An Observational Study of the Physical Processes Responsible for Tropical Cyclone Motion

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ABSTRACT

This paper presents an observational study of the physics of tropical cyclone motion. Analyses of the vorticity budget using both aircraft and rawinsonde composite data were performed. As expected, the results show a definite link between the local change in relative vorticity and tropical cyclone movement. The main contributor to this local change, at least in the middle troposphere, is the horizontal advection of absolute vorticity with the divergence term usually playing a secondary but not necessarily negligible role. The vertical advection and tilting terms are generally much smaller.

The contribution of the divergence term as an extra component in determining the movement of tropical cyclone is discussed. The mass to wind adjustment as a result of the increase in vorticity is viewed as a combination of the advection of temperature (or mass) and subsidence. Substantiating evidence of this viewpoint is presented for cyclones undergoing turning motion.

1. Introduction

Previous theoretical and numerical studies of tropical cyclone motion have always identified the maximum local change in relative vorticity as the future position of the cyclone.[2] While this appears to be physically reasonable and intuitively obvious, observational evidence of such a relationship has never been provided. Operational barotropic track forecast models have also assumed that the prediction of the maximum in vorticity tendency can be approximated by the advection of absolute vorticity.[3] However, the effects of including other contributing physical processes (the stretching and twisting of vortex tubes, frictional dissipation and mesoscale effects) have not been investigated. A better understanding of the relative importance of each of these effects might provide the possibility of improving track forecasts by incorporating the appropriate physics in empirical and numerical models.

The lack of observational studies on this subject in the past is largely a result of the unavailability of data. However, with the accumulation of rawinsonde data over the past 20 years and of research aircraft observations in the 1960s, new studies of this type now become possible. This paper is an attempt to document the relationships between tropical cyclone motion and the various terms in the vorticity equation. Analyses of these two types of data (aircraft and rawinsonde) not only provide observational justification of the assumption of linking the maximum vorticity tendency to cyclone motion (Sections 2, 3 and 4), but they also point to the possibility of some forecast applications (Section 4). Further analyses of these datasets suggest that while the concept of steering may be used to a large extent in explaining tropical cyclone motion, a certain percentage of the vortex movement may be a propagation rather than a translation phenomenon.

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[2] See Chan (1982) for a comprehensive review of these studies.

[3] See the report by the World Meteorological Organization (WMO, 1979) for a review of these models.

2. National Hurricane Research Project (NHRP) flight data

a. *Brief description of the dataset*

During the period 1957–67 and also in 1969, the NHRP made about 100 aircraft flights into and out of 22 hurricanes in the west Atlantic on 41 storm days, providing a total of 533 radial legs. Wind, pressure and temperature measurements were taken, mostly at levels between 900 and 500 mb. These data and their accuracy have been fully documented by Shea (1972), Shea and Gray (1973) and Gray and Shea (1973, 1976). The final validated dataset consists of radial and tangential winds, D-values and adjusted temperatures at 2.5 n mi (4.625 km) intervals between 5 to 50 n mi (9.25 to 92.5 km) from the cyclone center. Only the first two parameters were needed in this study.

Since gradients of winds and vorticity are involved in the calculations of the various terms in the vorticity equation, it is essential to have a very good azimuthal data coverage. No one single flight (which usually had

4 to 6 flight legs) had enough azimuthal coverage to allow a meaningful computation of these terms. Therefore, composites have to be made.

b. Method of compositing

The large variability in the inner core (radius < 100 km) structure of the vortex among different cyclones precludes compositing with reference to the cyclone center. A better way to composite the data is to use the radius of maximum wind (RMW) as the reference. Observations can then be composited on either side of the RMW. This method has been shown by Shea and Gray (1973) to be far superior to a composite made with respect to the cyclone center; it was therefore chosen in this study.

The composite grid is similar to that in Fig. 4 (Section 3a) with eight octants and a radial grid distance of 2.5 n mi (4.625 km). Each radial leg was assigned to one of the eight octants according to its azimuth relative to the direction of cyclone movement. Because the flights were made at various pressure levels, relatively few radial legs were available at one particular level. Therefore, the compositing procedure was performed using all data that fell within some pressure interval. These intervals or layers are the same as those used by Shea and Gray (1973). In this study, four layers were used: 1000–800, 799–700, 699–600, and 599–470 mb. Within each pressure interval, radial and tangential winds of all radial legs belonging to the same octant at the RMW and on either side of it (from −15 to +30 n mi, or −27.75 to 55.5 km) were then averaged. The mean RMW for each octant was also calculated. Since the mean RMW may differ slightly among the octants, and a common reference is necessary in order to calculate the derivatives of radial and tangential winds, the mean RMW of all eight octants were averaged to give an octant-mean RMW for a particular pressure level.

