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CHARACTERISTICS OF TROPICAL CYCLONES ACTIVITIES VARYING WITH ENVIRONMENTAL FIELDS OF MID- AND LOWER- LATITUDES

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ABSTRACT: Using historical data from 1951 to 1996, this paper makes statistical study and elaborate comparisons of tropical cyclone (TC) activity in middle and low latitudes. Some useful results have been achieved. For example, about 65% (90% in May) of the low-latitude tropical cyclones can move north into middle latitudes; TCs in middle latitudes move by about 60° more to the east and 10 km/h faster than in low latitudes; about 60% of the TCs dissipate in middle latitudes; the mean intensity is the maximum near the line dividing the middle and low latitude systems. The work paves the way for more work on revealing characteristics of interactions between middle and low latitude circulation systems.

Key words: tropical cyclones; mid-and low- latitude weather systems; interaction

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1 INTRODUCTION

Tropical cyclones (to be designated TC hereafter) act with significant latitudinal difference[1], some of which have been well documented. For instance, TC is a vortex system that forms and maintains with the support of some extent of Coriolis force, which is weak in areas near the equator (south of 4°N) and enables little TC activity[2]. As TC is mainly supplied by latent heating, higher SST is sure to be advantageous to the generation and development of TC; the summertime SST decreases with increasing latitude in the northwestern Pacific[3], being near 26.5°C around 32°N (considered the critical SST for TC formation[4]), which consists with the observation that TC does not generate over areas north of 32°N.

The TC intensity, however, does not decrease monotonously with latitude[4] and some rather stay alive long after landfall, with intensity increasing in some cases[2]. It cannot be satisfactorily explained from the SST effect. In addition, the so-called "β-effect" can account for the movement of TC traveling towards north (northwest) in the Northern Hemisphere[2, 5]. As the β value decreases with the poleward movement of TC, the "β-effect" reduces along with it, resulting in counter-clockwise rotation of the TC motion[6, 7] at decreased speed of movement[5, 7]. It is sharply inconsistent with mean features of clockwise rotation at increasing speed during TC's poleward movement. Tending to cause poleward-going TCs to accelerate and rotate clockwise, the "*g*-effect" has limited influence.

It is well-known that the TC activity is much subject to ambient field[2, 4]. Circulation regimes differ in nature for middle latitude and low latitude, where they are highly baroclinic and barotropic, respectively. Ambient fields varying with different latitudes may be a major reason for latitudinal difference of TC activity. How do TCs behave differently in ambient fields of

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middle and lower latitudes? It would be a question appropriate to raise and benefit from when one wants to probe interactions between TC and middle- and lower-latitudes circulation systems and improve the forecast of abrupt changes in TC and rainstorm intensity in middle latitudes.

2 ACCOUNT OF DATA USED

Subject to significant seasonal change in the middle- and lower-latitude circulation regimes, a given latitude may be controlled either by middle latitude systems or by lower latitude systems. It is therefore difficult to distinguish TC according to their activity features for geographic latitudes. Though there is no well-defined division of the two systems, baroclinity is the largest difference between them: the lower-latitude systems are barotropic while the middle latitude systems are baroclinic. It is usually the practice that the easterlies in the low latitudes are considered low-latitude circulation systems while the westerlies in the middle latitudes are taken as middle-latitude circulation systems. Consequently, the dividing line between the easterlies and westerlies is used to separate the middle-latitude circulation regimes from the low-latitude ones and the latitude corresponding to the line increases / decreases to indicate northward / southward movement of the systems in either latitudes. For the region of East Asia, the easterlies (westerlies) are usually south (north) of the ridge line of the subtropical high in the northwestern Pacific Ocean. It is therefore approximately accurate to take the ridge line as the dividing line between the easterlies and westerlies.

In this work, areas governed by middle-latitude systems are called "middle-latitude region" and areas by low-latitude systems "low-latitude region" (the same below). The mean ridge line of the subtropical high on a monthly basis from 1951 to 1996 as compiled by the China Meteorological Administration[8], the *Yearly Books on Typhoons* for 1951 – 1988[9] and the *Yearly Books on Tropical cyclones* for 1989 – 1996[10] are used.

3 SOURCE OF TC

As shown in statistical studies, the multi-year mean line dividing the two circulation systems lies on 18.1°N, being consistent with the characteristic[1] that TC tends to form in rapidly decreasing number with the increase of latitude north 18°N in the northwestern Pacific. It is noted that the dividing line for the two systems makes significant north-south oscillations, with significant marks of seasonal change (Fig.1); it is southernmost in February (12.3°N) but gradually moves northward with season till a jump in June, reaching the northernmost latitude (26.7°N) in August; it rapidly retreat southwards afterwards. Fig.1a gives a latitude-season

