-depth investigation was conducted to examine the impact of the ISO on changes in tropical cyclone (TC) tracks in the WNP during different ISO phases. The research results indicate that during the easterly phase of the ISO, under the impact of the northeastern airflow of anti-cyclonic ISO circulation, the easterly airflow south of the western Pacific subtropical high is relatively weak, and TCs generated in the subtropical high tend to change their tracks east of 140°E; during the westerly phase, there is a relatively high probability that TCs change their tracks west of 140°E. This work also analyzed the ISO flow field situation in cases of typhoons and determined that the track of a tropical cyclone will experience a sudden right turn when the center of the ISO cyclonic (anti-cyclonic) circulation coincides with that of the cyclone.

Key words: intra-seasonal oscillation; tropical cyclone; track change

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1 INTRODUCTION

In the western North Pacific (WNP), the atmospheric intra-seasonal oscillation (ISO) constitutes an extremely important atmospheric circulation system. This oscillation relates to some short-term climate anomalies, such as the monsoon onset and the occurrence of abnormal activity[1]; the incidence of El Niño–Southern Oscillation (ENSO) events[2], and the occurrence of tropical cyclones (TCs). Thus, the ISO possesses important research significance.

The tropical WNP is one of the primary sources of global tropical cyclone (TC) activity; on average, approximately 30 TCs are generated every year in this area, accounting for one third of the total number of TCs that are generated annually around the world. There are obvious discrepancies in the spatial distribution of TC activity on the decadal, inter-annual, and intra-seasonal time scales, and many studies have confirmed that a close relationship exists between different phases of the ISO and the active and inactive periods of intra-seasonal changes in TC activities[3-7].

Gray[3] studied the characteristics of TC genesis in various ocean and found that TCs exhibit the characteristic of clustered genesis on the intra-seasonal scale. The active and inactive periods of TC formation can each last up to two to three weeks. During the active TC stage, approximately 10 typhoons may be continuously produced during the course of two weeks, whereas during the inactive stage, there may be no typhoons over the course of the same time span. Liebmann[4] studied the influence of the Madden-Julian oscillation (MJO) on the tropical disturbances of the WNP and observed that during active periods of MJO convection, the quantities of tropical disturbances, tropical storms, and typhoons in the WNP increase by approximately the same factor

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(and thus maintain nearly the same relative proportions). Hall et al.[5] used 20 years of outgoing longwave radiation (OLR) data to study the relationship between the MJO and cyclones that affect Australia. These researchers found that there is a significant positive correlation between the TCs generated in the northwestern region of Australia and the wet phase of MJO convection and that the modulation of MJO on TCs is strengthened during El Niño years[6]. Zhu and Nakazawa[7] studied the influence of MJO activities on TCs that were generated in the Indian and the western Pacific Oceans and determined that more than half the TCs generated in areas other than the WNP are recorded during the wet phase of the MJO moving eastward, whereas TCs generated in the WNP are influenced by the eastward and westward propagation of the MJO. Chen and Huang[6] analyzed the role of MJO modulation in TC genesis in the WNP. Their results indicate that when the west side of the WNP is controlled by the westerly phase of the MJO, TC formation in this region is rather high; by contrast, when the west side of the WNP experiences the easterly phase of the MJO, the quantity of TCs that are generated is suppressed.

Thus, most previous studies in this field have analyzed the modulating effects of ISO activities on TC genesis, whereas research on the influence of the ISO on the tracks of TC activities is relatively limited.

The purpose of this study is to define an ISO index in the WNP and identify different ISO phases that allow for the analysis of the characteristics of spatial and temporal ISO variation in the WNP with respect to TCs. In particular, the modulating influence of the ISO on TC track changes in the WNP is examined, and the influence of low-frequency ISO flow fields on changes in TC tracks is assessed by analyzing the ISO situation in selected typhoon cases.

2 DATA

The time periods investigated in this study are the months from June to September between 1986 and 2009; these periods are consistent with the primary interval during which TCs are generated. The following data are used in this study.

(1) Daily OLR reanalysis data from the National Oceanic and Atmospheric Administration (NOAA), which have a spatial resolution of 2.5°×2.5°;

(2) Wind field data from the European Centre for Medium-Range Weather Forecasts (ECMWF), which have a spatial resolution of 2.5°×2.5°; and

(3) TC data from the U.S. Joint Typhoon Warning Center (JTWC), which include the center position and the maximum wind speed for TCs at time intervals of 6 hours; the selected TCs for this study are TCs with maximum wind speeds of at least 17.2 m/s; the time and location of TC genesis are defined as the time and location of a TC at the first moment when the JTWC issued a notice regarding the TC.

3 ESTABLISHMENT OF AN ISO INDEX

Taking reference to an all-season real-time multivariate MJO index, which uses a real-time multivariate MJO series, RMMs[8], which was first proposed by Wheeler and Hendon in 2004, we implemented the 20-90 d harmonic filtering process for the OLR field and the *u* and *v* wind fields at 850 hPa and then conducted a combined empirical orthogonal function (EOF) analysis of the filtered OLR field and the horizontal wind field. The first two derived modes are used as the major modes of the ISO, which can more clearly and intuitively reveal the spatial modes of the ISO and its variations in the ISO over time.