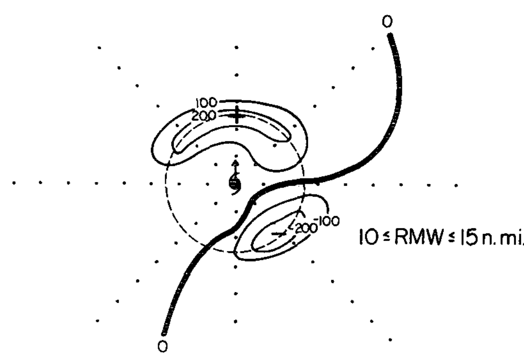
Near the RMW, the curvature vorticity (v/r)[4] usually dominates over the shear vorticity $(\partial v/\partial r)$. Since the composites were made with reference to the RMW (rather than absolute radius), the values of relative vorticity will be meaningful only if cyclones with similar RMW are composited together. Therefore, two stratifications were made: those with RMW in the range 10–15 n mi (18.5–27.75 km) (the "small" cyclones) and those in the range 20–25 n mi (37–46.25 km) (the "large" cyclones). This selection was based on the distribution of the mean RMW for all flights. See Chan (1982) for a more detailed description of this selection process.

c. Results

The number of radial legs for both stratifications is the largest in the layer 799–700 mb (centered at ~750 mb). Significantly fewer number of cases were available at the other three levels. Therefore, only the results in this layer (which will be referred to as 750 mb) will be presented.

Figure 1 shows the relative vorticity advection for the two RMW stratifications at 750 mb. As expected, both cases have the area of maximum positive vorticity advection in front of the cyclone and near the mean RMW. However, the magnitudes of this vorticity advection in the small cyclone stratification are about four times those in the large cyclone group, due to higher vorticity and stronger vorticity gradient present in the former group. In addition, the radial winds are more positive in this stratification (not shown). The advection by the tangential winds appears to be generally less significant in both stratifications. Since the gradients of the earth's vorticity at such close-in radii are negligible, these results approximate very well the advection of absolute vorticity.

Values of the divergence term $[-(\zeta + f)\nabla \cdot \mathbf{V}]$ for the two groups of cyclones are shown in Fig. 2. In the small cyclone group, because the divergence and the vorticity are both larger than in the other group, the magnitudes of the divergence term are also larger. The



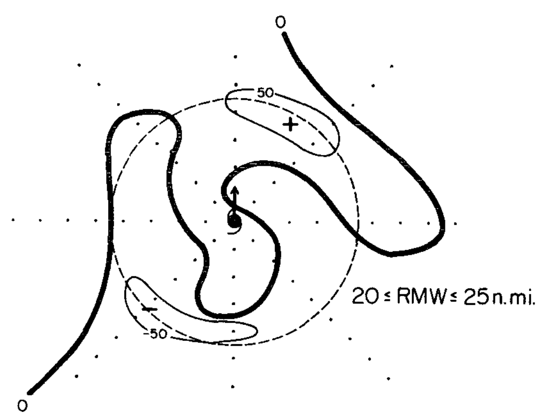


FIG. 1. Horizontal advection of relative vorticity (units of 10^{-8} s^{-2}) at 750 mb calculated from composite NHRL data for the two RMW stratifications. The dashed circle represents the octant-mean RMW. The arrow indicates the instantaneous direction of cyclone motion; spacing of the grid is 5 n mi (9.25 km).

[4] See Appendix for list of symbols.

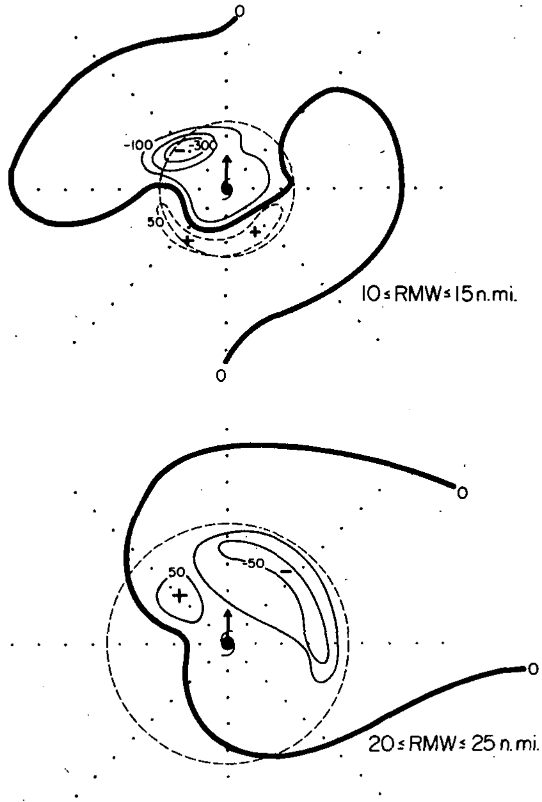


FIG. 2. As in Fig. 1 except for the divergence term in the vorticity equation.

divergence term is generally negative in the front in both cases because the radial winds in this area are divergent. Note that the magnitudes of the divergence term are generally comparable to those of the advection term, *and are by no means negligible.* However, because the relative positions of the maxima of these two terms differ, their sum (which gives an estimate of the local change of relative vorticity) is still positive in front of the cyclone, as can be seen from Fig. 3. This suggests that, even though the divergence term is significant, the directional movement of a cyclone may be closely approximated by the advection of absolute vorticity.

