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Contrasting contributions of flows on different time scales to tropical cyclone tracks over the South China Sea

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Abstract

This study investigates the relative contributions of components of flows on multiple time scales to westward and eastward-moving tropical cyclones (TCs) over the South China Sea (SCS) from a local and instantaneous perspective of TC position along the TC tracks during June to October from 1965 to 2015. The total steering flows obtained by vertical integration of winds from 850 to 300 hPa averaged along the entire TC tracks are separated into climatological mean flows, interannual, intraseasonal, and synoptic time scales. For westward-moving TCs, the zonal steering flows are contributed dominantly by climatological mean easterly, whereas the meridional steering flows are contributed dominantly by climatological mean and synoptic-scale southerly winds. In contrast, for eastward-moving TCs, the zonal steering flows are contributed equally by the intraseasonal and synoptic components, while the meridional steering flows are contributed dominantly by climatological mean southerly winds along with the secondary contribution of synoptic-scale southerly winds. This work provides a better understanding of relative contributions of different time scale components of steering flows to the TC motions over the SCS.

1. Introduction

The South China Sea (SCS) is one of the largest semi-enclosed marginal seas over the western North Pacific. Nearly all the tropical cyclones (TCs) that form over the SCS can make landfall to China, Vietnam, and Philippines, accounting for about 30% of total TCs affecting China. Those landfalling TCs can cause a great loss of human life and property damages in these areas (Zhang *et al* 2009, Li *et al* 2017). Thus, it is of great significance to understand the plausible factors affecting the TC tracks over the SCS. Liu and Chan (2003) showed that the location of TC landfall is mainly affected by the locations of TC formation and steering flow.

Previous studies have suggested that the TC track is chiefly determined by two processes including advection of relative vorticity by large-scale background flows and the beta drift (e.g. Anthes 1982, Holland 1983, Fiorino and Elsberry 1989, Wang and Holland 1996, Wang *et al* 1997). Anthes (1982) indicated that the most important factor controlling the TC motion is the environmental steering flow. Numerical and observational studies suggested that only when the TC steering flow is relatively weak, the beta drift effect can become important in inducing a systematic deviation of TC track (Wang and Li 1992, Franklin *et al* 1996). Besides the effect of horizontal advection of planetary vorticity mentioned above, other factors such as vertical shear (Wu and Emanuel 1993) and diabatic heating (Wu and Wang 2000) could also play a role in shifting the TC motion. In addition, the asymmetric TC structure has a contribution to the TC movement (Li and Zhu 1991). Holland

(1983) suggested that the interaction between a convergent flow of TC and the gradient of planetary vorticity could contribute to the TC motion. Those studies indicate that the factors influencing the TC motion are complicated and involve multiple-scale processes. Nevertheless, these factors including vertical shear, diabatic heating, asymmetric TC structure, and the interaction between TC and planetary vorticity are not always taken into consideration in estimating the influence of large-scale environment due to their relatively small effects.

The TC tracks over the SCS may be influenced by steering flows of different time scales. On the inter-annual time scale, El Niño-Southern Oscillation (ENSO)-induced large-scale circulation changes can affect the TC motion (Wang and Chan 2002, Camargo *et al* 2006, Yonekura and Hall 2012, Cao *et al* 2014a, Li and Zhou 2014, Yang *et al* 2015). For example, those TCs that form over the southeastern part of western North Pacific tend to recurve from northwestward to northeastward and affect the regions around Japan and Korean (Wang and Chan 2002). On the other hand, those TCs that are generated over the northwestern part of western North Pacific prefer to move westward or northwestward and likely make landfall in China, Vietnam, and Philippines Island. Hong *et al* (2011) found that during the central Pacific El Niño years, TCs have a tendency to recurve northward at a more westward location near the coastline of East Asia and make landfall to Taiwan and South China because of the westward shift of subtropical high and related steering flows.

The intraseasonal oscillation (ISO) is a pronounced mode in the atmosphere and the ocean over the western North Pacific and the SCS (Li and Wang 2005, Hsu and Li 2011, Cao *et al* 2014b, Li 2014). It has a vital influence on the TC track (Kim *et al* 2008, Li and Zhou 2013, Bi *et al* 2015a, Yang *et al* 2015, Ling *et al* 2016). For example, Kim *et al* (2008) found that when the ISO-related convection center is located near the tropical western North Pacific, a dense area of TC tracks migrates westward. They indicated that the density of TC tracks depends on the systematic shift in the main genesis regions, which is affected by the prevailing large-scale steering flows in each ISO phase. Bi *et al* (2015a) displayed that the interaction between Typhoon Megi (2010) and an intraseasonal monsoon gyre plays a significant role in the sharp northward turning of Typhoon Megi. Yang *et al* (2015) revealed that the westward-moving TCs are controlled by the background easterly flows and the eastward-moving TCs are affected by the ISO steering flows over the SCS during June–October.