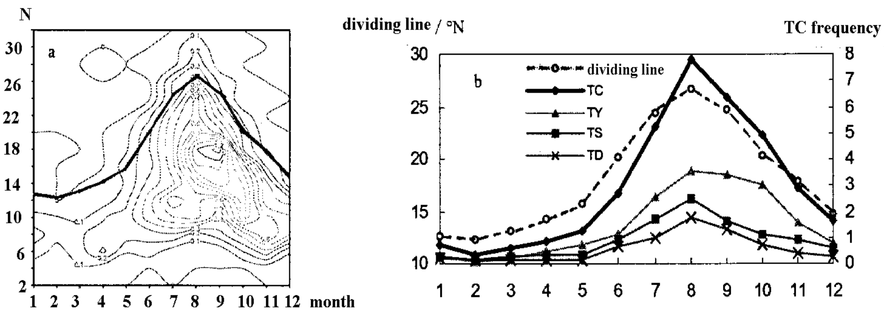

Fig.1 Latitudinal distribution (a) and seasonal variation (b) of border between middle and lower latitude circulation systems and TC genesis frequency. TD—tropical depression, TS—tropical storm and severe tropical storm, TY—typhoon. The first item from top in the legend inside the figure indicates the dividing line.

distribution for TC formation frequency. It is seen that the monthly frequency for the middle latitudes tends to decrease rapidly with latitude and the axis of high frequency is generally consistent with the seasonal change of the dividing line and always 8 – 10 latitudes south of it. With the northward movement of the line, the TC generates more frequently over a wider range of latitudes in places where there is higher incidence. Fig.1b gives a clear picture of seasonal change of TC formation frequency with southward (northward) advancement of middle-latitude systems, which shows high consistence for all levels of TC intensity (i.e. the maximum intensity I_{m} over the entire life cycle).

It is understood from Fig.1a that the TC shows large difference (Fig.2) in the number of genesis between middle and lower latitudes, which accounts for 95% and 5% of the total, respectively, as indicated in the calculation.

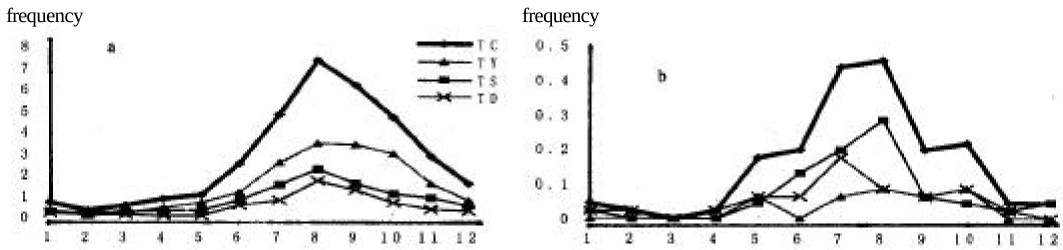

Fig.2 Seasonal variation of TC genesis frequency in lower latitudes (a) and middle latitudes (b). The numerals on the ordinates of both panels indicate the genesis frequency.

The north-south swing of the dividing line between middle and lower latitudes systems is also marked by significant interannual oscilation (shown as the bold, solid line in Fig.3a), locating the northernmost in 1961 (20.1°N) but the southernmost in 1968 (14.8°N). As shown in Fig.3a, the TC mainly generates within 10 latitudes south of the dividing line and in a frequency that decreases rapidly over the middle latitudes. There is much more genesis of TC in the low latitudes than in the middle latitudes (Fig.3b & 3c), which is in significant positive and negative

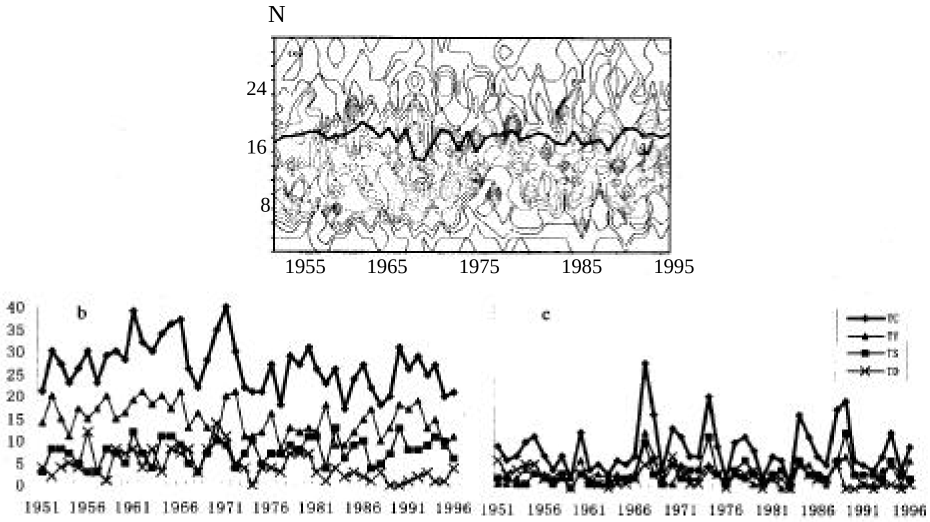

Fig.3 Interannual variation of TC genesis frequency for all latitudes (a), lower latitudes (b) and middle latitudes (c). The numerals on the ordinates of the panel "b" indicate the genesis frequency.

correlation with the interannual variation of the dividing line (surpassing the confidence level of 0.01).

As shown in statistic results, the TC originates on average around 14.0°N (the mean latitude where the TC originates from) in the western Pacific with seasonal and interannual variations having consistent tendency with that of the dividing line and the interval generally between 4 and 5 latitudes (Fig.4). Mean source latitudes differ with the intensity of TC (I_m) —the stronger a TC is, the more southward the mean source latitude will be. With basically consistent tendency in seasonal variation (Fig.4a), a tropical depression (TD) originates from 15.8°N[10], tropical storm and severe tropical storm (TS)[10] from 14.9°N[10], and typhoon (TY) from 12.7°N[10].

