Influence of varying time scale flows on tropical cyclone track changes

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Abstract
It is often difficult to predict tropical cyclone (TC) tracks for the case of binary or even multiple TCs. To investigate this issue, two TCs over the western North Pacific basin in September 2016, Meranti and Malakas, were explored in this study. The two TCs formed close to each other, and their tracks were similar at an early stage but then deflected northward over different regions. The results indicate that the Meranti track change may be due to the asymmetric high-frequency flows induced by topography, while the Malakas track change is attributed to the formation and strengthening of low-frequency southerlies. It was found that the formation and evolution of low-frequency monsoon circulation is the main cause for the emergence of the low-frequency flows, and the process is accompanied by the enhancement and movement of low-frequency positive vorticity. Therefore, based on the diagnostic results using the low-frequency vorticity budget equation, it is shown that the low-frequency vorticity advection and convergence induced by the low-frequency flows play varying roles in the development of low-frequency positive vorticity. More noteworthy is that the high-frequency positive vorticity of TCs can trigger the enhancement of low-frequency positive vorticity through nonlinear interactions, which have rarely been discussed in previous studies. It can be concluded that the interactions between high- and low-frequency flows and vorticity may affect the development and evolution of the TCs at different time scales, finally leading to TC track deflection.

KEYWORDS
different time scale steering flows, low-frequency vorticity, tropical cyclone track

1 | INTRODUCTION
The western North Pacific (WNP) is a basin with intense tropical cyclone (TC) activity. Landfall TCs usually cause tremendous economic losses and casualties. For instance, such disasters and their impacts have shown a significant upward trend during recent decades in China (Chen et al., 2011; Zhang et al., 2011). Thus, TC forecasts, including formation, track and intensity, are receiving increasingly more attention. Among these aspects, track prediction is always the foremost factor, because its accuracy directly determines the credibility.
of forecast results for other parameters such as intensity and precipitation.

TC tracks are dominated by large-scale environmental flows and ventilation flows defined as “beta-drift” (Holland, 1983). The former flows are dominant and are referred to as steering flows, and they are widely used for track prediction and analysis (Riehl and Burgner, 1950; Adem and Lezama, 1960; Chan and Gray, 1982; Chan, 1984; Wu and Chen, 2016). For example, some observational results indicate that flows averaging from 850 to 300 hPa in vertical layers are closer to the motion of TCs (Marks Jr et al., 1992; Franklin et al., 1996; Wang et al., 1998). Therefore, the evolution and development of large-scale environmental circulation may lead to changes in the steering flows, which in turn affect and even deflect TC tracks.

In recent decades, the TC activity over the WNP basin has demonstrated significant changes (Wu and Wang, 2004; Yu et al., 2016; Wang and Wu, 2018; Wang et al., 2019). The 24 hr TC track forecasts from the National Meteorological Center of the China Meteorological Administration have significantly improved, but there is still much room for improvement when considering sudden deflection and looping tracks in some special large-scale environments (Xu et al., 2010). According to previous studies, TC track deflections over the WNP are closely related to low-frequency monsoon circulation systems, e.g. monsoon troughs and monsoon gyres (Carr and Elsberry, 1995; Ko and Hsu, 2009; Liang et al., 2011; Wu et al., 2011a; 2011b). For instance, Liang et al. (2011) pointed out that both the long-term detention of TC Morakot (2008) near Taiwan and the extremely heavy precipitation caused by the TC were mainly caused by a low-frequency monsoon circulation. While examining four typhoons over the WNP basin that exhibited sudden deflections, Wu et al. (2011b) found that low-frequency monsoon gyres with quasi-biweekly time scales have crucial influences on TC track deflection. It was suggested by Duan et al. (2014) that the environmental fields at different time scales contributed differently to the sudden track changes of the two TCs (Aere and Meari) in 2004, and these effects corresponded well with the variations in the high- and low-frequency vorticity variations. Therefore, it is indicated that the environmental flows at various time scales play completely different roles in the abnormality or deflection of TC tracks.

Two TCs, i.e. Meranti and Malakas, formed successively in mid-September 2016. The formation locations were close, and the tracks were similar in the early stage (Figure 1). They coexisted over the WNP basin for a few days, but their tracks then deflected over different ocean areas. Was there a direct binary typhoon interaction or were there other types of indirect interaction between the two TCs in this process? How did the high- and low-frequency environments evolve, and what role did they play during the TC track changes? To solve these issues, our focus is on the influences of environmental flows with different time scales on the tracks of the two TCs, while providing a better understanding of the TC track forecasts over the WNP basin under the scenarios of binary and even multiple TCs.