Rawinsonde composite data available at larger distances (⩾100 km) from the cyclone center can also be used to study the relation between the vorticity budget and cyclone motion. This type of data provide information at different levels in the atmosphere so that vertical motion and hence the vertical advection and the tilting terms can be calculated. Results from these calculations will be presented in the next two sections.

3. Rawinsonde composite datasets of cyclone speed

These datasets consist of the fast- (>3 m s^{-1}) and slow- (1–3 m s^{-1}) moving tropical cyclones in the west Atlantic between 1961 and 1974 and the fast (>7 m s^{-1}), moderate (4–7 m s^{-1}) and slow (1–3 m s^{-1}) speed cyclones in the northwest Pacific between 1961 and 1970. All cyclones studied here were at least of tropical storm strength (17 m s^{-1} maximum sustained winds). The Atlantic composites are the same as those used by Gray (1977) and the Pacific composites were made by George and Gray (1976). The locations of the rawinsonde stations from which data were used in the composites have been shown in these papers and in Chan and Gray (1982). Similarly, the reasons for the necessity of compositing have been discussed in the papers by Williams and Gray (1973), Frank (1977), Gray (1981) and other Colorado State University tropical cyclone research reports. Therefore, they will not be repeated here. However, a brief description of how the data were composited and handled will be given.

a. Data handling

Wind data from rawinsonde stations around cyclones were composited for each speed stratification using the circular grid shown in Fig. 4. The center of the grid coincides with that of the cyclone center. The grid has a radius of 15° latitude with eight radial bands. Each radial band is divided into eight equal segments

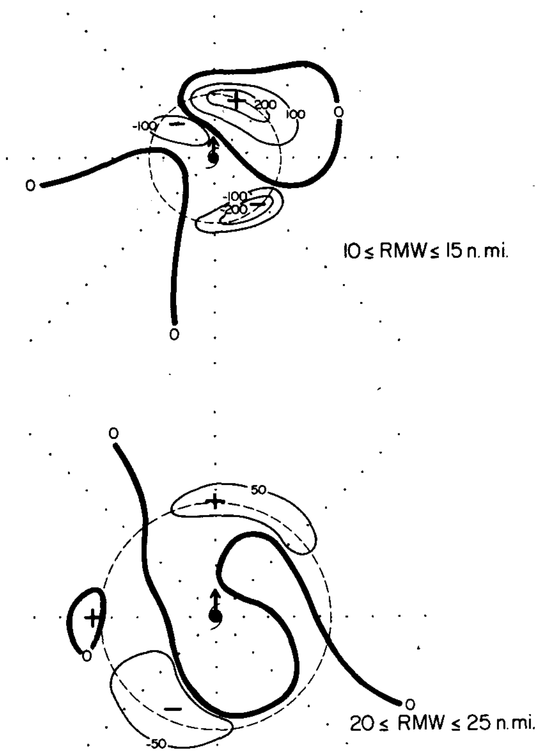


FIG. 3. As in Fig. 1, except for the sum of the horizontal relative vorticity advection and the divergence terms.

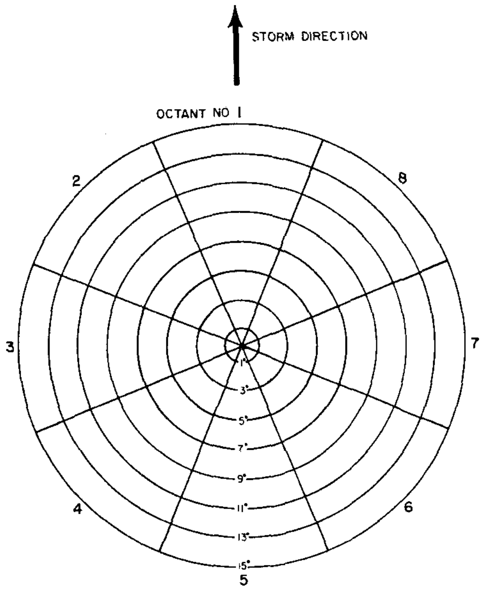


FIG. 4. Grid used for compositing rawinsonde data. The arrow points in the direction of storm motion. Outer numbers denote octants. Numbers inside grid indicate distances from the center in degs latitude.

or octants and numbered from 1 to 8 in a counterclockwise fashion, with octant 1 always being in front of the cyclone.

The ±6 h (from current position) best-track positions were used to determine the direction and speed of cyclone movement. The radial and tangential wind components of all soundings falling within any given grid box for each stratification were then averaged. This average value was assigned to the midpoint of the grid box, giving a total of 64 values of each wind component at each pressure level.