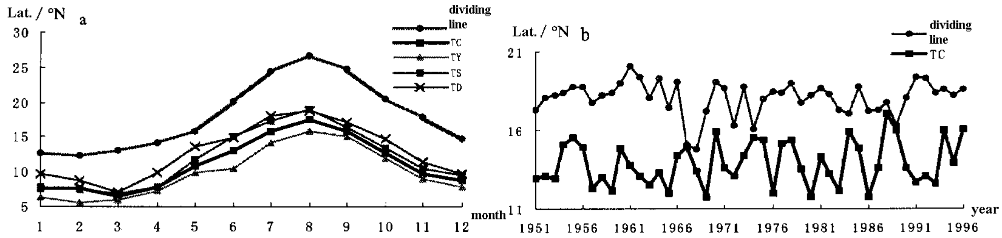

Fig.4 Seasonal variation (a) and interannual variation (b) of mean location of source of TC. The first item in the legend inside panels indicates the dividing line.

4 MOVING DIRECTION AND SPEED

The northwestern Pacific TC moves to NNW (at an azimuth of 154.4°①) at an average speed of 21.7 km/h, showing non-linear relationship with the intensity —a TC moves most westward on the TY level with a mean moving azimuth of 150°, most slowly on the TD level with a mean speed of 20.8 km/h and most eastward (158.4°) and fastest (22.8 km/h). In low-latitude regions south of 18°N, the average year mean location of the dividing line, most of the TCs move WNW but they usually travel NNW – ENE in areas north of the latitude. It is associated with the easterlies in low latitudes and westerlies in the middle latitudes.

Fig.5 gives the latitude-season distribution of the speed and direction of TC movement. The bold solid line in the figure is the dividing line between the middle and low latitude systems. It is seen that TC moves slower, usually less than 20 km/h and does not vary much with latitude in low-latitude areas while it moves much faster and increases significantly with latitude in the middle latitudes, especially over areas 5 latitudes away from the dividing line, with the isolines going consistently with that the dividing line (Fig.5a). For TCs around the dividing line, however, most of them move towards NNW (the azimuth being about 157.5°); TCs in the low-latitude areas move towards WNW-NNW and does not change much with latitude, which is in sharp contrast to those in the middle latitudes, which move faster with the increase of latitude and rotate clockwise towards ENE till it is aligning consistently with that of the isolines (Fig.5b).

As shown in statistical study, a low-latitude TC moves towards NW at an average speed of 18.5 km/h (an azimuth of 134.8°) while a middle-latitude TC moves towards NE at an average speed of 28.1 km/h (193.0°). Fig.6 shows the seasonal changes in mean speed and direction of TC movement in both latitudes. It is clear that the mean movement speed is the maximum in January (19.8 km/h) and minimum in April (15.6 km/h) in low latitudes; it is maximum in September (33.3 km/h) but minimum in March (21.3 km/h) in areas north of it. The difference in

①The movement is 0° if it is southward, 90° if westward, 180° if northward or 270° if eastward.

moving speed is the smallest in February (2.5 km/h) but largest in September (15.4 km/h) in both latitudes (Fig.6a). As shown in Fig.6b, low-latitude TCs move at a monthly mean azimuth of about 135°, being the largest in August (141.7°) but smallest in March (121.4°), in middle latitudes they move at about 180°, being the largest in March (217.8°) but smallest in July (176.6°).

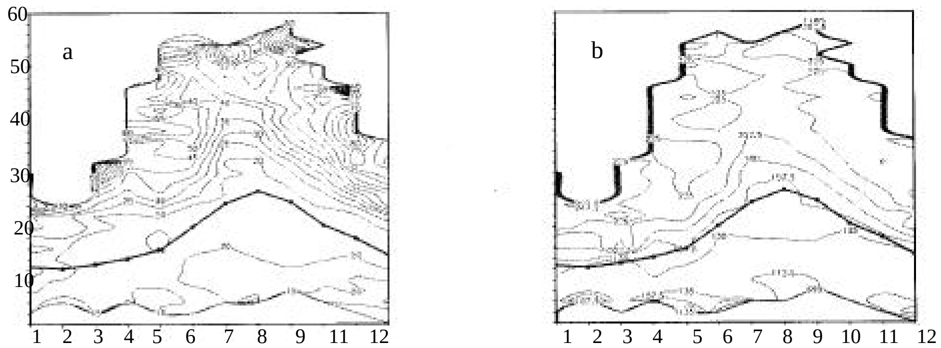

Fig.5 Latitudinal-seasonal distribution of mean TC moving speed (a) and direction (b).