The tracks of TCs that are generated in the SCS could be separated into two categories: westward motions including northwestward, southwestward, and straight westward, and eastward motions including northeastward, southeastward, and straight eastward (Yang *et al* 2015, Ling *et al* 2016). Previous studies mainly focused on the impact of the ISO on the TC tracks over the SCS (Yang *et al* 2015, Ling *et al* 2016). The quantitative analysis about contributions of multi-scale environmental flows to the TC tracks has not been conducted. Some recent studies have shown that the instantaneous state around the location of the TC genesis can better capture the relationship between the large-scale circulation and TC genesis (Cao *et al* 2018, 2019a, 2019b). As the TC genesis and development is a local and instantaneous weather event whose conditions are determined by a combination of various environmental factors on multiple time scales around the time and location of TCs, it is necessary to examine the instantaneous state around the location of TC to understand the contribution of multiple components of environment flows to TC tracks. Therefore, the purpose of this study is to contrast relative contributions of flows on different time scales to the westward and eastward TC tracks over the SCS from the local and instantaneous perspective as an extension of Yang *et al* (2015) and Ling *et al* (2016).

The rest of the paper is arranged as follows. Section 2 describes the data and methods used in the present study. Section 3 investigates the relative contributions of different time scale steering flows to the TC tracks over the SCS. The summary is provided in section 4.

2. Data and methods

The TC best-track data in the present study come from the Joint Typhoon Warning Center (JTWC), which is archived in the International Best Track Archive for Climate Stewardship (IBTrACS) v03r10 of the National Climate Data Center (NCDC, Knapp *et al* 2010). The TC dataset include longitude and latitude of the TC position center and the maximum sustained wind speed at the 6 h intervals. The definition of TC genesis is that the maximum sustained wind speed reaches 33 kts ($\sim$17 m s^{-1}). In the present analysis, we mainly focused on the TC genesis over the SCS region extending from 100°E to 120°E and from the equator to 25°N during the peak TC season (June–October, JJASO) of the period from 1965 to 2015. In addition, we use daily mean winds from 850 to 300 hPa from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay *et al* 1996). The NCEP–NCAR reanalysis winds have a horizontal resolution of 2.5° in latitude and longitude and are available from 1948 to the present. Note that we use NCEP–NCAR reanalysis because it extends further back compared to these more modern reanalysis such as the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) dataset and ERA5 dataset.

Generally, an integrated flow in a layer of atmosphere is defined as the steering flow of TC movement (Holland 1983, Dong and Neumann 1986). The choice of the atmospheric layer used to calculate the steering flow is diverse in various studies. For instance, a layer from 850 to 300 hPa is used to calculate the steering flow of TC (Chu *et al* 2012). A middle layer at 500 hPa is used to represent the steering flow of TC motion (Chan and Gray 1982, Ling *et al* 2016). Chan and Gray (1982) also indicated that the steering flow of the TC should be computed around the TC. Following the previous definition (Chu *et al* 2012, Bi *et al* 2015a), the steering flow of TC motion is obtained by vertically integrating the flows from 850 to 300 hPa following a TC track in the present study. In order to estimate quantitatively the relative contributions of multi-scale steering flows to TC tracks, the average of winds over a 7.5° × 7.5° box centered at the TC location along the entire TC track at the interval of 24 h is used as the steering flows. Note that there are some missing data along the TC entire track at the interval of 6 h. Thus, we choose the TC track at the interval of 24 h to avoid mismatch between the 6 h TC time and daily mean wind fields. We also calculated the steering flow of TC motion only at 500 hPa. It is found that the results at 500 hPa are almost similar to those based on vertically integrating of the flows from 850 to 300 hPa (figures not shown). It indicates that 500 hPa is a representative pressure level for the steering flow of TC motion. Only the results averaged from 850 to 300 hPa are shown in the present study, unless otherwise stated.