2 DATA AND METHODS

The final operational global analysis data at 6 hr intervals from the US National Centers for Environmental Prediction are used in this study, with a horizontal resolution of 1° × 1° and 26 vertical layers from 1,000 to 10 hPa. The horizontal wind field data in the middle and lower layers in the troposphere are mainly used in the analysis. Provided by the Japan Meteorological Agency, the TC best-track data used include the TC positions and their intensities at 6 hr intervals. The TC intensity consists of the maximum surface wind speed and the minimum sea-level pressure near the TC centre. The TC position primarily refers to the latitude and longitude of the TC centre at a given time.

The Lanczos filter method is adopted in this study to investigate the influences of circulations at various time scales on TC tracks (Lanczos, 1956; Duchon, 1979). The large-scale flows over the WNP basin are divided into two parts by the filter method, including low-frequency...
and high-frequency flows, respectively. The former is obtained using a 10 day low-pass filter, while the latter is the difference between the unfiltered flows and the low-frequency flows. The Lanczos method has been proven to be capable of effectively separating the original large-scale flows into different time scales (Wu et al., 2011b; Zong and Wu, 2015; Duan et al., 2014).

### 3 | DETAILS OF MERANTI AND MALAKAS

Meranti formed over the WNP basin east of 140 ° E at 0600 UTC September 10 and then moved northwestward after its genesis. It intensified and became a strong tropical storm after 18 hr. Its intensity then rapidly increased, and Meranti evolved into a typhoon after 6 hr. At 1800 UTC September 13, it reached its maximum intensity, with near-centre surface winds above 60 m s⁻¹ and a minimum surface pressure of 890 hPa. It continued moving northwestward and passed over the Bashi Strait. It gradually turned to move northward and made landfall on the coast of the Chinese mainland at approximately 1800 UTC September 14, with maximum surface winds above 36 m s⁻¹ and a minimum pressure of 965 hPa. After landfall, Meranti continued to weaken and began to deflect northeastward. On September 16, it re-entered the ocean from the coastline of eastern China.

Malakas moved northwestward after its formation at 1800 UTC September 12 and strengthened into a typhoon 30 hr later. After reaching its maximum intensity (surface wind speeds were near 50 m s⁻¹ and the minimum surface pressure was 930 hPa) at 1800 UTC September 16, it began a turn to the north and then deflected northeastward after 18 hr; it landed in Japan on September 19. More details of the two TCs are provided in Table 1.

As shown in Figure 1, Meranti and Malakas formed over adjacent oceanic regions successively and both of them moved northwestward after their genesis. When entering the Philippine Sea, significant differences occurred to the two TC tracks and the crossing point of the two TC tracks located east of the Bashi Strait. It should be noted that the two TCs passed the crossing position around 0000 UTC September 13 and 1800 UTC September 15, respectively. After that, Meranti continued to move northwestward, passed the Bashi Strait, and began to move northward. By contrast, Malakas deflected northward over the area, passed the Philippine Sea and moved toward the northeast. It is found that the distance between the two TCs was above 1,500 km during the whole period, which is apparently larger than the distance causing interaction between binary typhoons (Fujiwhara, 1931; Lander and Holland, 1993). Therefore, our main attention of this study is focused on what roles the high- and low-frequency circulations played during the processes.

It should be pointed out that a TC formation time is defined as the time when a TC reaches the tropical storm (TS) intensity (with maximum near-centre surface winds above 17.2 m s⁻¹) for the first time during its lifespan. In addition, 0600 UTC September 15 and 1200 UTC September 17 are defined as the deflection times when Meranti and Malakas, respectively, changed their northwest movements to the northeast.