Although this compositing procedure would reduce the amount of noise inherent in the data, calculations of gradients (of winds and vorticity in this study) require rather smooth data fields especially when the grid points are so widely spaced (see Fig. 4 for the grid size). Therefore, a smoothing routine available from the National Center for Atmospheric Research was applied to the composite radial and tangential wind fields. This routine uses a bi-cubic spline and fits a smooth surface to a two-dimensional data field. A minimum amount of smoothing was used. From the functional form of the smoothed surface, values of the parameter can be computed at any point within the domain. This provides estimates of the parameter at grid points where no raw information was available. These estimates are essential in the calculations of gradients when the method of finite-differencing is used. For a more detailed discussion of this smoothing procedure, the reader is referred to Lee (1982) and Chan (1982).

The smoothed radial winds were mass-balanced. The divergence at each level was also adjusted to satisfy the condition of zero net tropospheric divergence. The vertical p-velocity can then be calculated from the continuity equation in isobaric coordinates.

The radial gradient was calculated using a finite difference of 4° latitude (±2°), except at 2° latitude where a 2° latitude difference (between 4° and 2°) was used. With the aid of the smoothing routine, values of the radial and tangential winds can be interpolated at points in between the standard 8 octants shown in Fig. 4. In this way, an azimuthal gradient of 45° (±22.5°) can be evaluated. The sum of all the terms on the right-hand side (RHS) of the vorticity equation in cylindrical-isobaric coordinates (except for the frictional term) will be called the residual R; i.e.,

$$R = -\mathbf{V}\cdot\nabla(\zeta + f) - (\zeta + f)\nabla\cdot\mathbf{V} - \omega\frac{\partial\zeta}{\partial p} + \left(\frac{\partial u}{\partial p}\frac{\partial\omega}{r\partial\theta} - \frac{\partial v}{\partial p}\frac{\partial\omega}{\partial r}\right), \quad (1)$$

where the symbols have their usual meaning (see Appendix). The residual R therefore represents the local change of relative vorticity plus all the sources and sinks of vorticity such as friction and subgrid scale effects; it might also include errors in the analyses, i.e.,

$$R = \frac{\partial\zeta}{\partial t} + [\text{sources and sinks of vorticity}].$$

b. Calculations of the residual

An examination of the results from all the five speed composite datasets (two in the west Atlantic and three in the northwest Pacific) shows that the largest differences between datasets occur at 2° and 4° latitude radii. Therefore, comparisons will be presented only for these radial bands.

Figure 5 shows a pressure-azimuth cross section of the residual at 2° latitude radius for slow-(1–3 m s^{-1}) and fast-(>3 m s^{-1}) moving cyclones in the west Atlantic. In both cases, the residual is generally positive in front of the cyclone (azimuth between 335° and 45°) and negative behind it (azimuth between 135° and 225°) at the levels of cyclonic flow (below ~250 mb). At the upper levels, it is generally negative. A comparison between the two stratifications shows that the fast-moving cyclones have a larger residual (both in front and behind) than those that are slow-moving. Also, the maxima (both positive and negative) are well-defined in the mid-troposphere (500–700 mb) in fast-moving cyclones. In the slow-moving cyclones, the maxima occur in the lower troposphere. Similar, though weaker, differences in the values of the residuals between the two stratifications were found at 4° latitude radius (not shown).

In the theoretical studies by Chan (1982) and Holland (1983), the speed of a cyclone was assumed to be related to the ratio of the maximum vorticity change to the radial gradient of relative vorticity. This estimate

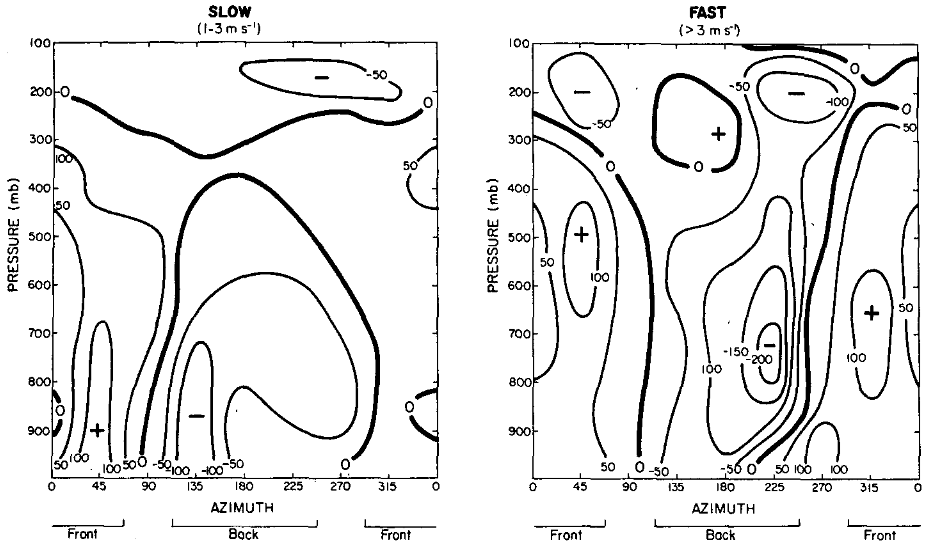


FIG. 5. Pressure-azimuth cross section of the residual R (units of 10^{-6} s^{-1} d^{-1}) in the vorticity equation defined in Eq. (1) at 2° lat radius for slow- and fast-moving cyclones in the west Atlantic. The azimuth is with respect to direction of cyclone motion, with a value of zero along this direction and increasing counterclockwise.

of cyclone speed is analogous to the formula used by Pettersen (1956) in the calculation of movement of pressure centers. If these two groups of cyclones have similar intensities, the radial gradients of ζ would be similar and one would expect fast-moving cyclones to have a larger $\partial\zeta/\partial t$. If the residual is a good representation of $\partial\zeta/\partial t$, as will be shown to be true later, these results appear to substantiate the assumption used in those two theoretical studies.

