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CALCULATION OF BASIC ENVIRONMENTAL GEOSTROPHIC FLOW AND STATISTICAL STUDY ON TC TRACK AND ITS DEVIATION

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ABSTRACT: Using the T63L16 analysis data with the resolution of 1.875×1.875 degree of latitude and longitude obtained from National Meteorological Center (NMC) and the real central position information of tropical cyclone (referred to as TC hereafter) numbered by NMC, the basic environmental geostrophic flow at 126 time levels of 25 TCs in 1996 are calculated. The vertical distribution features of the flows are analyzed. Besides, the deviation of real TC tracks from the flows (referred as steering deviation hereafter, namely, the deviation between the real central position of TC and the position calculated according to the steering flow) is also investigated. The result shows that the steering deviation would be different if the domain used to calculate the steering flow is different. The present paper obtains the optimum domain size to calculate the steering flow. It is found that the steering deviation is related to the velocity of steering flow and the initial latitude and intensity of TC itself, and that TC motion has relationship with the vertical shear structure of environmental geostrophic flow. The result also shows that the optimum steering flow is the deep-layer averaged basic flow from 1000 hPa to 200 hPa. Having the knowledge of these principle and features would help make accurate forecast of TC motion.

Key words: environmental geostrophic basic flow; steering deviation; TC motion

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1 INTRODUCTION

As we know, TC movement can be affected by many elements, such as environmental steering flow, interaction among different motion scale systems, inner structure and structure changes of TC itself, beta effect and underlying surface conditions (including SST, coastal lines, islands and topography) etc. All of the above factors can exert different impact on TC motion[1, 2]. However, generally speaking, environmental steering flow is the main factor affecting the TC motion.

Studies on TC (referred as TC hereafter) mainly focus on the dynamic theory and forecast techniques for TC motion. Either in theoretic study or operational forecast, TC motion has long been described with large-scale weather systems around it. As a result, the concept of steering flow appears and prompts forecast on TC motion. Generally, two basic methods are adopted to determine it: (1) In a specific environment around a TC, the averaged real wind field on a certain level or weighted average of several levels is used to determine the steering flow; (2) Assuming that the basic flow satisfies the geostrophic approximation law, the geostrophic wind at a certain level or deep-layer weighted average of several levels calculated from the geopotential height gradient is taken as the steering flow of the TC motion. Chan et al[3]. used the wind averaged in a circular ring with the inner and outer radius of 5 and 7 lat./long. degrees away from the TC center as the envi-

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ronmental steering flow of the TC. In their investigation of TCs in different ocean basins with different intensities and intensity changes and by different moving direction and moving speed, they found that for the above different types, the real tracks of TCs have small deviation from the environmental basic flow in the middle troposphere. Dong et al[4]. once calculated and analyzed the relation between Atlantic TC motion and the environmental geostrophic basic flows on 10 mandatory levels from 1000 hPa to 100 hPa and obtained similar results. Specifically, the steering effect of the environmental geostrophic basic flow in the middle troposphere on TC motion is the best one. Besides, the optimum steering level would be a little bit higher with the increase of TC intensity. The differences between TC real track and environmental geostrophic basic flow at the bottom and upper levels of troposphere are quite large.

Besides, there are also many different patterns of multi-level weighted average including weighted average by pressure[3, 4], arithmatical average[4] and pure empirical average. Although different schemes adopt different steering levels or different ways of weighted average, it is generally agreed that the basic flows at middle-tropospheric levels such as 500, 600 and 700 hPa or multi-level weighted average can have better steering effects on TC motion[3, 4]. It is found[5] that on average, the speed of westward moving TCs is 3.4 m/s faster than that of the environmental geostrophic steering flow. The northward moving TCs are faster by 0.9 m/s. These results show that the movement of TC has a westward moving component apart from the effect of the steering flow. These kinds of average results can help us get further knowledge on the steering mechanisms of environmental basic flow.

However, just as what is put forward by Dong[4], although the averaged environmental steering flow is closer to the mean motion of TC, the averaged result may be significantly different from certain case condition. The reasons for this kind of difference are multiply induced. First, the TC separated from its environment field is not as simple and clear as that described from theoretic point of view. Secondly, TC motion is not determined purely by steering flow. Besides, lack of data inside and around a TC also makes it difficult to locate the steering flow.