### 4 | THE ROLE OF CIRCULATION AT DIFFERENT TIME SCALES

#### 4.1 | Large-scale environmental steering flows

According to previous studies, TC movements are jointly guided by large-scale environmental flows and ventilation flows, i.e. “beta-drift”, that are generated by the interaction between TCs and large-scale environmental steering flows (Riehl and Burgner, 1950; Chan and Gray, 1982; Holland, 1983; Fiorino and Elsberry, 1989). The time series of the translation speeds and steering flows of the two TCs are shown in Figure 2. On comparing Figure 2a,b, the variations in the translation speeds are in good agreement with those of the total steering flows, which are calculated within a radius of 5° from the TC centres and are then averaged vertically between 850 and 300 hPa from the unfiltered flows. Thus, the movements of both TCs can be explained by the changes in their steering flows, which verifies the results of previous studies.

### Table 1 Details of the two tropical cyclones (TCs)

| TC     | Formation time | Formation location | Peak intensity | Deflection time |
|--------|----------------|--------------------|----------------|-----------------|
| Meranti | 0600 UTC September 10 | 14.8 ° N 139.2 ° E | 62 m s⁻¹ 890 hPa | 0600 UTC September 15 |
| Malakas| 1800 UTC September 12 | 13.8 ° N 139.4 ° E | 50 m s⁻¹ 930 hPa | 1200 UTC September 17 |
In recent years, studies of sudden deflections of TC tracks have attracted much attention, and the results demonstrate that sudden changes of TC tracks are mainly due to the variations in steering flows at different time scales (Wu et al., 2011a; 2011b; 2013). Therefore, understanding the contributions of circulations at varying time scales is of great significance for studying TC track changes. Before 1200 UTC September 13, Meranti generally moved northwestward under the steering of the zonal flows. Figure 2a shows that the variations in the zonal component of the total steering flow during this period generally occurred in the low-frequency band, indicating that the TC track during this stage was guided by the low-frequency southeasterlies. At 1200 UTC September 13, Meranti began to move northward and deflected completely towards the northeast 12 hr later, during which time the speed of its zonal steering flow increased from $-5.3$ to $2.7$ m s$^{-1}$ (Figure 2a), suggesting that the easterly component gradually decreased and then turned to the westerly component. More importantly, the increase in the zonal total steering flow is clearly derived from the variations in the low-frequency zonal steering flows (Figure 2a). After that, the southerly component of the meridional total steering flow increased rapidly after 1200 UTC September 13 from $3.1$ to $7.2$ m s$^{-1}$ at 0000 UTC September 16. This change is quite apparent and can explain the northward movement of the TC. The meridional high-frequency steering flows increased from approximately $0.8$ to $4.9$ m s$^{-1}$, which agrees with the increase in the total steering flows, whereas the meridional low-frequency steering flows contributed little (Figure 2b). Therefore, the increase in the southerly component of the high-frequency steering flow led to changes in the meridional component of the total steering flow, resulting in the northward deflection of the TC track.

During the early stage of the Malakas track, this TC was also steered by the low-frequency zonal steering flows (Figure 2c). After 1200 UTC September 14, the meridional component of the total steering flow increased from $2.3$ to $6.5$ m s$^{-1}$. With relatively small fluctuations, the high-frequency meridional steering flow provides little contribution to the changes in the TC motion. However, during the same period, the low-frequency meridional steering flow increased from $3.4$ to $6.6$ m s$^{-1}$, with its increase and variation trend being close to those of the total steering flow (Figure 2d). Thus, the northward deflection of Malakas was caused by the enhanced southerly component of the low-frequency steering flow.

To investigate the causes of the track change of Meranti, the evolution characteristics of the high-frequency time scale circulation are shown in Figure 3. The three images in the left panel show the high-frequency...
circulation at 700 hPa during the period before the TC track deflection. At 0600 UTC September 14, the high-frequency circulation of Meranti was located near Taiwan Island (Figure 3a), with maximum flows near the centre climbing above 60 m s\(^{-1}\). Meanwhile, the TC structure shows a symmetric pattern within the inner-core area, whereas the peripheral asymmetric circulations may be affected by the topography of Taiwan Island. When Meranti was close to making landfall on the Chinese mainland (1800 UTC September 14), the increasing friction of the land surface caused weakening of the high-frequency northerlies on the western quadrants of the TC but exerted less influence on the southerlies on the eastern side (Figure 3c). Therefore, the
asymmetric high-frequency structure led to enhancement of the high-frequency southerly in the steering flows (Figure 2c). By 0600 UTC September 15, the land surface friction continued to affect the TC and the asymmetric distribution of the high-frequency flows was maintained (Figure 3e). In general, under the effects of the increased land surface friction during landfall, the asymmetric structure of high-frequency TC circulation gradually developed and persisted. This is consistent with previous findings of landfall TC structure (Tuleya et al., 1984; Bender et al., 1985). The high-frequency southerlies on the eastern quadrants of the TC centre were clearly stronger than the northerlies on the western side, resulting in an increasing southerly component of the high-frequency steering flow, which led to the northward movement of Meranti.