In accordance with the method of Matthews et al.[9], a vector *Z* may be used in two-dimensional phase space to represent the ISO at a certain moment, and the two components of *Z* correspond to the two time series of PC1 and PC2 after the decomposition of the EOF:

$$Z(t) = [PC1(t), PC2(t)]$$

We define the amplitude of the ISO, $A(t)$, as follows:

$$A(t) = [PC1^2(t) + PC2^2(t)]^{1/2}$$

The phase angle between PC1 and PC2, $\alpha(t)$, may be expressed as follows:

$$\alpha(t) = \mathrm{a}\tan[PC1(t) / PC2(t)]$$

In the above expressions, the amplitude A can reflect the magnitude of the ISO, and the phase angle α can reflect the phase propagation of the ISO. For convenience, the ISO cycle is divided into four phases according to the phase angle α and the centers of these four phases are $\alpha=-\pi/2$, $\alpha=0$, $\alpha=\pi/2$, and $\alpha=\pi$. Each phase covers one quarter of the complete cycle. This approach allows for the ISO to be effectively divided into different phases, enabling propagation signals to be more intuitively and clearly extracted from the examined data.

To illustrate when the oscillation signal of the ISO reaches a given intensity, the standard deviation (σ) of amplitude *A* is used as a reference point, and the time when amplitude *A* is greater than or equal to one standard deviation (σ) is regarded as the ISO time.

4 EFFECT OF THE ISO ON TC TRACKS

To investigate the impact of the ISO on TC tracks in the WNP, we performed the aforementioned processing of the 20-90 d filtered OLR field and the *u*-*v* wind field at 850 hPa for June to September of each year between 1986 and 2009 across a spatial range of 40°E-60°W and 20°S-30°N. From the combined-EOF decomposition, the variance contributions of the first mode and the second mode are 12.94% and 9.25%, respectively. Fig. 1 displays a schematic diagram illustrating the situation at different ISO phases after the modal reconstruction. In phase 1, the active convection center emerges near the Indian Ocean at approximately (2°S, 85°E). During phases 2 and 3, a portion of this convection moves northward toward the Indian Peninsula, and a portion of the convection gradually shifts eastward to cross the Bay of Bengal and Indochina, propagating to the South China Sea and the western Pacific as an active convection zone in the northwest-southeast direction. At this time, the convection activity is gradually enhanced in the WNP. During phase 4, the convection activity moves northwest and weakens; the center of this activity is located near (17°N, 135°E). During the course of these phases, an evident easterly-westerly conversion occurs in the WNP area. In particular, easterly prevails in the WNP area during phases 1 and 2, whereas westerly prevails during phases 3 and 4; during the westerly phase, cyclonic circulation occurs over the WNP, and the cyclone center is approximately one quarter of a phase ahead of the active convection area. Therefore, it is evident that the defined ISO index can provide a useful illustration of the temporal and spatial periodic evolution of the ISO.