Figure 6 shows the residual at 2° for the three speed composite datasets in the northwest Pacific. In general, the faster the cyclone is moving, the larger the magnitude of the residual. These results are in agreement with those in the west Atlantic. Also, notice that fast-moving cyclones have positive and negative residuals extending through a very deep layer of the troposphere. Such a phenomenon is less obvious for moderate-speed cyclones. Slow-moving cyclones have both positive and negative residuals in the front. Xu and Gray (1982) pointed out that environmental flow fields around slow-moving cyclones are weak, with different directions at different levels in the lower to middle troposphere. The latter would cause different vorticity advection, and hence different residual (other terms being equal or less significant) patterns at different levels. On the other hand, fast-moving cyclones have environmental flows with similar directions at all low to mid-tropospheric levels. The areas of maximum vorticity advection, and thus residual, would therefore tend to be aligned in the vertical. The results presented here agree very well with their observations. The differences in the residuals at 4° latitude radius for the three cases of cyclones in the northwest Pacific are similar but weaker (not shown). Detailed comparisons between datasets of 4° latitude radius for both ocean basins can be found in Chan (1982).

A comparison between west Atlantic and northwest Pacific cyclones shows that the latter have, in general, stronger residuals for the same cyclone speed. This is probably because cyclones in the northwest Pacific are usually more intense than those in the west Atlantic. Therefore, for cyclones moving at the same speed, the local change of relative vorticity for Pacific cyclones is larger.

c. Relative importance of various terms in the vorticity equation

The residual R computed using Eq. (1) represents the sum of the local change of relative vorticity $\partial\zeta/\partial t$, frictional effects and any "subgrid" effects that cannot be resolved by the grid point composite data. The last two effects are difficult to evaluate. However, $\partial\zeta/\partial t$ can be estimated by moving the composite vortex with the mean speed of the composite for a short time and then calculating the change in ζ at each grid point, assuming that the intensity of the cyclone is in steady-state. Such an assumption is probably valid since composite, instead of individual, cyclones are studied here. The $\partial\zeta/\partial t$ calculated this way can then be compared with the residual R.

Theoretical studies by Chan (1982) and Holland (1983) suggest that the azimuthal position of maximum $\partial\zeta/\partial t$ varies with the amount of convergence, the presence/absence of a cross-wind, the uniformity of the environmental flow, etc. In the speed composite data-