It has been illustrated in Figure 2d that the northward deflection of the Malakas motion was mainly caused by the increased southerly component of the low-frequency steering flows. To verify this phenomenon, the evolution of the high- and low-frequency circulation at 700 hPa during the period is shown in the right panel of Figure 3. Symmetric high-frequency flows around the TC centre can be found, leading to fewer changes in the high-frequency steering flows. As shown in Figure 3b, at 1200 UTC September 15, Malakas moved to the bottom of the monsoon trough while the region of low-frequency positive vorticity and strong southeasterlies (reaching above 12 m·s⁻¹) was located in the northwestern quadrant of the TC. As the TC continued to move northwestward, it approached the strong low-frequency southerlies, resulting in an increase in the meridional component of the low-frequency steering flows. Of great interest is that the location of the strong low-frequency flows coincided well with the track crossing position demonstrated in Figure 1, implying that the emergence of strong low-frequency flows may play a dominant role during the northward deflection of the TC track. It is also consistent with the changes in the steering flows (Figure 2d).

### 4.2 Characteristics of low-frequency large-scale circulation

According to the above results, a new question arises regarding how the strong low-frequency flows formed and persisted. To investigate this issue, the evolution of the large-scale low-frequency environmental background is shown in Figure 4. At 1800 UTC September 11, when Malakas had just reached TS intensity, the main part of

**FIGURE 4** Evolution of low-frequency flow (m·s⁻¹) at 700 hPa at (a) 1800 UTC September 11 (when Malakas reached tropical storm intensity); (b) 0600 UTC September 13 (when low-frequency flows greater 12 m·s⁻¹ emerged); (c) 0600 UTC September 14; (d) 1200 UTC September 16. The low-frequency vorticity (×10⁶ s⁻¹) is shaded, and the black contours indicate areas with flows greater than 12 m·s⁻¹.
the WNP basin was influenced by the subtropical high, and there was an apparent region with low-frequency positive vorticity on the southern edge of the subtropical high. Low-frequency positive vorticity developed during the following hours and led to evolution of the monsoon system while cyclonic circulation occurred over the southeastern coast of the Chinese mainland (Figure 4b). Within the area between the subtropical high and the monsoon trough, due to the increase in the geopotential height gradient, strong low-frequency southerlies (≥12 m s⁻¹) appeared (Figure 4b). At 0600 UTC September 14, the monsoonal circulation and positive vorticity continued to develop, while the southeasterlies between the monsoon circulation and the subtropical high strengthened as well (Figure 4c). Approximately 2 days later (Figure 4d), the monsoon system evolved into a closed circulation pattern. The monsoonal cyclone located to the west of the subtropical high while the low-frequency flows between the monsoonal circulation and the subtropical high significantly increased, and the flow direction changed from southeasterly to southerly.

In summary, the low-frequency flows leading to the Malakas track change were closely associated with the evolution of the monsoon circulation. The low-frequency positive vorticity increased before the TC’s track deflection and resulted in strengthening of the low-frequency monsoon system. As a result, a closed cyclonic circulation formed and caused a rapidly increasing geopotential height gradient between the low-pressure system and the subtropical high. According to the gradient wind equation, strong low-frequency southerlies emerged, thus causing Malakas to move northward.

5 | Diagnosis Conducted Using the Low-Frequency Vorticity Budget Equation

The above results show that the two TC track deflections were due to different mechanisms. The increasing high-frequency southerlies, which were caused by the asymmetric structure induced by land roughness, steered Meranti in a northward direction. On the other hand, the low-frequency southerlies that caused the northward motion of Malakas can be attributed to the increased geopotential height gradient induced by the development of low-frequency vorticity and monsoonal circulation. According to Duan et al. (2014), rapid increases in high-frequency vorticity, which are caused by the advection of low-frequency vorticity by high-frequency flow, comprise an important effect that leads to sudden track deflections of TCs. However, it is worth noting that the development and evolution of the low-frequency vorticity played a crucial role during the Malakas track change. Therefore, to analyse the cause of the variation in low-frequency vorticity, the contributions of different physical processes to the low-frequency vorticity budget will be explored, referring to the derivation of the vorticity equation provided by Duan et al. (2014).