In order to exclude the effect of TC circulation on the steering flows from 850 to 300 hPa, we remove the 850–300 hPa cyclonic circulations related to TCs from the original flows before obtaining the four components of steering wind fields. The removal of TC-related cyclonic circulation from 850 to 300 hPa is based on the algorithm proposed by Kurihara *et al* (1995). Meantime, we follow the procedure of Bi *et al* (2015b). The outer boundary of TC domain is obtained according to the 850 hPa cyclonic circulation. The criterion of the outer boundary of TC domain and the particular procedure could be referred to Cao *et al* (2018, 2019a).

After the TC signals are removed, the remaining flows are separated into climatological mean flows and interannual, intraseasonal, and synoptic time scale variations. Climatological mean flows at a specific day are calculated by averaging flows of the same day over the period 1965–2015. Such obtained climatological daily mean flows only vary with the day. Then, we obtain daily anomaly winds by subtracting climatological daily mean winds from TC-signal removed original daily mean winds. After that, we extract interannual, intraseasonal, and synoptic components from daily anomaly winds. Following Cao *et al* (2018), the interannual component is obtained as the 91 d running mean winds that include the interdecadal variation. The intraseasonal component is defined as the
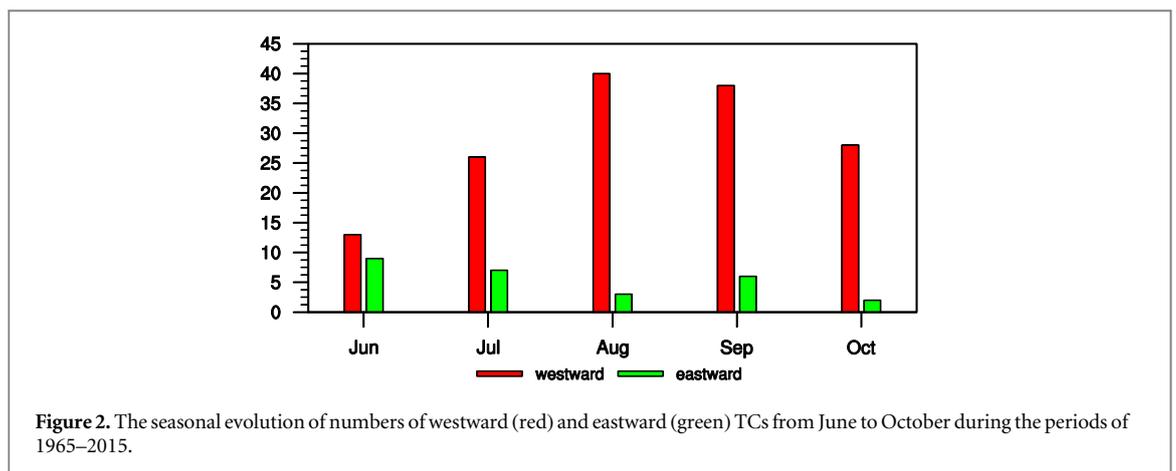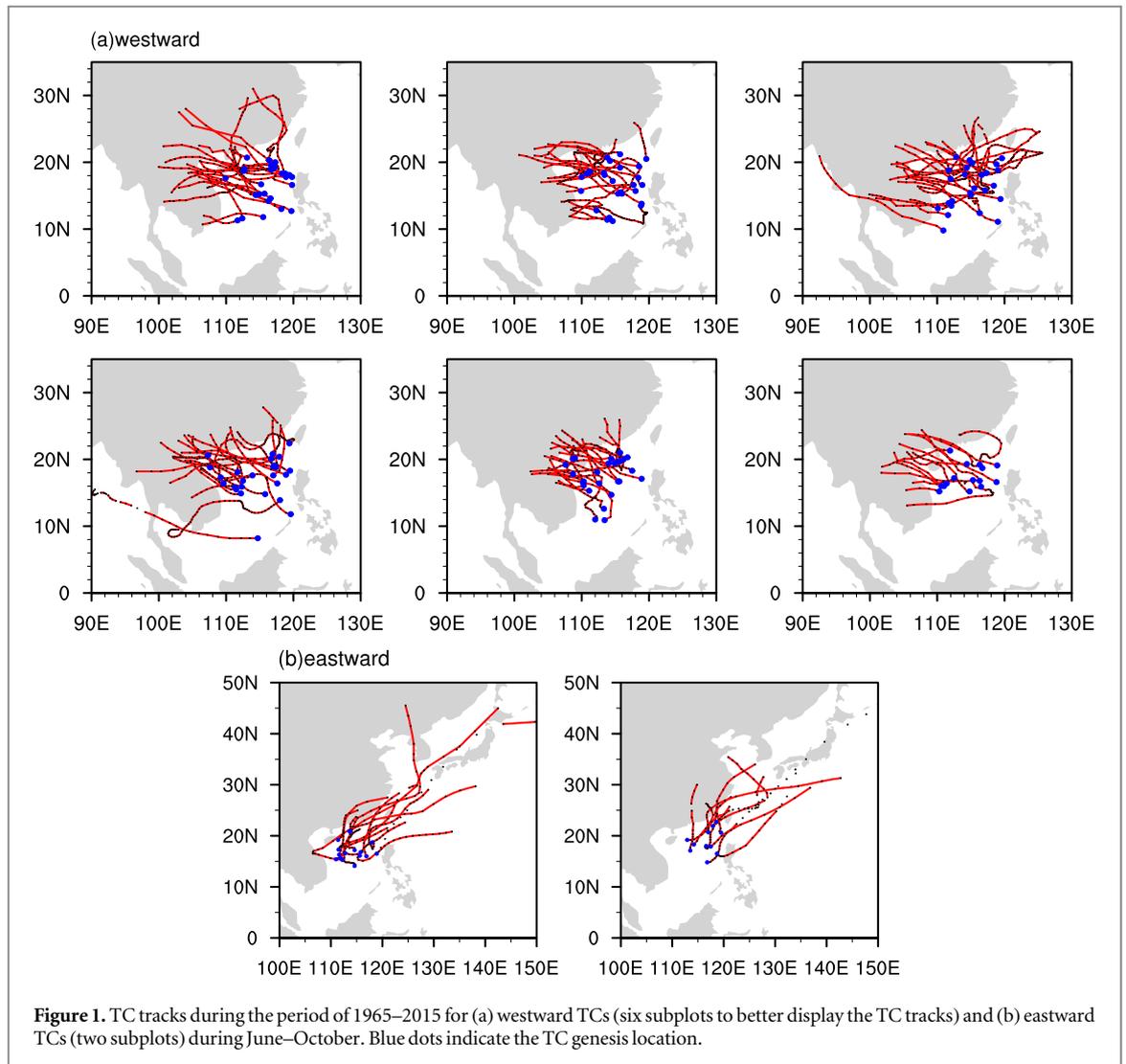
10–90 d filtered winds, which is obtained as 9 d running mean winds minus 91 d running mean winds. The synoptic component is defined as variations with periods less than 9 d and it is obtained as the difference of daily anomaly winds minus their 9 d running means.