In summary, the environmental steering flow is a main, but not the only, factor that affects TC motion. Thus, there is difference between real motion of TC and steering flow. Sometimes, the difference may be very large.

Previous studies on steering flow mainly focus on the choice of optimum steering level and causes for TC deviation from the steering flow. However, infrequent effort has been made on the steering deviation itself. Grasping the steering deviation law would definitely help to improve the operational forecast of TC motion.

In this paper, the distribution law of steering deviation is investigated through analyzing the steering deviation of 126 time levels. The vertical distribution feature of environmental basic flow and the distribution characteristics of the deviation of TC real motion from the environmental steering flow under different environmental steering conditions and different initial latitudinal positions of TCs are obtained.

2 DATA AND METHODOLOGY

2.1 *Data sources and processing*

In this paper, the global analysis data T64L16 with the resolution of 1.875°× 1.875° provided by the National Meteorological Center of China as well as the real central position of TCs (in this paper, TC represents the tropical cyclone with the near-center maximum wind force equal to or beyond Force 8 on the Beaufort scale, including tropical storm, severe tropical storm and typhoon.

Tropical storm stands for TCs with about Force 8-11 on the Beaufort scale of near-center maximum wind force, including tropical storm and severe tropical storm. Typhoon only refers to TC with the near center maximum wind equal to or beyond Force 12 on the Beaufort scale, which are numbered by Central Meteorological Observatory. 25 TCs with a total of 126 time levels in 1996 are adopted here to calculate the environmental geostrophic basic flow on 10 mandatory levels (100,150, 200, 250, 300, 400, 500, 700, 850, 1000 hPa), based on which, deep layer environmental geostrophic basic flow is obtained through weighted average by pressure and weighted log average by pressure.

Generally, the central position of TC does not always coincide with the grid point of T63L16, which brings some difficulties to the calculation of environmental geostrophic basic flow. Consequently, nine grid points that are the closest to the TC center are chosen first, whose latitudinal and longitudinal coordinates are $x_{p-1} < x_p < x_{p+1}$ and $y_{p-1} < y_p < y_{p+1}$ (in which, (x_p , y_p) is the grid point nearest to the TC center), then interpolation is performed by dualistic three-point formula as follow:

$$Z(x,y) = \sum_{i=p-1}^{p+1} \sum_{j=q-1}^{q+1} \left(\prod_{\substack{k=p-1 \\ k \neq i}}^{p+1} \frac{x - x_k}{x_i - x_k} \right) \left(\prod_{\substack{l=q-1 \\ l \neq j}}^{q+1} \frac{y - y_l}{y_j - y_l} \right) z \tag{1}$$

Besides, the same interpolation is also performed in certain extent around the TC to make the TC center coincide with a grid point. In this way, a new latitude-longitude mesh of 1.875°× 1.875° is obtained.

2.2 *The calculation of environmental geostrophic basic flow*

Concerning the calculation of environmental geostrophic basic flow, it is very important to choose proper grid points. Based on the work of Dong and Neuman, grid point mesh as shown in Fig.1 is adopted. The environmental geostrophic basic flow is calculated by the following geostrophic wind formulas:

$$u_g = -g \frac{z_{1y} - z_{2y}}{f_0 D} \tag{2}$$

$$v_g = g \frac{z_{1x} - z_{2x}}{f_0 D \cos \Phi_0} \tag{3}$$

$$f_0 = 2\Omega \sin \Phi_0 \tag{4}$$

$$D = \frac{\Pi}{180} \cdot n \cdot 1.875 \cdot RA \tag{5}$$

The formulas used to calculate deep-layer environmental geostrophic basic flow by pressure weighted average are as follows:

$$u_{pg} = \sum_{i=T}^{N-1} \frac{u_{gi} + u_{gi+1}}{2} \frac{p_i - p_{i+1}}{p_T - p_N} \tag{6}$$

$$v_{pg} = \sum_{i=T}^{N-1} \frac{v_{gi} + v_{gi+1}}{2} \frac{p_i - p_{i+1}}{p_T - p_N} \quad (7)$$