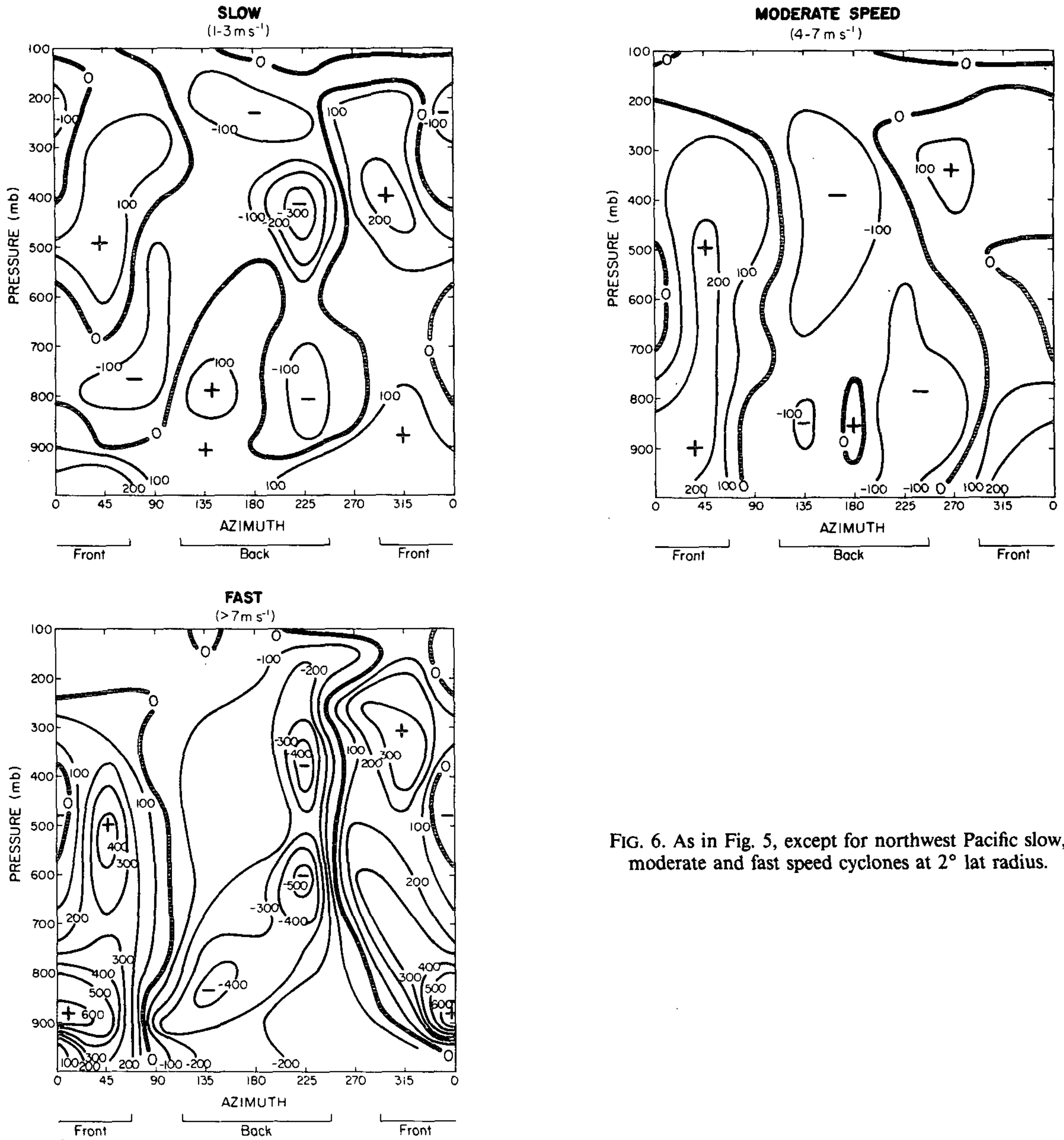


FIG. 6. As in Fig. 5, except for northwest Pacific slow, moderate and fast speed cyclones at 2° lat radius.

sets studied here, no consideration was given to these conditions when the cases were selected by George and Gray (1976) and Gray (1977). Therefore, it would not be meaningful to study the various parameters at one azimuthal location. However, if the values of these parameters are averaged for the three azimuthal locations in front of the cyclone (i.e., octants 2, 1 and 8 in Fig. 4), those variations among individual cases mentioned earlier might be averaged out and the comparisons may provide some insight into the importance of the various terms in the vorticity equation.

Figure 7 shows the average between octants 2, 1 and 8 (relative azimuth between 335° and 45°) at 2° latitude radius of all the terms in the vorticity equation, including the estimated local change of relative vorticity, at various levels for slow- and fast-moving cyclones in the west Atlantic. In general, the tilting and vertical advection terms are relatively small and have opposite signs. They both have maximum values at ~300–400 mb where the mean vertical motion is the strongest. The divergence term appears to be very important in both the upper and lower troposphere. However, in the mid-troposphere, the most dominant term is the horizontal advection of absolute vorticity. The estimated local change in relative vorticity has magnitudes very similar to those of the residual in the middle levels. In the upper troposphere, however, the value of the residual R far exceeds that of the estimated

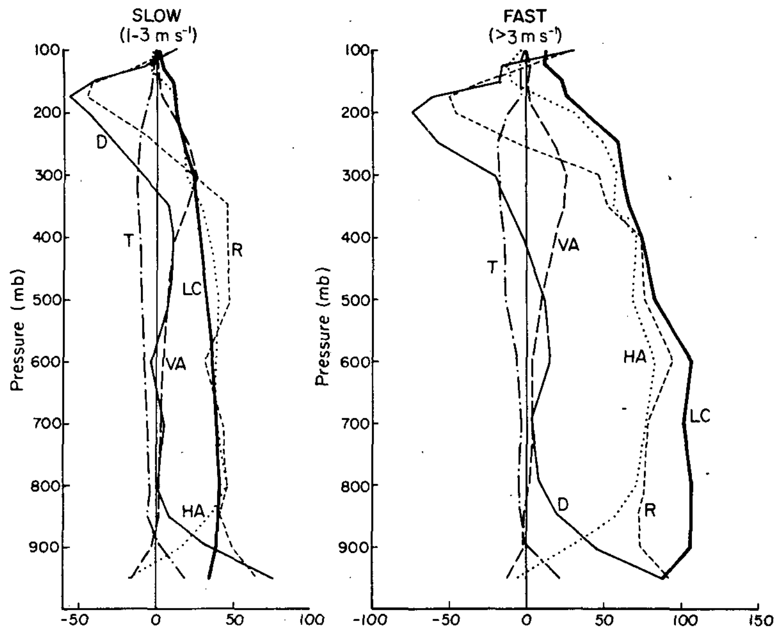


FIG. 7. Vertical variation of parameters in the vorticity equation in front of the cyclone (average between octants 2, 1 and 8—see Fig. 4) at 2° lat radius for slow- and fast-moving cyclones in the west Atlantic. The labels are LC, local change of relative vorticity; R, residual; HA and VA, horizontal and vertical advection of absolute vorticity respectively; D, divergence term; T, tilting term. The unit is 10^{-6} s^{-1} day^{-1}.