5.1 | Equation and details

Assuming that the friction in the P coordinates is ignored, the vorticity equation in a moving coordinate system can be expressed as follows:

\[
\frac{\partial \zeta}{\partial t} = -(V - C) \nabla \eta - \eta \nabla V - \frac{\partial \zeta}{\partial p} \frac{\partial \omega}{\partial p} - k \nabla \omega \frac{\partial V}{\partial p} = 0
\]  

(1)

The flow can be considered to be composed of a low-frequency component (with periods longer than 10 days) and a synoptic scale component (with periods equal to or shorter than 10 days), i.e. \( V = V_L + V_H, \ \zeta = \zeta_L + \zeta_H, \ \omega = \omega_L + \omega_H, \ \eta = \eta_L + \eta_H = \zeta_L + f + \zeta_H, \) \( C \) represents the translation speed of the TC, and the subscripts \( L \) and \( H \) represent the low-frequency and high-frequency variables, respectively. All of these are substituted into Equation (1) and a time-average calculation is then made. Assuming that the local variation at the synoptic scale is zero on a low-frequency time scale and that changes in the low-frequency circulation variables can be neglected, then the following low-frequency vorticity equation can be obtained:

\[
\frac{\partial \zeta_L}{\partial t} + \eta_L \nabla V_L + V_L \nabla \zeta_L + \rho \omega_L + \omega_L \frac{\partial \zeta_L}{\partial p} + k \nabla \omega_L \frac{\partial V_L}{\partial p} + \nabla \frac{\partial \zeta_H}{\partial t} + \omega_H \frac{\partial \zeta_H}{\partial p} + k \nabla \omega_H \frac{\partial V_H}{\partial p} = 0
\]

The detailed derivation process is referred to in the appendix in Duan et al. (2014).

5.2 | Diagnostic analysis

The diagnostic results indicate that the enhanced low-frequency positive vorticity is mainly attributed to three processes during the track change of Malakas, namely the divergence term (\( \eta_L \nabla V_L \), hereafter referred to as VT1); the advection of the low-frequency vorticity by low-frequency flows (\( V_L \nabla \zeta_L \), referred to as VT2); and the term containing the high-frequency vorticity variations averaged at a low-frequency time scale (\( \nabla \frac{\partial \zeta_H}{\partial t} + \omega_H \frac{\partial \zeta_H}{\partial p} \), referred to as VT3). The remaining
terms are negligible because of their small contributions to the low-frequency vorticity.

VT1 represents the influences of divergence or convergence caused by the low-frequency flows on the low-frequency vorticity. The evolution of VT1 during the movement of Malakas is demonstrated in Figure 5. When Malakas reached TS intensity (1800 UTC September 11), positive VT1 contributions were observed to the southeast of the subtropical high, especially over the Bashi Strait and the ocean areas to the east (Figure 5a). The distribution of positive VT1 corresponded well to the region of the low-frequency positive vorticity, indicating that VT1 may play an important role in the development of low-frequency positive vorticity as discussed above.

**FIGURE 5** Contribution of the VT1 term (shaded, $\times 10^{10}$ s$^{-2}$) and evolution of the 700 hPa low-frequency vorticity (black solid lines, $\times 10^6$ s$^{-1}$) and flows (m s$^{-1}$) at (a) 1800 UTC September 11 (when Malakas reached tropical storm intensity), (b) 0600 UTC September 13 (when low-frequency flows above 12 m s$^{-1}$ emerged) and (c) 1200 UTC September 15

**FIGURE 6** As for Figure 5 but for the VT2 term
As the contribution made by VT1 gradually increased, the low-frequency vorticity over the areas also strengthened (Figure 5b). Meanwhile, the low-frequency flows greater than 12 m s⁻¹ were just beginning to appear (0600 UTC September 13), suggesting that the convergence induced by the low-frequency flow was beneficial to the increase in low-frequency positive vorticity and further resulted in the development of the monsoon circulation. The closed low-frequency monsoon circulation formed after this point (Figure 5c) and significant convergence caused by low-frequency flows was shown over the Bashi Strait and the oceanic areas to the east. Hence, convergence led to an increase in low-frequency positive vorticity and strengthening of the low-frequency flow that steered the track of Malakas. However, it is worth noting that during this period the contributions to negative vorticity made by VT1 began to appear near Taiwan Island, while the region of low-frequency positive vorticity began to extend northward (Figure 5c). This outcome means that VT1 did not contribute significantly to the northward extension of the low-frequency positive vorticity.