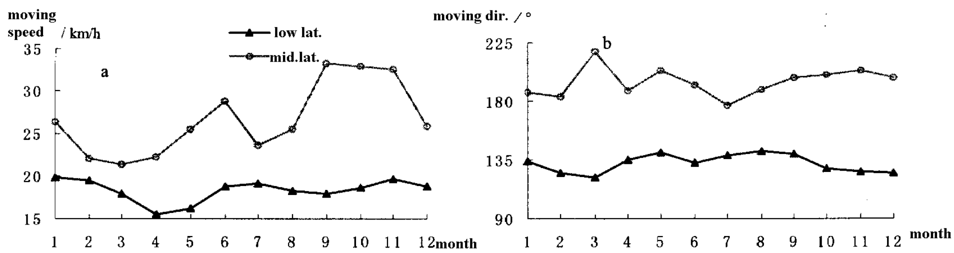

Fig.6 Seasonal variation of mean TC moving speed (a) and direction (b)in middle and lower latitudes. The items in the legend of the left panel indicate low and middle latitudes, respectively, form top to bottom.

Similar features are found in the interannual variation. Fig.7 gives the latitudinal-interannual distribution of mean moving speed and direction, in which the bold solid line divides low-latitude systems from the middle-latitude counterparts. It is seen that low-latitude TCs mostly move

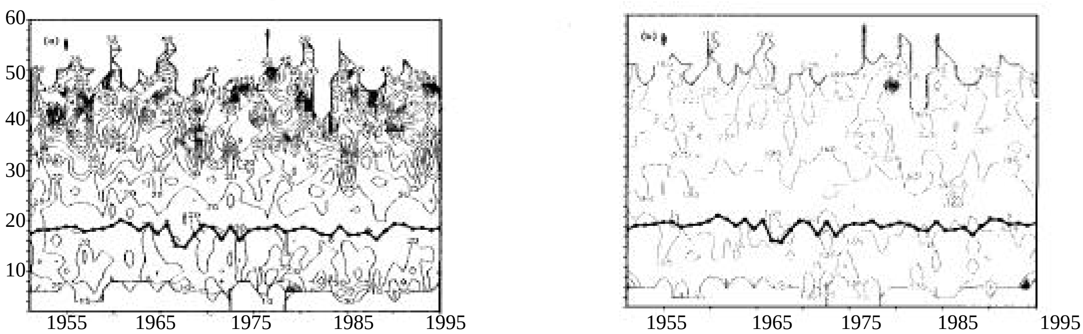

Fig.7 Latitudinal-interannual distribution of mean TC moving speed (a) and direction (b).

WNW with the azimuth seldom over 135° and at steady speeds, usually around 20 km/h; middle-latitude TCs normally move towards from NNW to ENE and at higher speeds, especially in areas 5 latitudes north of the dividing line, which increase dramatically with the increase of latitude.

The middle-latitude TCs have an mean speed of 28 km/h or so, about 10 km/h higher than the low-latitude ones do; the azimuth of movement is around 190°, about 60° more eastward than the low-latitude counterparts are. Fig.8 is the interannual variation of mean TC moving speed and azimuth in both latitudes. It is obvious that the TC has a small annual difference of mean moving speed, about 7 km/h, with the maximum in 1952 (22.9 km/h) and minimum in 1979 (15.9 km/h), in low latitudes; the annual difference is larger in middle latitudes (16.2 km/h, see Fig.8a), with the maximum in 1962 (37.0 km/h) and the minimum in 1967 (20.8 km/h). As for the moving direction of TC in both latitudes, the interannual amplitude is quite small with the azimuth of movement varying between 135° and 180°.

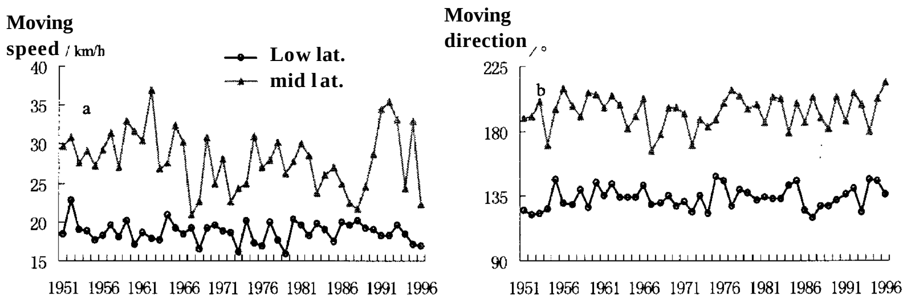

Fig.8 Interannual variation of mean TC moving speed (a) and direction (b)in middle and lower latitudes. The items in the legend of the left panel indicate low and middle latitudes, respectively, form top to bottom.

5 FREQUENCY OF NORTHWARD ADVANCEMENT

As stated above, few TCs are directly generated over the middle latitudes while most of those forming over low latitudes are moving poleward. Then, how many TCs will move northward into the middle latitudes? It is important for the study of the interactions between the TC and middle-latitude systems. It is noted that the peak latitudes in which northward-going TCs are usually near the average year position, the line dividing weather systems in both latitudes. As shown in statistical studies, about 65% of the TCs forming over low latitudes (about 20 annually) can cross the average year location of the dividing line to move into the middle latitudes[1]. It is obvious that the TC frequency migrating into the region are subject to seasonal and interannual variation of the dividing line. Fig.9 gives the latitudinal-seasonal distribution of the TC northward advancement[1], in which the bold line divides systems in the two latitudes. It is then clear that the seasonal change of the northward advancement rate is of bimodal distribution and peaks appear in May and September. The TC goes across the dividing line to head north in the middle latitudes by the smallest rate in February (less than 30%), the largest rate in May (more than 90%). The rate is about 80% in April and June and between 50% and 60% in the remaining months (Fig.9a). With the intensity (I_m) varying, the northward advancement rate of TC is similar in the seasonal distribution pattern (Fig.9b – 9d) but substantially differs if the dividing line crossing is accounted for —the rate is over 90% from April to June but around 70% in the remaining months (except in February when it is 40%), for TY (Fig.9b); it is over 50% in January, May, June and July, being the maximum in May (around 80%) for TS (Fig.9d); it is 90% in May but less than or close to 50% in other months, especially from August to December when it is

20% – 30%.