The formulas used to calculate deep-layer environmental geostrophic basic flow by log pressure weighted average are as follows:

$$u_{\lg} = \sum_{i=T}^{N-1} \frac{u_{gi} + u_{gi+1}}{2} \frac{\ln p_i - \ln p_{i+1}}{\ln p_T - \ln p_N} \quad (8)$$

$$v_{\lg} = \sum_{i=T}^{N-1} \frac{v_{gi} + v_{gi+1}}{2} \frac{\ln p_i - \ln p_{i+1}}{\ln p_T - \ln p_N} \quad (9)$$

In the above formulas, u_g, v_g denote the zonal and longitudinal wind components of the environmental geostrophic basic flow on the 10 mandatory levels respectively, u_{pg} and $u_{\lg}$, v_{pg} and $v_{\lg}$ represent the zonal and longitudinal wind components of the deep layer environmental geostrophic basic flow on the 10 mandatory levels obtained by pressure weighted and log pressure weighted average respectively. f_0 is the latitude of TC center, g is acceleration of gravity (g = 9.8 $\mathrm{m/s^2}$), RA is the mean radius of the Earth (RA = 6371.229 km), Z_{1y}, Z_{2y}, Z_{1x} and Z_{2x} are the averaged geopotential height of the grid points in the areas of 1*y*, 2*y*,1*x* and 2*x*, which are to the north, south, east and west of the TC center respectively, P_T , P_N are the bottom and top level pressures for the deep layer weighted average respectively.

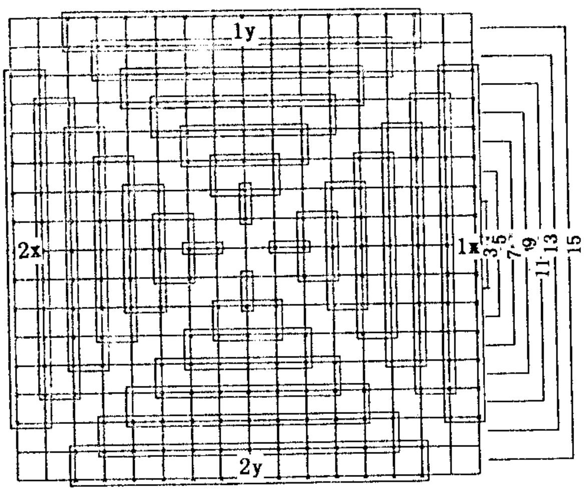

Fig.1 Selection of gridpoints and domain size *n* (number of gridpoints) in the calculation of the steering flow

To compare the results obtained with different *D* values, squares with *n* equal to 15, 13, 11, 9, 7, 5, and 3 are chosen to calculate the environmental geostrophic basic flow of the TCs of total 126 time levels respectively.

Study shows (Fig.2) that different domains would result in different environmental geostrophic basic flow and thus different deviation between real TC track and environmental basic flow. The minimum distance deviation appears when *n* is 7 ~ 9. When *n* is larger, the distance deviation would be larger; When *n* is smaller, the distance deviation would be even larger. When *n* is larger than 9, the distance deviation increases gradually with the increase of *n*. When *n* is below 7, the distance deviation would increase rapidly with the decrease of *n* (curve A). This kind of change trend of distance deviation with the domain size *n* fits not only tropical storm (curve B) but also typhoon (curve C).

Consequently, to prevent the situation that deviation increases rapidly because of small domain, calculation is done to seek the standard root-mean-square error of distance deviation with different *n*, discovering that the root-mean-square error is the minimum when *n* is equal to 9, whose mean deviation is very representative. Thus, discussion will be carried out only on the results obtained with *n* equal to 9 ($9\Delta S = 16.9°$, ΔS =1.875°, which is the latitude-longitude grid size).

Generally speaking, when the 12-h steering position is far from (close to) real one, the deviations of the following time levels would be relatively larger (smaller). Thus, this paper will analyze mainly the principle and feature of 12-h difference between steering position and real one.