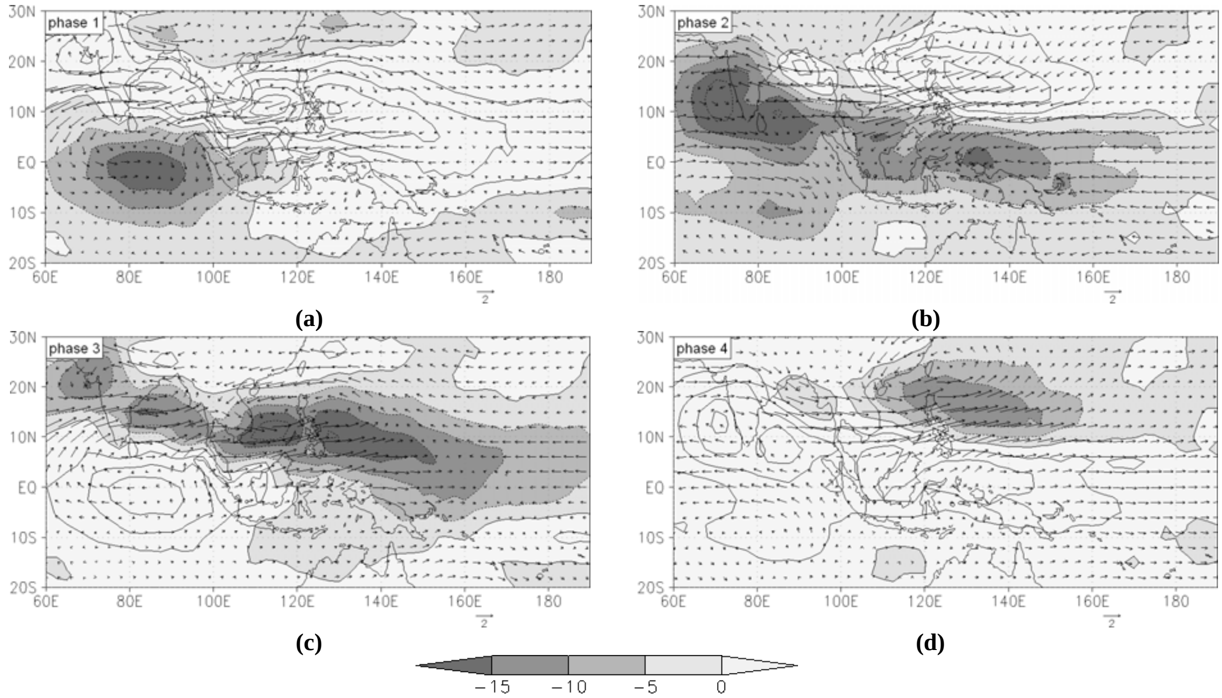


Figure 1. Composite maps of 20-90 d filtered wind fields and anomalous OLR fields after modal reconstruction during the four ISO phases (panel a, b, c, and d for phase 1, phase 2, phase 3, and phase 4, respectively) during June-September of the years 1986-2009 (the shaded areas represent negative anomalous areas of the filtered OLR field; the contour interval is 5 W/m^2).

To analyze the impact of various phases on the TC track, we divided typhoon tracks into five different types based on traditional typhoon track classifications: going westward, going northwestward, turning direction west of 140°E, turning direction east of 140°E, and going northward. These types of typhoon tracks may be described as follows. a) The westward category: typhoons in this category move from the east of the Philippines towards the west, through the South China Sea, and land in coastal areas of South China, Hainan Island, or Vietnam. b) The northwestward category: typhoons in this category move from the east of the Philippines either to the west-northwest, landing in Taiwan and Fujian regions of China, or to the northwest, passing the Ryukyu Islands and making landfall in the area of Zhejiang before disappearing; c) The turning categories: typhoons in these categories move from the east of the Philippines to the northwest and subsequently turn in a northeasterly direction and follow a parabolic track; using 140°E as the boundary, these tracks are statistically divided into TCs that recurve west of 140°E and TCs that recurve east of 140°E; d) The northward category: typhoons in this category move in north or northeast directions from the east of the Philippines. There are other unusual types of tracks that are not included in the examined statistics.

Figure 2 and Table 1 provide statistics regarding the number and proportion of TCs of the different types of tracks that have been generated during the various phases of the ISO. These statistics reveal that the proportion of TCs of each track type exhibits significant variation at various examined phases. It is evident that the proportions of TCs with westward tracks and recurving tracks west of 140°E are highest during phase 3, when they reach 20.37% and 38.89%, respectively. By contrast, the proportion of TCs with northwestward tracks is highest during phase 2 followed by phase 3; this proportion is lowest during phase 1. The proportion of TCs with recurving tracks east of 140°E is highest during phase 1 (21.13%) and lowest during phase 3 (4.63%), whereas the proportion of TCs with northward tracks is lowest during phase 3. Clearly, the ISO exerts certain modulating effects on TC activities in the WNP.