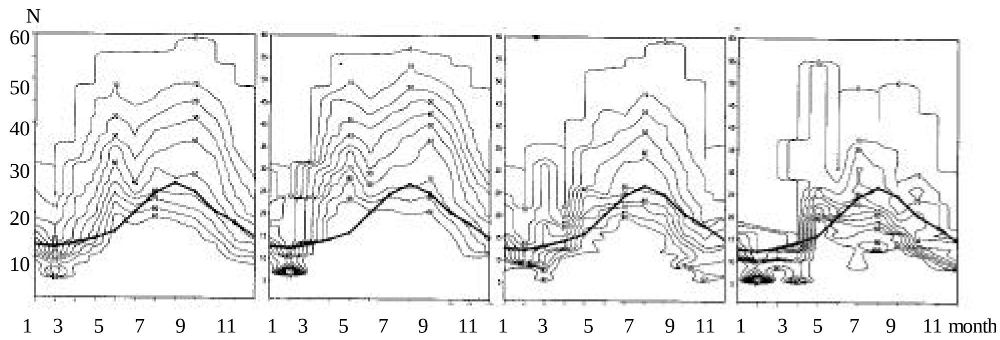

Fig.9 Latitudinal-seasonal distribution of northward moving rate of TC(a), TY(b), TS(c) and TD(d).

6 PLACE OF ACTIVITY

Based on the location of TC every 6 hours (a point) is provided in the *Yearly Book on Typhoons*[9] and *Yearly Book on Tropical Cyclones*[10], the number of these points over the same intervals can be used to describe how active the TC[1] is. As shown in statistical study, the number is of unimodal distribution with latitude, with the peaks (belts of most active TC) usually 2 latitudes south of the average mean location of the dividing line[1].

Fig.10 gives the latitudinal-seasonal distribution of degree with which the TC is active. The

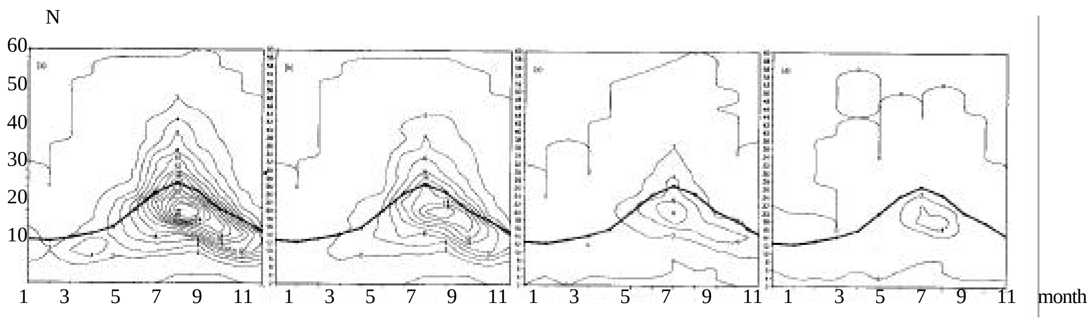

Fig.10 Same as Fig.9 but for degree of TC activity (number of points with occurrence).

bold, solid line divides the weather systems for both latitudes. It is obvious that the axis of most active TCs aligns consistently with the dividing line, which is about 2 latitudes south of it. The activity degree differs with TCs of different intensity (*I*). Usually, the higher the intensity level, the more active the TC will be. Patterns of latitudinal-seasonal distribution are also found that are similar to the one described above. As shown in the statistics, the TC is more active in low latitudes than in the middle latitudes, as about 2/3 of the TC number occur in the former. The weaker the intensity, the larger the ratio will be —it 64.2% for TY, 68.3% for TS and 75% for TD.

In addition, the degree of active TC peaks also increases with the northward movement of the dividing line as indicated in Fig.10. One can know how the TC differs in the activity degree due to difference in latitudes. Fig.11 further gives how it varies in both latitudes.

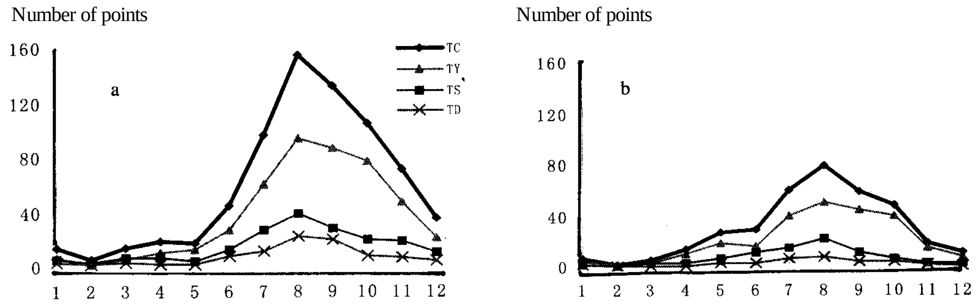

Fig.11 Latitudinal-seasonal variation of the degree of TC activity (number of points with occurrence) in lower latitude (a) and middle latitude (b). The numerals on the ordinate indicate the number of appearance points.