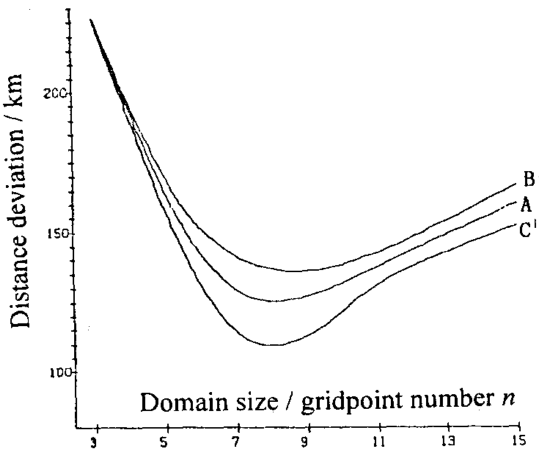

Fig.2 The variation tendency of the minimum averaged distance deviation chosen from the 10 standard vertical levels with changes of the domain size *n*. A denotes TCs (sample number is 126); B denotes tropical storms (the 69 samples less than typhoon intensity in the 126 time levels); C represents typhoons (57 samples with typhoon intensity in the 126 time levels)

3 RELATION BETWEEN THE VERTICAL DISTRIBUTION FEATURE OF ENVIRONMENTAL GEOSTROPHIC BASIC FLOW AND TC MOTION

Result shows that there is certain relation between the moving direction of TC and turning direction of environmental geostrophic basic flow with the increase of elevation.

When TC moves towards the west (i.e. its moving direction is between azimuth angles 202.5°~337.5°), the environmental geostrophic basic flow would turn anticlockwise with the increase of elevation. Fig.3a shows the mean turning status of the environmental geostrophic basic flow of westward moving TCs of 65 time levels. From 850 hPa to 150 hPa, the environmental

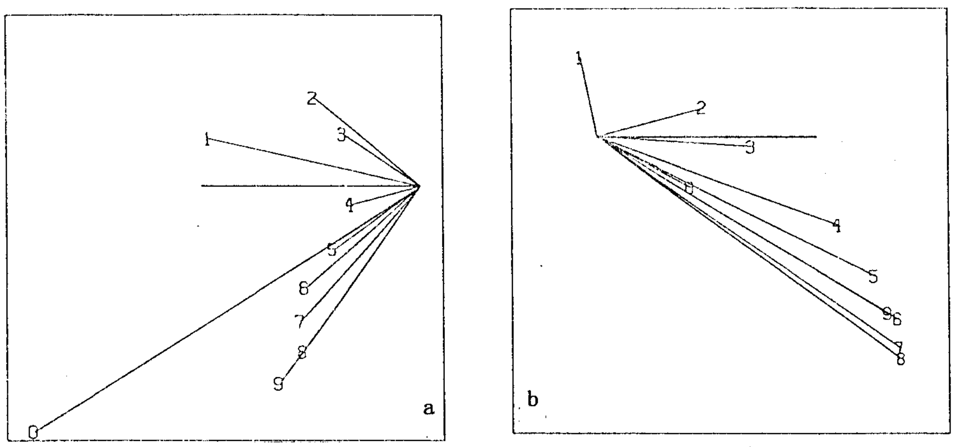

Fig.3 The anticlockwise turning of the environmental geostrophic basic flow with height for westwards moving TCs (a) and the clockwise turning of the environmental geostrophic basic flow with height for the TCs moving towards other directions (b). Numbers of 1,2, ⋯ 0 represent 1000 hPa, 850 hPa, ⋯100 hPa respectively.

geostrophic basic flow shows apparent anticlockwise turning with the increase of elevation. The environmental geostrophic basic flow is the northwesterly (southwesterly) flow at the lower (upper) levels of troposphere. Case study also shows that 42 time levels of the environmental geostrophic basic flow out of the 65 time levels of westward moving TCs display significant anticlockwise turning, which is about 64.4%. 15 time levels of environmental geostrophic basic flow show clockwise turning. The remaining 8 have no significant turning features.