VT2 is the contribution made by the advection of low-frequency vorticity by low-frequency flow. In comparison to VT1, the contribution made by VT2 to the low-frequency vorticity varied significantly with time. At 1800 UTC September 11, VT2 made negative vorticity contributions to the northern part of the low-frequency positive vorticity region and positive contributions to the southern (Figure 6a). This phenomenon occurred because the southeasterlies, located on the southern edge of the subtropical high, advected the negative low-frequency vorticity to the positive region, thus causing a negative vorticity tendency on the southern part. The opposite situation was indicated on the northern part due to the same mechanism. VT2 did not contribute significantly to the enhancement of low-frequency positive vorticity before the occurrence of the strong low-frequency southeasterlies. At 0600 UTC September 13, VT2 contributed positively around the Bashi Strait but negatively over the seas on the eastern side (Figure 6b). This low-frequency vorticity tendency is closely associated with the advection of the low-frequency flows. The low-frequency positive vorticity was transported by the southerlies to the region where the closed monsoonal circulation gradually formed. Afterwards, the strong low-frequency southerlies began to emerge, as shown in Figure 4b. At 1200 UTC September 15, the VT2 distribution was completely opposite to that of the initial pattern illustrated in Figure 6a. The southerlies advected the low-frequency vorticity to the north, thereby forming a negative vorticity tendency on the southern edge of the low-frequency vorticity positive region and a positive tendency on the northern edge (Figure 6c). Such distributions can

**FIGURE 7** Contribution of the VT3 term (shaded, ×10¹⁰ s⁻²) and evolution of the 700 hPa low-frequency vorticity (black dotted lines, ×10⁶ s⁻¹) and flow (m s⁻¹) at times (a) 1800 UTC September 11 (when Malakas reached tropical storm intensity), (b) 0600 UTC September 13 (when low-frequency flows above 12 m s⁻¹ emerged), (c) 1200 UTC September 15 and (d) 0000 UTC September 17. The tracks (from formation to deflection time) of Meranti and Malakas are plotted in black solid lines with arrows.
explain the northward extension of the region of low-frequency positive vorticity. As a result, VT2 played a critical role for the northward shift of the low-frequency positive vorticity.

It has been suggested in the above analysis that changes in the intensity and extension of low-frequency positive vorticity can be partially explained by VT1 and VT2, respectively. VT3 reveals the influences of high-frequency vorticity on low-frequency vorticity at low-frequency time scales. In other words, VT3 can be viewed as the interaction between high- and low-frequency vorticity and flows. At 1800 UTC September 11, positive VT3 was distributed near the Bashi Strait and the ocean areas to the east of the strait. This positive vorticity tendency was significantly greater than the contribution made by VT1, and this phenomenon persisted for several days (Figure 7a,b). It can be concluded that the enhancement of the low-frequency positive vorticity was mainly caused by the influence of the high-frequency vorticity on the low-frequency vorticity. More notably, during this process, the contribution of the positive vorticity tendency induced by the VT3 generally coincided with the track of Meranti, implying that the high-frequency vorticity was directly related to the TC. As Meranti passed the area, the high-frequency vorticity of the TC was transformed to low-frequency vorticity through the interaction between varying time scale vorticity and flows and resulted in an increase in low-frequency positive vorticity. As the region of low-frequency positive vorticity began to extend northward at 1200 UTC September 15, VT3 showed a negative vorticity contribution over the area. However, at 12 hr before the track deflection of Malakas, the distribution of the positive vorticity tendency caused by VT3 coincided with the northward expansion of the low-frequency vorticity region (Figure 7c,d), and this pattern was also in accordance with the Malakas track. These results mean that the interactions between different time scales of TC vorticity may play a non-negligible role in the development and shift of the low-frequency vorticity in this case. When a TC passes through a certain region, the low-frequency vorticity intensifies through its interaction with the high-frequency vorticity. This interaction is an important factor that leads to an increase in low-frequency vorticity and to the development of low-frequency monsoon circulation, further resulting in the formation of strong low-frequency southeasterlies that affected the Malakas track.