7 INTENSITY

The mean intensity of TC is in unimodal distribution with latitude with peaks locating about 7 latitudes north of the line dividing the middle and lower latitudes weather systems. Fig.12 gives the latitudinal-seasonal variation of mean intensity of TC in which the bold solid line is the

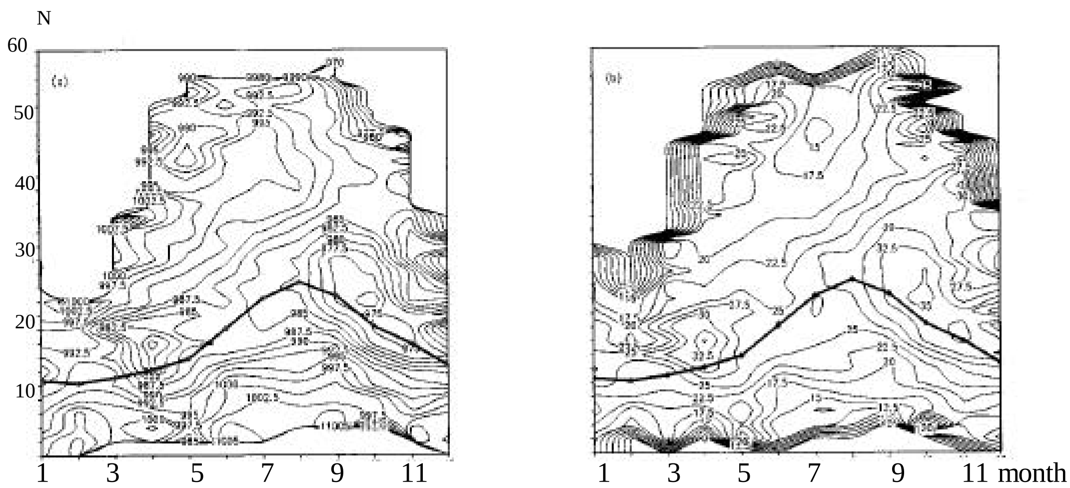

Fig.12 Latitudinal-seasonal distribution of mean TC intensity of pressure (a) and wind speed (b).

dividing line. It is obvious that TC is stronger around the line with the strongest locating near 18°N in April and 24°N in October (pressure is 975 hPa and wind speed is 32.5 m/s) and the axis of strong centers going parallel with the dividing line, about 2 to 8 latitudes north of the line.

As shown in statistical results, the mean intensity does not differ much between the two latitudes, though the TC is a little stronger in the middle latitudes, with mean pressure and wind speed of 985.2 hPa and 27.1 m/s, respectively, in contrast to 987.9 hPa and 26.0 m/s. Some differences are found from month to month (Fig.13): except for July and August, the TC is stronger on average in the middle latitudes than in the lower latitudes and biggest difference is seen in October (7.5 hPa and about 5 m/s in the difference of pressure and wind speed, respectively). The seasonal variations are basically consistent for both latitudes and so are the interannual variations (figure omitted).

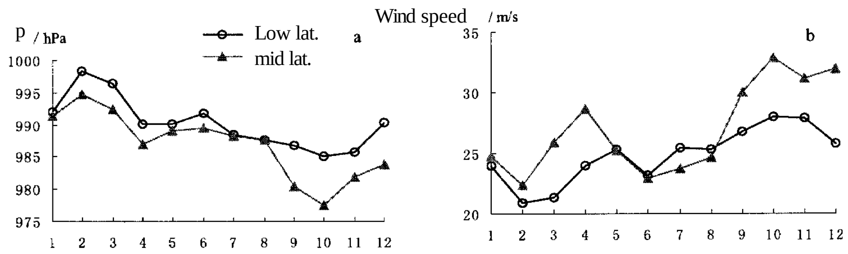

Fig.13 Seasonal variation of mean TC intensity of central minimum pressure (a) and maximum wind speed (b) near the eye in middle and lower latitudes. The legend items, from top down, in the left panel stand for low and middle latitudes, respectively.

8 TRANSFORMATION

The lowest latitude at which the northwestern Pacific TC transforms is 16.0°N (recorded with Typhoon No.7101 at 14:00 January 8, 1971). Being about 2 latitudes from the average mean location of the line dividing the weather systems in both latitudes[1], the transformation takes place in the middle latitudes because the dividing line is near 10° N.