Last, we construct the composite of the four components of steering flows from the four subsets of data as well as the total (with the TC signal removed) steering flows based on the respective values at the date of TC events for each TC category in the following analysis.

3. Effect of multi-scale steering flows on TC tracks

In this study, westward TCs are defined as the movement directed to the west of TC genesis location; whereas eastward TCs are defined as the movement directed to the east of TC genesis location. Note that we define westward and eastward-moving TCs mainly according to the location of TC weakening compared to the location of TC genesis. That is to say, for westward TCs, straight westward TCs are defined when the last location of TC is located within 10 degrees of north and south to the west of the TC genesis location. Northwest and southwest TCs are defined when the last location of TC is located outside of 10 degrees of north and south to the west of the TC genesis location. Those TC tracks are called as straight westward, northwestward, and southwestward movements, respectively. Eastward TCs are defined in a similar manner. Following this definition, figure 1 displays the westward and eastward-moving TCs during June–October from 1965 to 2015. In order to better display the TC tracks, the westward-moving TCs are shown in six subplots and the eastward-moving TCs are shown in two subplots because there are much more westward-moving TCs. Note that due to the absence of observations, several TC tracks are discontinuous. The westward-moving TCs (145 number) include straight westward, northwestward, and southwestward movements with the number of TCs being 36, 98, and 11, respectively. Among these, the northwestward movement occupies 68% of total westward-moving TCs over the SCS. Those westward-moving TCs tend to make landfall in the southern, southeastern China, and Vietnam coast (figure 1(a)). The eastward-moving TCs mainly include northeastward movement with the number of 27. Those eastward-moving TCs easily make landfall at the Philippines, Taiwan, Japan, Korea, or the southern China coast (figure 1(b)).
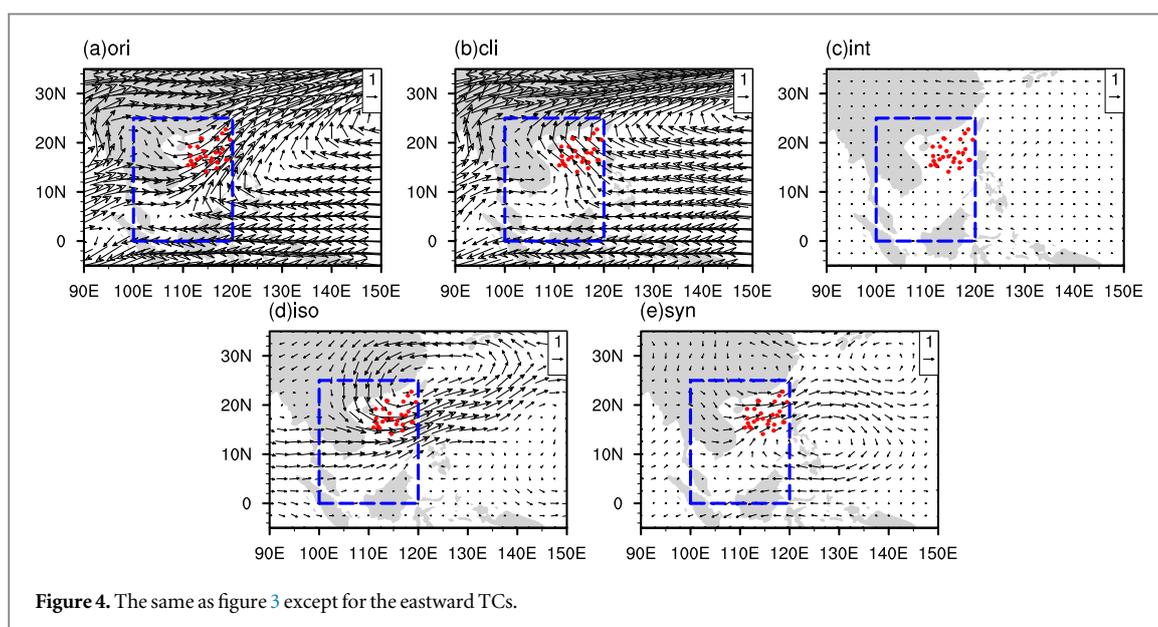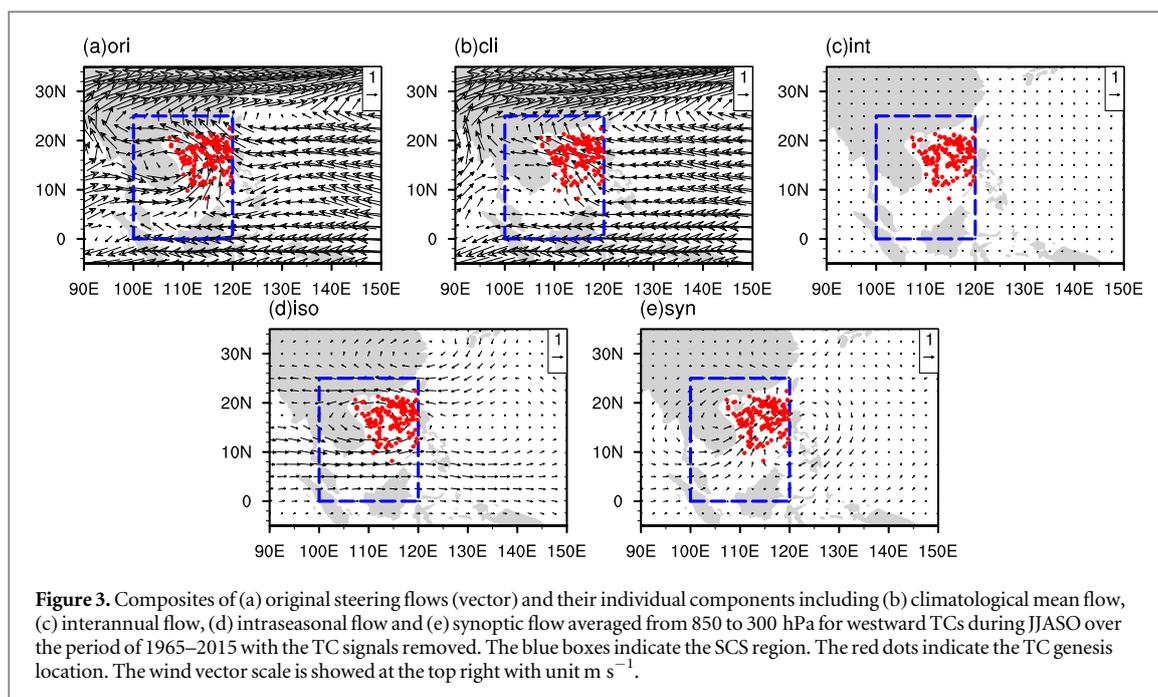
The TC tracks over the SCS display seasonal variability. During June to October, the TC geneses are mainly distributed in the northern SCS (north of 10° N) (figure 1). The westward TC tracks occur more in August and September, while eastward TC tracks