vorticity tendency. This suggests that in the mid-troposphere, the frictional and subgrid effects are not very important while at the upper levels, they are very significant, acting as an additional vorticity source. This result qualitatively agrees with Lee's (1982) computations of subgrid-scale (cumulus) effects in tropical cyclones. In general, all the terms in fast-moving cyclones are larger in magnitude than those in slow-moving cyclones. Similar results are obtained at 4° latitude radius, except that the magnitudes of all the terms are smaller (not shown).

These results demonstrate that, at least in the mid-troposphere, the residual computed using Eq. (1) provides a very good estimate of the local change of relative vorticity. The most important contribution to the residual, in this case, is the horizontal advection of absolute vorticity. This observational result therefore justifies the basic assumption in nondivergent barotropic track prediction models (see, for example, Sanders and Burpee, 1968; WMO, 1979). Note, however, that because the horizontal vorticity advection and the local vorticity change terms differ very much below ~800 mb and above 300 mb, models of this type that predict cyclone tracks from a deep tropospheric mean flow might not be as appropriate as those using only middle level data.

The vertical variations of the terms in the vorticity equation for northwest Pacific speed composite cyclones at 2° latitude radius are shown in Fig. 8. In general, all the terms have a larger magnitude compared with those for west Atlantic cyclones. However, the tilting and vertical advection terms are still relatively small compared with the horizontal terms. The divergence term for slow-moving cyclones varies considerably in the vertical, contributing to a large variation of the residual. Nevertheless, the horizontal advection of absolute vorticity still provides a good estimate of the local change of relative vorticity in the middle to upper troposphere. The moderate and fast speed cyclones have smoother profiles of the divergence term. Again, the horizontal advection term is a better estimate of the local change than the residual. The existence of such differences between the local change of relative vorticity and the residual for northwest Pacific cyclones suggests the importance of subgrid scale effects at this relatively close distance from the cyclone center. The presence of such apparent vorticity sources and sinks is not as obvious in west Atlantic cyclones, except in the upper troposphere. This is probably because northwest Pacific tropical cyclones are, in general, bigger and stronger so that subgrid-scale effects at ~2° latitude radius are important.

At 4° latitude radius, the curves are relatively smoother, as shown in Fig. 9. Now the residual approximates the local change in relative vorticity very well in the mid-troposphere for all three cases. This apparently results from the diminishing effect of the divergence term. For fast-moving cyclones, a large difference between R and $\partial\zeta/\partial t$ still exists in the lower troposphere.

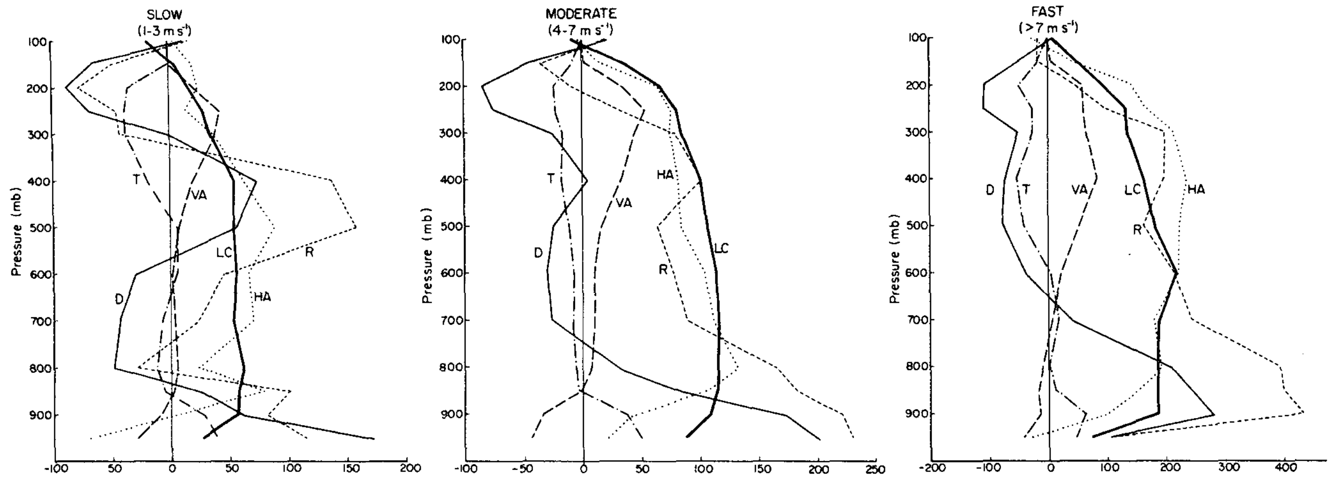


FIG. 8. As in Fig. 7, except for speed composite datasets in the northwest Pacific at 2° lat radius. Note the change in scale for the fast-moving dataset.