Fig.14a gives the latitudinal-seasonal distribution of transformed TC frequency where the

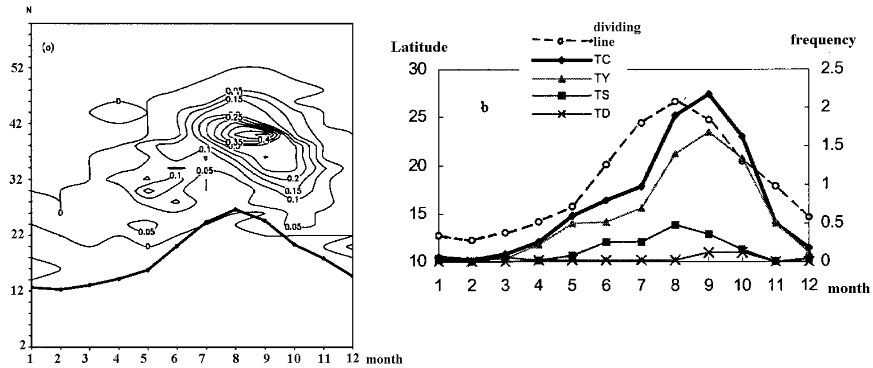

Fig.14 Seasonal variation (a) and latitudinal distribution (b) of frequency of TC transformation. The top item in the legend is for the dividing line, the left ordinate is for latitude and right one for frequency of transformation.

bold, solid line stands for the dividing line. It is seen that the transformation all occurs in the middle latitudes within 25 latitudes off either side of the line, suggesting direction links between transformed TC and middle-latitude systems. In addition, the peak axis of the transformation frequency goes consistently with the dividing line, which is about 10 latitudes from the line. The peak values of transformed TC frequency are increasing with the northward advancement of the line. Then, the frequency of transformed TC also increases. As shown in Fig.14b, the seasonal change tends to go consistently with the dividing line. Furthermore, about 78% of the transformed TC are on the TY level (I_m), though not much difference is found between individual levels of TC in the seasonal variation of transformation frequency.

The "mean transformation location" of TC (mean latitude at which TC transforms) can be used to describe the relationship between the region of TC transformation and north-south advancement of middle-latitude systems. As shown in the statistics, the TC transforms at 35.4°N on average over the western Pacific, with the TY at 36.1°N, the northernmost, TS at 33.3°N and TD at 31.4°N, the southernmost, when the transformation begins.

On average, the seasonal variation of TC transformation goes consistently with the advancement trend of the line dividing the weather systems in the middle and lower latitudes, being separated by a distance of about 10 latitudes (Fig.15).

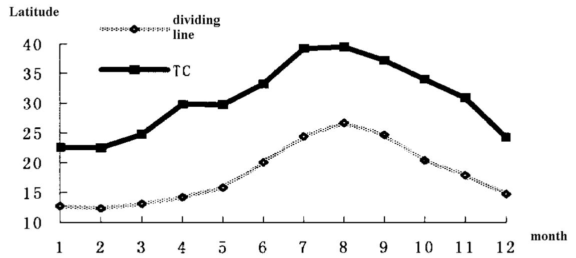

Fig.15 Seasonal distribution of mean location of TC transformation. The top item in the legend is for the dividing line.

9 DISSIPATION

The TC dissipates on average at the southernmost latitude of 4.5°N and the northernmost latitude of 58.0°N, in the northwestern Pacific, over an extensive area. The latitudinal distribution of TC dissipation frequency is of bimodal pattern with the principal peak being about 5 latitudes north of the average mean location of the line[1]. It is known from the latitudinal-seasonal change of the dissipation frequency (Fig.16) that the axis of high dissipation frequency has a consistent variation tendency with the dividing line, particularly so in the second half of the year but it is about 2 to 5 latitudes south of the line.

From Fig.16, we also learn that TC dissipates over a larger area with the northward advancement of the dividing line. The area moves northward as a whole and is much larger in the middle latitudes than in the lower ones. As shown in the statistics, there are on average 14 TCs that dissipate over low latitudes, which is about 40% of the total. In other words, 60% of them die

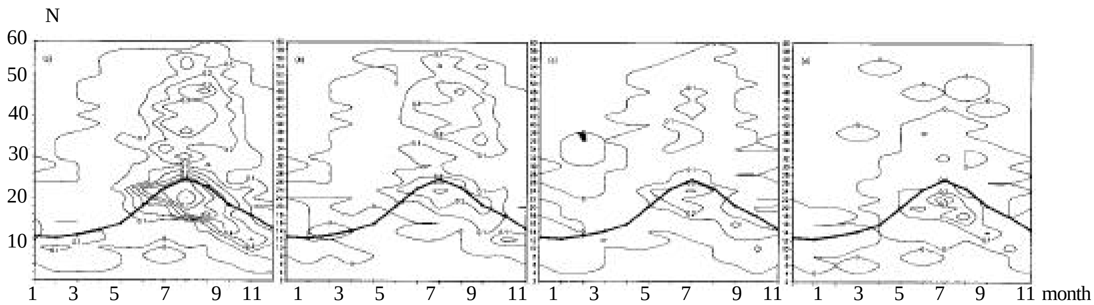

Fig.16 Latitudinal-seasonal distribution of frequency of TC dissipation (border dividing circulation systems in middle and lower latitudes is designated by the thick solid line).

out in the middle latitudes. The ratio differs with individual intensity (I_m) —about 75% of TY, 51% of TS and 34% of TD come to the end of their life cycle. Fig.17 gives the monthly distribution of the dissipation frequency of TC in both latitudes.