Figure 1. TC tracks during the period of 1965–2015 for (a) westward TCs (six subplots to better display the TC tracks) and (b) eastward TCs (two subplots) during June–October. Blue dots indicate the TC genesis location.

Figure 2. The seasonal evolution of numbers of westward (red) and eastward (green) TCs from June to October during the periods of 1965–2015.

appear more in June and July (figure 2). Note that in the present study, the westward-moving TC number is largest in August, while Yang *et al* (2015) showed that the westward-moving TC has a peak in September. This discrepancy may be due to the different analysis periods. Yang *et al* (2015) focused on the period 1970–2010 while this present study focuses on the period 1965–2015. Overall, the number of westward TCs

is much greater than the number of eastward TCs with the largest contribution from those generated in August.

In order to reveal the influence of different time scale steering flows on westward and eastward TC tracks over the SCS, firstly we conduct a qualitative analysis. We calculate the steering flows for the westward and eastward-moving TCs defined as the three-

Figure 3. Composites of (a) original steering flows (vector) and their individual components including (b) climatological mean flow, (c) interannual flow, (d) intraseasonal flow and (e) synoptic flow averaged from 850 to 300 hPa for westward TCs during JJASO over the period of 1965–2015 with the TC signals removed. The blue boxes indicate the SCS region. The red dots indicate the TC genesis location. The wind vector scale is showed at the top right with unit m s^{-1}.

Figure 4. The same as figure 3 except for the eastward TCs.

day average wind fields from 850 to 300 hPa after the TC genesis, as used in Yang *et al* (2015) and Ling *et al* (2016). Here, we mainly emphasize on the early stage of the lifecycle of the TC tracks. The whole TC tracks will be discussed in the quantitative analysis later. Figures 3 and 4 show five kinds of steering flows including total wind fields, climatological mean flows, interannual flows, intraseasonal, and synoptic flows for westward TCs and eastward TCs with the TC signals removed, respectively.

The westward-moving TCs mostly formed in the northeastern part of the total cyclonic circulation and then moved northwestward under the influence of southeasterlies in the northeast part of the total cyclonic circulation (figure 3(a)). The climatological mean flows are obviously southeasterlies in the northern

part of the SCS (figure 3(b)). This strong southeasterly background flows are similar to the total flows and guide the TCs to move northwestward. The interannual components of the winds (0.2 m s^{-1}) are much weaker than the total flows (3–5 m s^{-1}) (figure 3(c)). Thus, the contribution of the interannual flows can be neglected for westward TCs. The intraseasonal and synoptic components of flows display a cyclone similar to the total flows occupying nearly the whole SCS, but with a weaker magnitude (figures 3(d) and (e)). One difference between intraseasonal and synoptic flows is that most of TCs are under the influence of intraseasonal southeasterly winds, whereas the synoptic southwesterly winds control most of TC motions. This difference is related to the different horizontal structure of the anomalous cyclonic circulation in the

two time scales (figures 3(d) and (e)). The intraseasonal cyclonic circulation is zonal in an east-west direction, while the synoptic cyclonic circulation is slightly tilted in a northeast-southwest direction (figures 3(d) and (e)). Overall, the climatological mean flows may play a dominant role in the movement of westward TCs.