5.3 | Discussion

According to the above results, the strong low-frequency flow was mainly caused by the evolution of the monsoon circulation. During this process, the development and extension of the low-frequency positive vorticity played an important role and it has been proved that different physical processes have significantly variable effects.

The low-frequency positive vorticity generated by the convergence of the low-frequency flow contributed positively to the formation of a strong low-frequency flow in the initial stage, but the contribution is clearly less than that from the conversion of high-frequency vorticity into low-frequency vorticity. The combined effects of the two terms strengthened the low-frequency positive vorticity, thereby resulting in the development of the low-frequency monsoon circulation and the formation of strong low-frequency southeasterlies. Thereafter, due to the advection of the low-frequency vorticity by the low-frequency southeasterlies and the conversion of high-frequency vorticity into low-frequency vorticity, the region of low-frequency positive vorticity shifted northward, with the low-frequency southeasterlies gradually turning into southerlies, eventually leading to the deflection of the Malakas track. During this process, it is worth noting that the interaction between the high- and low-frequency vorticities and flows have key influences. When a TC passes through a certain area, its high-frequency flows and positive vorticity interact with low-frequency flows and lead to increasing low-frequency positive vorticity and affect its distribution. This phenomenon has rarely been mentioned in previous studies. It was suggested by Liang and Wu (2015) that the interaction between TCs and monsoon gyres leads to sudden TC track deflections while the monsoon gyres are low-frequency systems. Other studies also demonstrated that the interactions between the two systems at different time scales may affect TC intensities (Yu et al., 2014; Liang et al., 2018). Therefore, the interactions between high- and low-frequency vorticity and flows may play a critical role in this case. The high-frequency vorticity of the TCs of both Meranti and Malakas exerted great influences on the changes in the low-frequency vorticity, as well as forming and strengthening the strong low-frequency flows, leading to the track deflection of Malakas.

6 | CONCLUSIONS

In September 2016, two tropical cyclones (TCs), i.e. Meranti and Malakas, formed successively over adjacent ocean areas. The tracks of the two TCs were similar in the early stage, and both of these tracks shifted northward and then finally deflected northeastward. Nevertheless, there were significant differences between the areas where their deflections occurred, which caused difficulty
in track forecasting. To solve this issue, this study focused on exploring the different contributions of flows and vorticity budgets at different time scales to the TC track changes, which can provide more information and guidance for TC track prediction over the western North Pacific (WNP) basin from the background of binary TCs.

Since the distances between the two TCs were always greater than 1,500 km, there were few chances for a binary typhoon interaction to be triggered. By analysing the variations in the large-scale environmental steering flows at various time scales, it was determined that the track deflections of the two TCs had different causes. The track change of Meranti was due to the rapid development of asymmetric high-frequency flows induced by topography, whereas the track change of Malakas was attributed to the formation and enhancement of strong low-frequency flows. Further analysis demonstrated that the formation of the low-frequency flows was due to the development and evolution of the low-frequency monsoon circulation over the WNP basin, and the increase in the low-frequency positive vorticity during this process had direct and important influences on the development of the system. Based on the diagnostic methods suggested by previous studies, the low-frequency vorticity budget equation was used in this study to investigate the evolution of the low-frequency positive vorticity. Several physical processes exerted varying influences on the variations in the low-frequency positive vorticity. The convergence caused by the low-frequency flow and the interaction between high- and low-frequency vorticity were favourable for increasing the low-frequency positive vorticity. These contributed to the development of a low-frequency monsoon system and the formation of strong low-frequency southeasterlies. The enhanced low-frequency southeasterlies later advected the low-frequency vorticity, leading to a northward extension of the region of low-frequency positive vorticity. Additionally, the high-frequency vorticity of Malakas had a great impact on the low-frequency vorticity, so the low-frequency positive vorticity developed further. As a result, as the low-frequency flow gradually strengthened and changed to southerlies, Malakas eventually deflected northward.

Throughout this process, it is of great interest that the high-frequency vorticity of a TC itself can affect the low-frequency vorticity budget of background systems through nonlinear interactions, which have rarely been discussed in previous work. This mechanism remains unresolved and needs deeper investigation since it may provide the key to tracking forecasts for binary or even multiple TC scenarios.

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