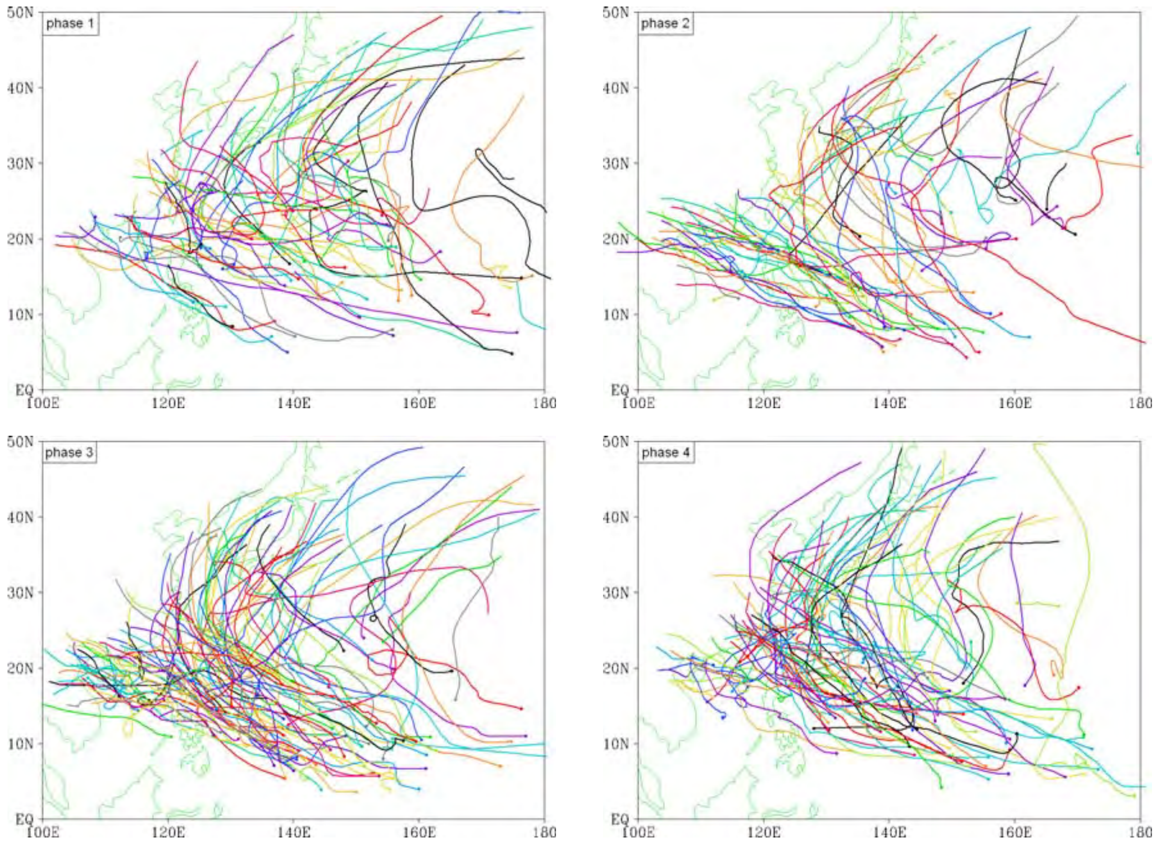


Figure 2. Composite plots of the motion tracks of the TCs that were generated during the four ISO phases (phase 1, phase 2, phase 3, and phase 4) in the WNP during June-September of the years 1986-2009.

Table 1. Numbers and proportions of TCs with different track types that were generated during the four ISO phases (phase 1, phase 2, phase 3, and phase 4) in the WNP during June-September of the years 1986-2009.

phase	track	westward	northwestward	recurving west of 140 °E	recurving east of 140 °E	northward
ISO phase1	TC number	11	11	21	15	7
	Total number			71		
	Percentage	15.49%	15.49%	29.58%	21.13%	9.86%
ISO Phase2	TC number	11	17	19	10	6
	Total number			68		
	Percentage	16.18%	25.00%	27.94%	14.71%	8.82%
ISO Phase3	TC number	22	23	42	5	9
	Total number			108		
	Percentage	20.37%	21.30%	38.89%	4.63%	8.33%
ISO Phase4	TC number	11	17	30	9	11
	Total number			87		
	Percentage	12.64%	19.54%	34.48%	10.34%	12.64%

The motion of TCs has a significant relationship with the basic airflows in the large-scale environmental field around TCs. The development and evolution of ISO phases in the WNP will cause changes in the location and strength of the western Pacific subtropical high and the southwest monsoon. Under normal circumstances, generated TCs are affected by easterly airflow south of the subtropical high over the surface of the WNP after they are generated and move toward the west or northwest, being guided by this easterly airflow. On the west side of the subtropical high, the influence of the southwest monsoon airflow and southeast airflow causes TCs to move clockwise in a northerly or northeasterly direction and rapidly diminish and disappear.

During the easterly phase of the ISO in the WNP, as illustrated in Figs. 1 and 3, ISO anti-cyclonic circulation prevails in this region, and the easterly airflow south of the western Pacific subtropical high weakens under the influence of the northeast airflow of ISO anti-cyclonic circulation. No monsoon trough exists in the WNP at this time. During phase 1, because the easterly guiding airflow south of the western Pacific subtropical high is relatively weak, TCs generated in this area can readily change their tracks at early stages. Thus, the probability that TCs will change their tracks east of 140°E is highest during this phase. During phase 2, a relatively high number of TCs are generated south of the western Pacific subtropical high, and easterly airflow south of this subtropical high causes this high to gradually shift to the east and north over time. TCs develop to the southwest of the western Pacific subtropical high and can readily move to the northwest under the guidance of southeasterly airflow at the outer edges of the subtropical high. Therefore, the proportion of TCs with northwestward tracks is higher during phase 2 than during any other phase.

When the ISO in the WNP enters its westerly phase, cyclonic ISO circulation is prevalent over the WNP. During this time, the westerly airflow in the tropical Indian Ocean strengthens and demonstrates eastward motion, cross-equatorial airflows are established, and a monsoon trough develops in the WNP (Fig. 3). The location of the western Pacific subtropical high shifts towards the east and north, and the northeast airflow southwest of the western Pacific subtropical high is strengthened by the northeast airflow of cyclonic ISO circulation and the monsoon trough. During phases 3 and 4, the location of the subtropical high in the WNP moves to the northeast, and TCs generated during these phases first move toward the west or northwest, due to the influence of the southeast airflow that exists southwest of this subtropical high. After TCs encounter southwest monsoon airflow in the WNP, the motion tracks of these cyclones are prone to deflect clockwise along the outer western edge of the subtropical high as a result of the combined impact of these two airflows. Therefore, the proportion of TCs with tracks changing west of 140°E is higher during these phases than during other phases. It is evident that track changes of TCs in the WNP are significantly influenced not only by the evolution of the western Pacific subtropical high and the southwest monsoon in the WNP but also by ISO development in this region.