For the eastward-moving TCs, the total flows are characterized by the southwesterly winds and the intraseasonal component of winds has an obvious westerly wind over the SCS (figures 4(a) and (d)). Therefore, the total flows are mainly favorable to the northeastward movement of TCs, whereas the intraseasonal flows are characterized by westerly winds to steer TCs eastward (figures 4(a) and (d)). In addition, the intraseasonal component of winds displays a cyclone extending from the northern SCS to the subtropical western North Pacific with most of eastward TCs located in the southwestern part of the anomalous cyclone (figure 4(d)). The climatological mean flows display obvious southeasterly winds in the northern SCS, similar to westward TCs (figures 3(b) and 4(b)). As the days used in constructing the composite climatological mean winds are different for the westward and eastward-moving TCs, the obtained climatological mean flows may be different in two TC categories. This indicates that the climatological zonal mean flows have a negative contribution to zonal movement of eastward-moving TCs because it is unfavorable for zonal movement of those TCs. However, the climatological mean southerly flows have a positive contribution to steer eastward-moving TCs northward. The interannual components of flows are rather weak and their contribution to eastward-moving TC tracks is limited (figure 4(c)), which is similar to westward-moving TCs (figure 3(c)). The synoptic wind component displays an anticyclone over the SCS and the western North Pacific (figure 4(e)). Most of eastward TCs are located in the northwestern peripheral of the anticyclonic circulation, displaying a northeastward movement (figure 4(e)). Therefore, for the eastward-moving TCs, the intraseasonal and synoptic components have a dominant contribution to the movement of the TCs.

The above analyses are based on the composite according to the early lifetime of TC over the SCS similar to previous studies (Yang *et al* 2015, Ling *et al* 2016). In the following analysis, we estimate quantitatively the contributions of different components of zonal and meridional flows to westward and eastward TCs along the entire TC tracks at the interval of 24 h.

The composite zonal and meridional parts of steering flows are displayed in figure 5 for the different components over the SCS. A salient feature is that the zonal steering flow in westward TCs is dominated by the climatological mean wind. For eastward TCs, the intraseasonal and synoptic components have a major comparable contribution to the zonal steering flow with the secondary contribution from the
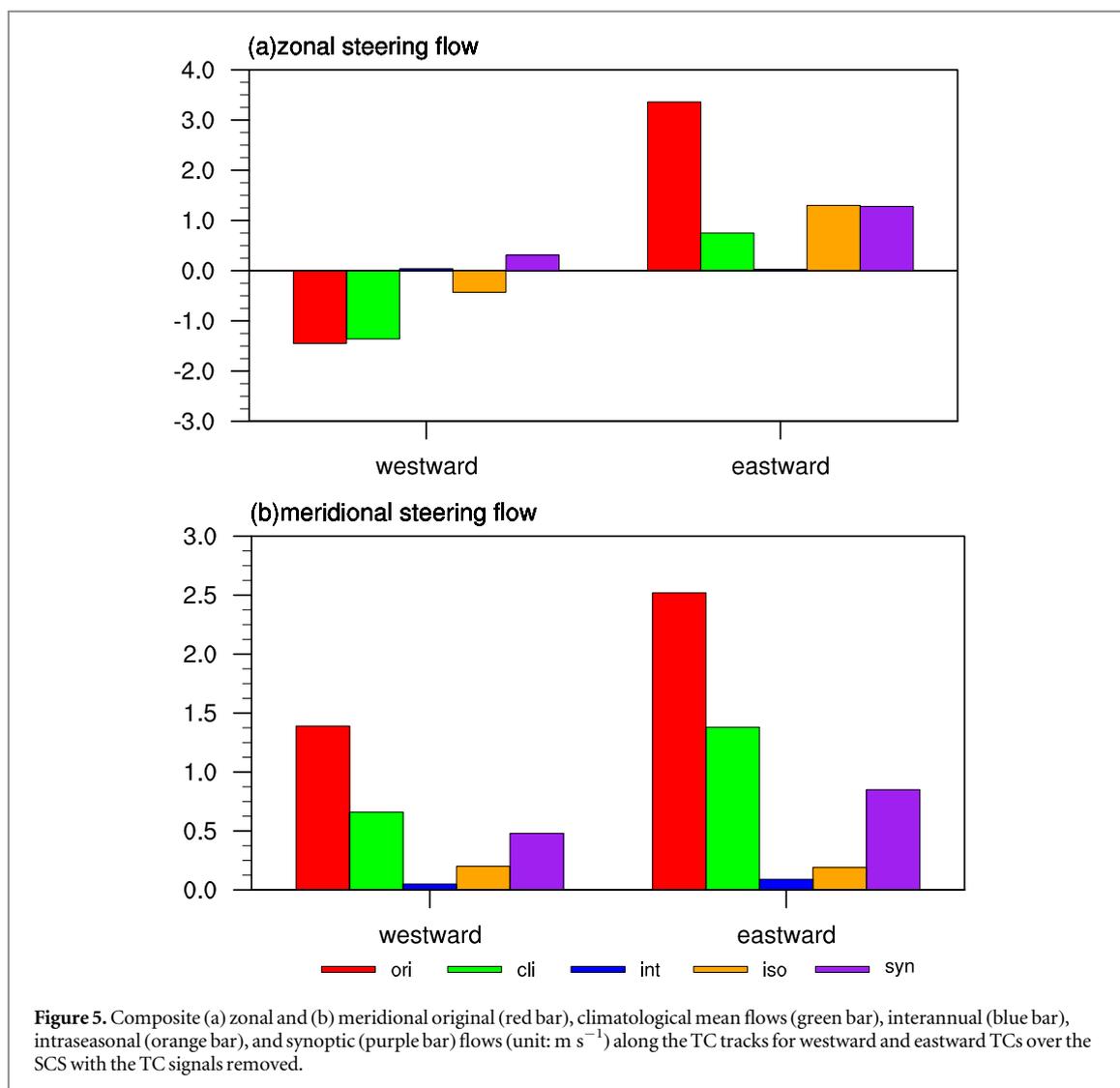
climatological mean wind (figure 5(a)). Those results are consistent with figures 3 and 4. Previous studies showed that in the TC genesis peak seasons of JJASO, the westward-moving TCs are controlled by climatological easterlies, and the eastward-moving TCs are associated with the intraseasonal components of flows (Yang *et al* 2015, Ling *et al* 2016). Our composite results pointed out that the synoptic components of flows also have a significant and considerable contribution to eastward-moving TCs.