When TC moves towards other directions (mainly towards the north with azimuth between 337.5°~360.0° and 0.0°~22.5°, northeast with azimuth between 22.5°~67.5°, and east with azimuth between 67.5°~112.5°), the environmental geostrophic basic flow would turn clockwise with height. Fig.3b shows the mean turning status of TC environmental geostrophic basic flow of other 61 time levels. It can be seen that the environmental geostrophic basic flow shows clockwise turning from 1000 hPa to 200 hPa. Case study shows similar results. 42 time levels display significant clockwise turning, taking up about 68.9%. 7 time levels show anticlockwise turning. The last 12 have no apparent turning.

4 ANALYSIS ON STEERING DEVIATION OF ENVIRONMENTAL GEOSTROPHIC BASIC FLOW FOR TC MOTION

4.1 *Definition of steering deviation*

In this paper, mean steering deviation of TCs with different intensity on 10 mandatory levels are calculated (Tab.1). The result shows that smaller deviations always appear at the middle and lower troposphere whether or not the TC is strong. Generally, the minimum deviations appear on the layers of 500 hPa and 700 hPa.

Tab.1 The vertical distribution of the distance deviation of the real motion of TC from the steering flow (the intensity is represented by the maximum wind speed near TC center, its unit is m/s; the unit of the distance deviation is km)

sample size	14	12	12	16	15	15	13	16	13	126
grades	18	20	23	25	30	33	35	40	45	total
100 hPa	255.9	320.7	357.3	318.4	358.6	264.3	296.4	340.9	280.0	310.3
150 hPa	222.4	293.7	349.8	317.9	377.5	300.2	304.4	310.7	219.3	300.5
200 hPa	221.0	258.7	327.2	293.3	309.3	287.9	278.4	269.2	200.5	271.9
250 hPa	208.8	217.3	277.0	260.8	260.2	261.7	237.3	220.1	174.3	235.9
300 hPa	195.8	185.8	221.0	231.8	216.5	230.1	195.6	174.5	148.3	200.8
400 hPa	173.2	162.9	153.1	175.4	168.8	168.7	119.7	133.3	120.1	153.4
500 hPa	142.1	158.8	125.4	128.2	141.4	130.6	88.0	111.2	109.0	125.9
700 hPa	122.0	141.6	119.2	136.4	152.0	123.2	135.2	123.1	102.2	128.8
850 hPa	147.6	112.4	158.1	193.6	192.1	152.1	186.7	156.6	113.2	158.5
1000 hPa	210.2	118.8	190.4	279.8	232.5	181.5	266.1	204.6	152.1	206.8

Since its environmental fields on various levels may affect TC motion, we perform different kinds of weighted average on the environmental geostrophic basic flow on the 10 mandatory levels. It is found that real TC motion has the best correlation with deep-layer environmental geostrophic basic flow obtained through pressure weighted average over the environmental geostrophic basic flow at various levels from 1000 hPa to 200 hPa. The distance deviation between them is also the smallest. We will take this basic flow as the steering flow of TC motion to investigate the deviation feature of real TC track from it. And we call this deviation as steering deviation.

4.2 *Relation between steering deviation and environmental steering flow*

We calculate the wind components (u, v) of the environmental geostrophic basic flow of all those 126 samples, which are also compared to corresponding mean steering deviation. The result shows that different zonal component u of the basic flow can cause different steering deviation (Tab.2).

In this paper, the 126 samples are divided into four groups by $u<-3.0$ m/s, $-3.0\le u<0.0$m/s, $0.0\le u<3.0$ m/s, $u\ge 3.0$ m/s to calculate mean latitude deviation, longitude deviation and distance deviation. The result shows that the latitude and distance deviations decrease (increase) with the increase (increase) of westward (eastward) component of steering flow. Furthermore, the latitude deviation is generally to the south. This result demonstrates that under strong easterly steering, there might be no latitude deviation. Besides, the longitudinal deviation keeps stable under both easterly and westerly steering conditions. The deviation is generally around 0.3 degree of longitude.