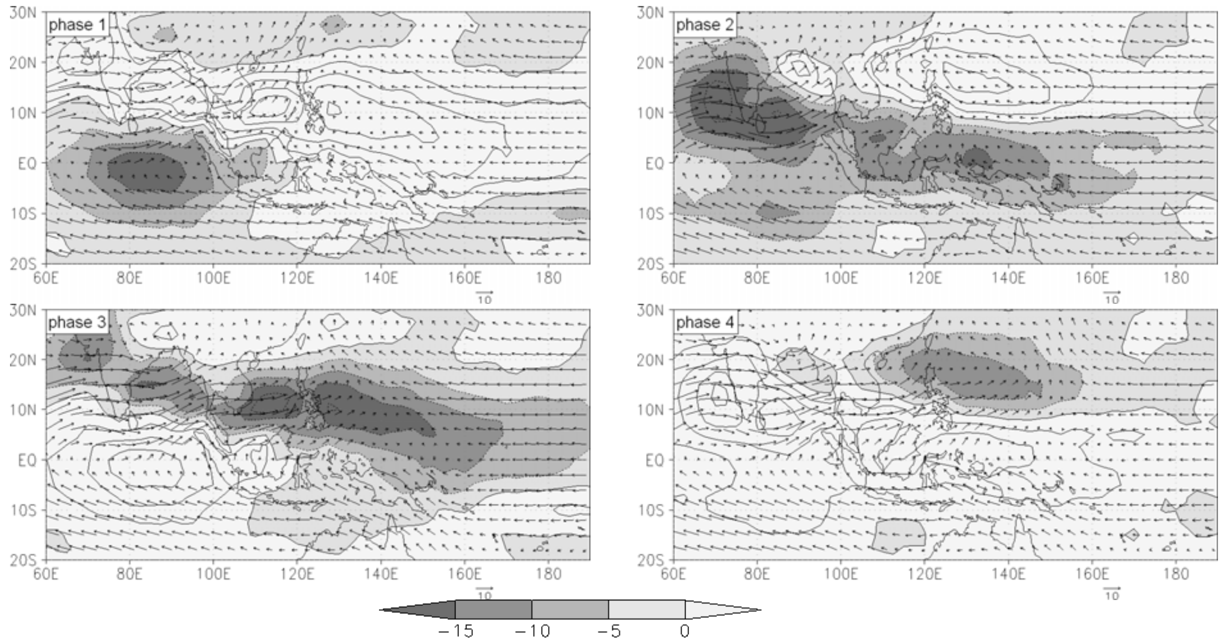
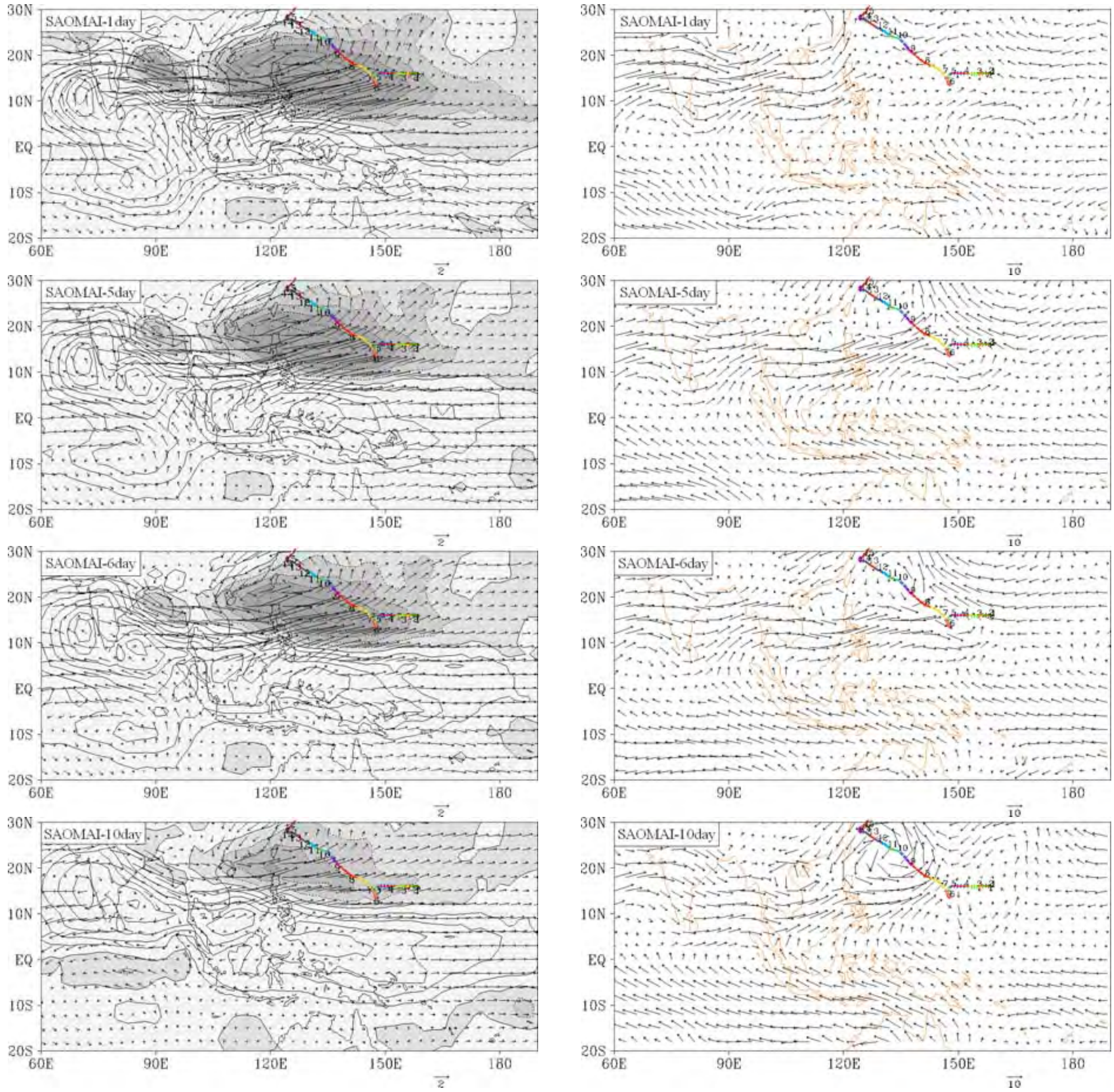