For meridional movement of the westward TCs, the climatological mean winds have a major contribution to the southerly steering flows and the synoptic component of winds contributes secondly to the northward motion of westward TCs (figure 5(b)). Similarly, for meridional movement of the eastward TCs, the climatological mean winds contribute dominantly and the synoptic component of winds has a secondary contribution to the northward motion of eastward TCs (figure 5(b)). Our analysis is distinct from previous studies. Previous studies mainly made a qualitative description of the TC tracks with a focus on the TC genesis time (Yang *et al* 2015, Ling *et al* 2016). This present study has revealed the relative contributions of different time scale flows to TC tracks in the zonal and meridional directions with a quantitative diagnosis following the entire TC tracks.

4. Summary

Previous studies have examined the contributions of climatological background flows and intraseasonal components of winds to westward and eastward TCs in the zonal direction over the SCS (Yang *et al* 2015, Ling *et al* 2016). Our research extends the previous works in the following three aspects: (1) to separate the steering flows into four components, (2) to provide a quantitative estimation of the relative contributions of four components to westward and eastward TCs in the zonal and meridional directions over the SCS, and (3) to analyze the steering flows from the local and instantaneous perspective of TC position along the entire TC tracks as shown in figure 5.

In this study, we mainly focus on two types of TCs over the SCS including the westward and eastward TCs during the TC peak season of JJASO from 1965 to 2015. There are 145 westward TCs and 27 eastward TCs, respectively. Different from previous studies, we calculate the steering flows following the entire TC tracks, i.e. by averaging the winds from 850 to 300 hPa in a $7.5° \times 7.5°$ box around the TC center. This method can quantitatively estimate the relative contribution of different components to westward and eastward TC motions. The total steering flows are separated into four components: climatological mean flows, interannual, intraseasonal, and synoptic time scales.

Figure 5. Composite (a) zonal and (b) meridional original (red bar), climatological mean flows (green bar), interannual (blue bar), intraseasonal (orange bar), and synoptic (purple bar) flows (unit: m s^{-1}) along the TC tracks for westward and eastward TCs over the SCS with the TC signals removed.

The results of composite analysis show that for westward-moving TCs, the zonal steering flows are contributed dominantly by climatological background easterly winds. The meridional steering flows for westward-moving TCs are contributed dominantly by climatological background and synoptic southerly components. In comparison, for eastward-moving TCs, the zonal steering flows are contributed positively and equally by the intraseasonal and synoptic components. The climatological westerly winds have a secondary contribution to the eastward movement. The meridional steering flows for westward-moving and eastward-moving TCs are contributed dominantly by climatological mean southerly winds with a secondary contribution from the synoptic scale southerly flows. Our result provides a better understanding of the relative contributions of different time scale components of flows to the SCS TC movement. This may be of help to improve the prediction of the SCS TC tracks.

Data availability statement

The data that support the findings of this study are openly available.

The IBTrACS data file 'Basin.WP.ibtracs_all.v03r10.nc' was obtained from http://ncdc.noaa.gov/ibtracs/index.php. The NCEP–NCAR reanalysis data were obtained from http://esrl.noaa.gov/psd/.

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