Tab.2 Relation between the steering deviation and the u component of environmental steering flow

u(m/s)	<-3.0	[–3.0,0.0)	[0.0,3.0)	≥3.0	total
sample size	30	36	31	29	126
mean lat. deviation (°)	0.0	–0.2	–0.5	–0.8	–0.3
mean long. deviation (°)	0.2	0.3	0.3	0.3	0.3
mean distance deviation (km)	86.5	93.9	117.4	122.5	104.5

4.3 *Relation between steering deviation and initial latitude of TCs*

The deviation of TC motion from its environmental steering flow is related to not only the speed and direction of steering flow itself, but also the initial latitude of the TC.

Tab.3 shows that when TC is located within 20.0°N ~26.5°N, the distance deviation is small, about 94 km. The distance deviations are large when the initial position of TC is to the south of 20°N and to the north of 26.5°N. Besides, the latitude deviation will increase gradually with TC position located more to the north.

4.4 *Relation between steering deviation and intensity of TCs*

The calculation of this paper shows that the mean distance deviation of real motion of TC

Tab.3 Relation between the steering deviation and the initial latitude of TC (same unit as in Tab.2)

initial lat.	<17.3	[17.3,20.0)	[20.0,23.0)	[23.0,26.5)	≥26.5	total
sample size	26	25	24	25	26	126
mean lat. deviation	-0.1	-0.2	-0.1	-0.4	-0.7	-0.3
mean long. deviation	0.2	0.5	0.2	0.3	0.3	0.3
mean distance deviation	104.3	109.1	94.4	94.5	119.2	104.5

from its environmental steering flow is 104.5 km. However, when TC intensity is different, the steering deviation would be different as well.

Tab.4 shows that a stronger (weaker) TC would result in smaller (larger) distance deviation, which is about 85 km (generally beyond 100 km). The result of the bottom line in Tab.4 is the mean distance deviation obtained through adding the latitude and longitude mean deviation (–0.3 for latitude deviation and 0.3 for longitude deviation, see the last row of Tab.3 and Tab.4) to the 12-h steering position of each sample. It can be seen that compared to the situation without adding longitude and latitude mean deviation, the distance deviation decreases by about 9% with the addition of longitude and latitude mean deviation.

Tab.4 Relation between the steering deviation and TC intensity (same unit as in Tab.2)

sample size	14	12	12	16	15	15	13	16	13	126
grades	18	20	23	25	30	33	35	40	45	total
Lat. deviation	–0.4	–0.1	–0.4	–0.2	–0.2	–0.4	–0.5	–0.3	–0.4	–0.3
Long. deviation	0.4	0.4	0.3	0.2	0.5	0.5	-0.1	0.3	0.2	0.3
dist. deviation	120.0	125.2	110.1	106.1	116.0	103.8	86.1	89.2	86.5	104.5
Lat. +0.3 Long. –0.3	107.0	110.2	97.5	104.0	106.0	81.5	87.2	82.0	80.2	94.9

5 CONCLUDING REMARKS

a. The deviation between TC motion and environmental geostrophic basic flow is related to the domain size used to calculate the basic flow. The optimum domain length to calculate the basic flow is 16.9 degrees of longitude and latitude.

b. The vertical distribution feature of environmental geostrophic basic flow has certain guiding reference for TC moving direction. When the environmental geostrophic basic flow displays an anticlockwise turning with the increase of elevation, TC usually moves to the west (within 202.5°~337.5°). When it displays clockwise turning with the increase of elevation, TC usually moves to the east or north.

c. There exists the minimum difference between real motion of TC and deep layer weighted average environmental geostrophic basic flow from 1000 hPa to 200 hPa, which is about 104.5 km. This basic flow can be taken as the steering flow of TC motion.

d. Steering deviation is related to the speed of steering flow. The stronger the eastward component of the steering flow, the smaller the steering deviation would be. The stronger the westward component of the steering flow, the larger the steering deviation would be, which is usually to the south.

e. Stronger TC has smaller steering deviation.

f. Steering deviation is also related to the initial latitude position of TC. Smaller steering deviation appears in the latitude belt of 20.0°N ~ 26.5°N. The TCs locating far to the south or far to the north all have larger steering deviation.

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