Figure 3. Composite plots of the original 850 hPa wind fields and anomalous OLR fields after modal reconstruction during the ISO phases (phase 1, phase 2, phase 3, and phase 4) in June-September of the years 1986-2009 (the shaded areas represent the negative anomalous areas of the filtered OLR field; the contour interval is 5 W/m^2).

5 ISO SITUATION ANALYSIS OF SELECTED TYPHOON CASES

To explore the relationship between ISO and TC further, this paper selected Saomai (2000), Lekima (2001), Choi-wan (2003), Soudelor (2003), Mindulle (2004), Meari (2004), and Linfa (2009) as multiple typhoon cases for analysis.

Figure 4 illustrates the schematic diagram of circulation patterns, indicating changes in the ISO and the original 850 hPa wind field during Typhoon Saomai in 2000. It is evident that Saomai occurred during the westerly phase of the ISO at a time when the active convection center of the ISO spread toward the northwest over time and gradually decreased in strength. On the first day of Saomai, the active convection center of the ISO was located in the west front of the TC. Accordingly, a relatively strong cyclonic ISO circulation occurred in the northwest front of the TC, an easterly airflow developed, and the TC circulation moved westward to the east of the TC with respect to the original 850 hPa wind field. From the second to the fifth day of this typhoon, the cyclonic ISO circulation at the northwest front of the TC moved toward the northwest, and the northward ISO longitudinal wind shear acting on the TC therefore decreased over time; concurrently, monsoon-related westerly airflow and cross-equatorial airflow appeared in front of the TC, which provided favorable conditions for the abrupt deflection of Saomai toward the equator on its 5th day. On the 6th day of Saomai, the eastern portion of the southwest monsoon airflow turned counterclockwise towards the north, and the modification of the ambient environmental field of the TC caused the storm to begin to move northwest under the guidance of the cross-equatorial airflow and the easterly airflow south of the subtropical high. Over time, the active convection center and cyclonic circulation of the ISO continued to move northwest with gradually decreasing strength, and the TC gradually moved towards the center of the cyclonic ISO circulation. On the 14th day of the storm, the center of the TC coincided with the cyclonic ISO circulation, and the track demonstrated a sudden right turn. From the analysis above, it may be noted that the cyclonic ISO circulation in the WNP provided a relatively favorable, low-frequency circulation environment for the track change of Saomai, and the influence of the development of the southwest monsoon in combination with the ISO on the TC facilitated this track change.