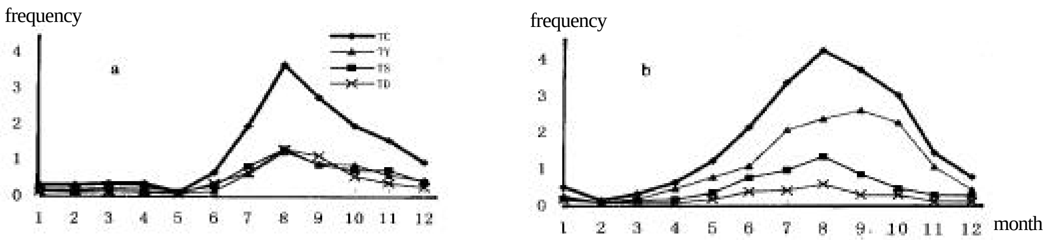

Fig.17 Seasonal variation of TC dissipation frequency in lower latitudes (a) and middle latitudes (b).

As shown in the statistics, the northwestern Pacific TC dissipates near 28.1°N on average, about 10 latitudes north of the average mean location of the dividing line. The mean latitude of dissipation is the smallest for TD (21.2°N), highest for TY (32.6°N) and somewhere in between for TS (25.2°N). The seasonal change has the following characteristics (Fig.18). It is about 1 latitude south of the dividing line in February. The distance gradually increases with the season and reaches the maximum in May (about 16 latitudes) but decreases and maintains a distance between 5 and 7 latitudes. The trend keeps on in November – January till the distance reduces and stays around 2 latitudes. For the latitude at which the TC dissipates, February is the smallest, about 11°N, and May, August and September are the largest, about 32°N, generally in consistence with the dividing line, except for May. Additionally, Fig.18 also shows that TY has the northernmost location of dissipation on average, which always stays in the middle latitude with the change of seasons while TD and TS vary substantially and can be seen in low latitudes.

It is interesting to note that the mean location of TC transformation happens in regions north

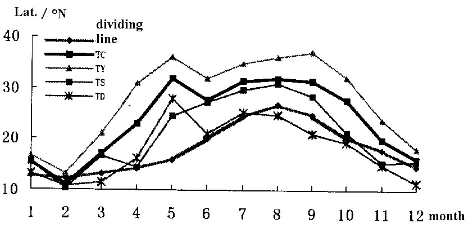

Fig.18 Seasonal variation of mean location of TC dissipation.

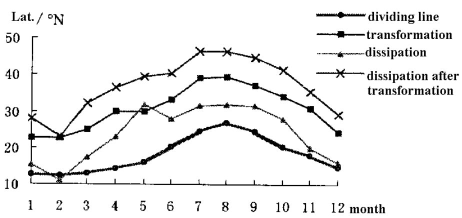

Fig.19 Seasonal variation of mean location of transformed TC dissipation.

of the average one, except for May. We thus study the mean location of TC dissipation for the cause. The result shows that the mean location of dissipation for transformed TC is 42.6°N, or, specifically, 43.2°N for TY, 40.0°N for TS and 38.3°N for TD. Fig.19 gives the seasonal change of the mean dissipation location of transformed TC together with the dividing line, the mean location of transformation and mean location of dissipation. It is then seen that the seasonal trend of mean location of transformed TC is also consistent with the dividing line, about 10 latitudes north of the mean location of dissipation. February is the month with stationary transformed TC when the mean location of dissipation is comparable with the mean location of transformation.

10 CONCLUDING REMARKS

a. For the northwestern Pacific TC, it originates on average about 4 to 5 latitudes south of the line dividing weather systems in the middle and low latitudes, with the source of high generation about 8 to 10 latitudes south of the line. The frequency of TC formation rapidly decreases with latitude in the middle latitudes, though about 5% of the total are generated there.

b. In the low latitudes, the TC moves at smaller speed (the fastest being about 20 km/h) and does not change much with latitude; in the middle latitudes, however, the moving speed increases with latitude (much faster in areas 5 latitudes north of the dividing line). The mean moving speed of middle-latitude TC is more than 10 km/h higher than that of low-latitude one while the moving angle is 60° more eastward.

c. On average, about 65% of the low-latitude TC will move northward into the middle latitude. The rate of northward advancement varies much with the seasonal oscillation of the dividing line, with the smallest in February (only 30%) but the largest in May (about 90%), increasing with the strength of TC.

d. The TC is mainly active in low latitudes (the number of appearance points is about twice as many as that in middle latitudes), with the peaks being about 2 latitudes south of the line dividing the weather systems in both latitudes.

e. The TC is relatively stronger near the line and the peaks are about 2 – 8 latitudes north of the dividing line.

f. The transformation of TC happens in the middle-latitude region within 25 latitudes of the dividing line with peaks staying about 10 latitudes from the line.

g. The TC can dissipate as far south as at 4.5°N. Although the dissipation peaks are about 2 – 5 latitudes south of the dividing line, about 60% of the TC come to the end of their life cycle in the middle latitudes and the stronger it is (I_m), the higher the ratio of dissipation in the middle latitudes. The mean location of TC dissipation is about 10 latitudes north of the dividing line.

Isolating the low-latitude weather systems from the middle-latitude ones in terms of the effect on TC activity is useful for the study of its physical mechanism. More work needs to be done.

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