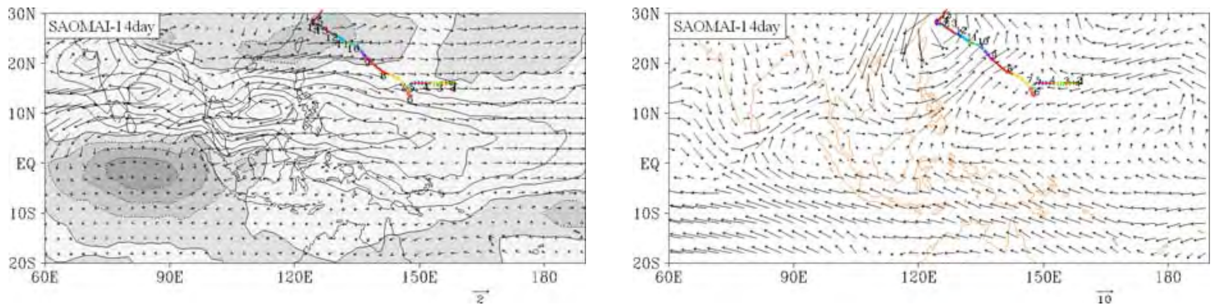
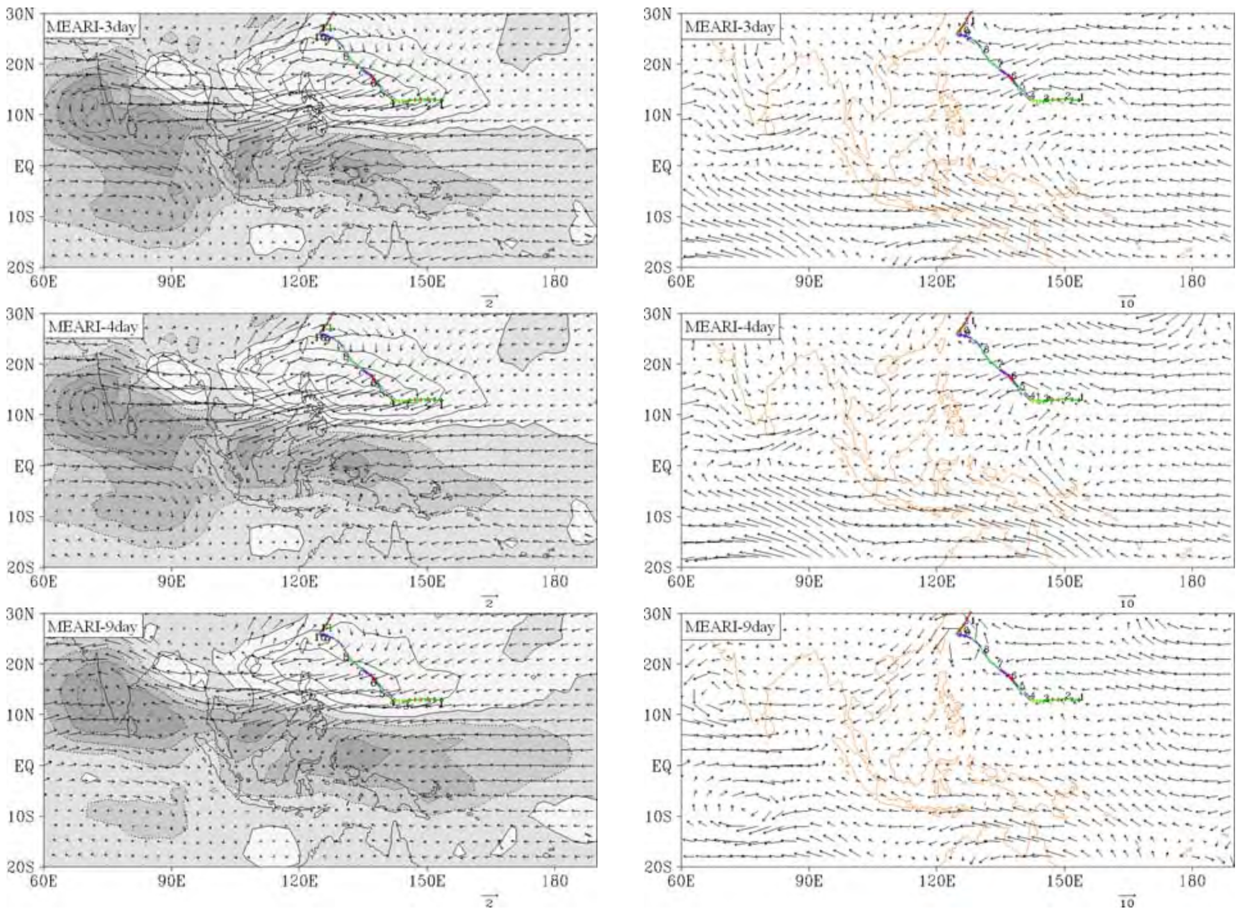


Figure 4. Circulation patterns of the ISO and the original 850 hPa wind field during Typhoon Saomai (left: ISO; right: original wind field; the shaded areas represent negative anomalous areas of the OLR field; the contour interval is 5 W/m^2).

Figure 5 presents a schematic diagram of circulation patterns of the ISO and the original 850 hPa wind field before and after the track change during Typhoon Meari in 2004. With respect to ISO circulation, Meari was generated during the easterly phase of the ISO. From the first day to the third day of the storm, the TC was located on the southeastern edge of the anti-cyclonic ISO circulation and was affected by the easterly phase of the ISO. The TC moved westward under the guidance of the easterly airflow south of the subtropical high. On the fourth day of the storm, with respect to the original 850 hPa wind field, a cross-equatorial airflow was enhanced and was merged into the tropical cyclonic circulation to the southeast of the TC. The track of the TC shifted toward the northwest. Over time, the anti-cyclonic ISO circulation continued to move northwest and the TC gradually moved northwest to approach the center of this anti-cyclonic circulation. On the ninth and tenth days, from the perspective of ISO circulation, the TC center coincided with the center of the ISO anti-cyclonic circulation and the TC underwent a sudden right turn.



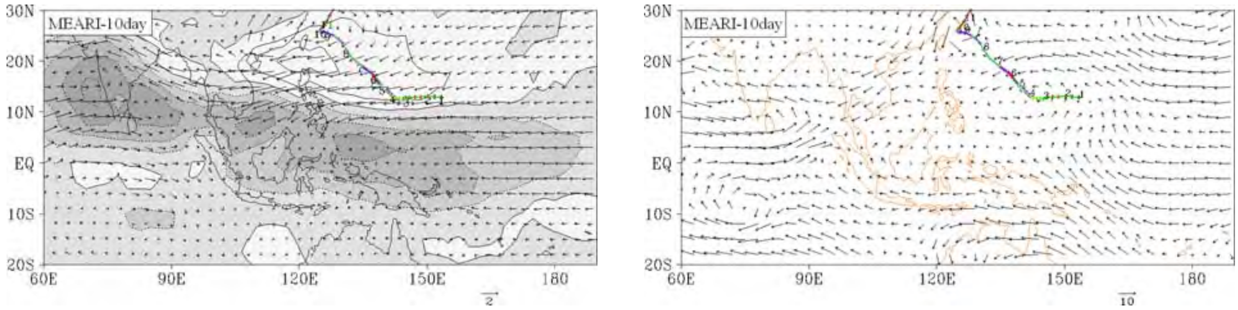


Figure 5. Circulation patterns for the ISO and the original 850 hPa wind field during Typhoon Meari (left: ISO; right: original wind field; the shaded areas represent negative anomalous areas of the OLR field; the contour interval is 5 W/m^2).

In accordance with the following barotropic relative vorticity equation,

$$\frac{\partial \zeta}{\partial t} = -V \cdot \nabla \zeta - \upsilon\beta ,$$

where ζ is the relative vorticity, $\boldsymbol{V}=u\,\boldsymbol{i}+v\,\boldsymbol{j}$ is the non-divergent wind, β is the Coriolis parameter f changing with latitude, Carr and Elsberry[10] designed a barotropic non-divergent relative vorticity model. The simulation results of this model indicate that interactions between a monsoon vortex and a TC vortex cause the track of the TC to abruptly turn northward. The mutual influence and interaction between a monsoon vortex and a TC vortex is one of the important factors that affect the evolution and change of TC tracks in the WNP. The initial location, initial strength, and scale of a monsoon vortex, the initial location of a tropical cyclone vortex relative to a monsoon vortex, and different combinations of vortex sizes cause a TC to develop various types of changes in its track. If the initial location of a TC vortex is to the east of a monsoon vortex and within the radius of influence of this monsoon vortex, then the TC vortex begins to move towards the west and northwest. This phenomenon is similar to the Fujiwhara effect. The TC vortex begins to coincide with the monsoon vortex as time passes. Through the β effect, the TC vortex obtains energy from the monsoon vortex, stimulating the generation of northwest-southeast Rossby waves that form anti-cyclones southeast of the monsoon and typhoon vortices. At this point, this southeast anti-cyclone becomes the key factor governing the motion and development of the TC vortex, which begins to turn north. During the westerly phase of the ISO in the WNP, the location and magnitude of cyclonic ISO circulations that influence TCs change as the ISO propagates, creating favorable conditions for track changes of TCs. It is clear that the ISO in the WNP has vital modulating effects on track changes of TCs.

This paper only provides preliminary analyses of the influences of anti-cyclonic and cyclonic ISO circulations on cyclones. Further interactions between anti-cyclonic or cyclonic ISO circulations and the TC must be investigated and verified in greater depth through future work involving the design of simulation experiments.

6 SUMMARY

This paper examined the ways in which the tropical atmospheric ISO modulates TC tracks in the WNP. This study uses the Wheeler-Hendon MJO index to construct a well-defined ISO index for the WNP. The conclusions of this investigation may be summarized as follows.

The atmospheric ISO in the WNP exerts certain effects that modulate TC tracks. The probability that TCs will change tracks east of 140°E is much higher during the easterly phase than during the westerly phase of the ISO. During the westerly phase of the ISO, the proportion of TCs that change tracks west of 140°E is relatively high. During the easterly phase of the ISO, the influence of airflow northeast of the anti-cyclonic ISO circulation causes the easterly airflow south of the western Pacific subtropical high to be relatively weak, and the tracks of TCs that are generated in this subtropical high are prone to early-stage changes. During the westerly phase of the ISO, the western Pacific subtropical high gradually withdraws to the east and north, and the impact of cyclonic ISO circulation on easterly airflow south of the subtropical high is strengthened. This airflow causes the TCs generated in this area to first move west and northwest to offshore areas. They are then likely to turn clockwise to the north as a result of the combined impact of the southwest monsoon airflow and the southeasterly airflow west of the subtropical high.

Through the analysis of ISO circulation in multiple typhoon cases, it was determined that the movement of a TC toward the center of cyclonic or anti-cyclonic ISO circulations will cause the track of this TC to turn right abruptly when the center of the cyclonic or anti-cyclonic ISO circulation coincides with the center of the TC in question. The easterly airflow south of the western Pacific subtropical high and the southwest monsoon airflow are the major guiding factors that affect TC tracks, and the interactions between anti-cyclonic ISO circulation and TC cyclones must be investigated through additional simulations.

Overall, by modulating the ambient field around TCs and interaction with TCs, the low-frequency cyclonic and anti-cyclonic circulations of the atmospheric ISO in the WNP influence the changes in TC tracks and this influence may be utilized as one of the bases for future forecasting of TC tracks.

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