The profiles of the various terms in the vorticity equation for speed composite datasets in the two ocean basins are remarkably similar. They appear to demonstrate the usefulness of estimating the local change of relative vorticity through calculations of the residual, at least in the mid-troposphere. These results also point to the predominance of the horizontal advection term in determining the local change in relative vorticity at middle levels.

As pointed out earlier, it is not possible to study the terms in the vorticity equation at one azimuthal location for these datasets because the cyclone speed is the only criterion used in their selection. However, the turning motion datasets of Chan *et al.* (1980) have well-defined directional changes. Therefore, it should be possible to analyze the terms in the vorticity equation at different azimuths. Results of such analyses will be presented in Section 4.

4. Turning motion datasets

Chan *et al.* (1980) studied the relation between the flow around tropical cyclones undergoing turning mo-

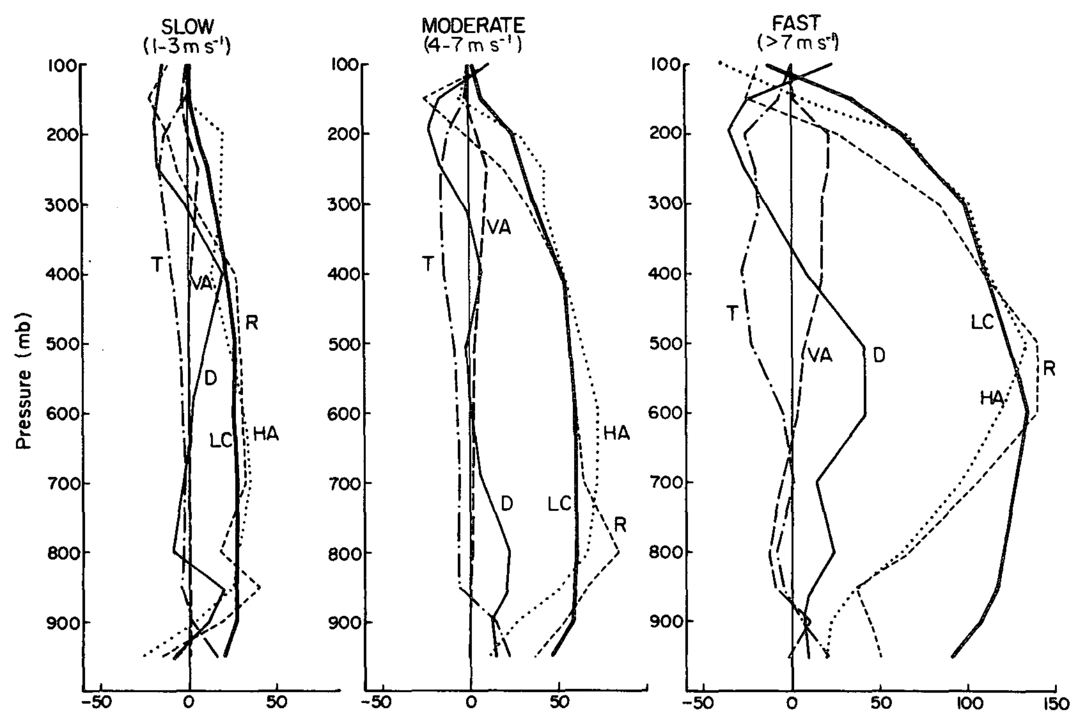


FIG. 9. As in Fig. 7, except for speed composite datasets in the northwest Pacific and at 4° lat radius.

tion. They composited rawinsonde data around west Atlantic cyclones (in the manner described in Section 3a) between 1961 and 1974; these cyclones underwent a left or right turn (directional change in 12 h $\geqslant \pm 20°$), or moved in a relatively straight direction (change in 12 h $< 20°$) for a period of at least 36 h. The composites consist of datasets at turn time T and 12, 24 and 36 h before turn time (labeled as $T - 12$, $T - 24$ and $T - 36$, respectively). A schematic of the tracks for these three classes of cyclones is shown in Fig. 10. For a complete description of the datasets, the reader is referred to the subject paper. The smoothing scheme discussed in Section 3a was also applied to these composite data for all time periods before the computations of the vorticity budget were made.

Since data were available at each time period, the local change in relative vorticity ($\partial\zeta/\partial t$) between any two periods can be easily derived using the method of graphical subtraction. In the present study, the $\partial\zeta/\partial t$ between $T - 12$ and T is analyzed. The level that shows the best correlation between this local change and subsequent cyclone motion is 500 mb. Results are shown in Fig. 11. Two positive maxima of $\partial\zeta/\partial t$ are present near the center of a left-turning cyclone, one situated in front and the other to the left. The largest negative maximum occurs between octants 5 and 6 (rear and right-rear, respectively). For straight-moving cyclones, the positive maximum is in front of the cyclone and slightly to the right of the direction of cyclone movement at time T. Right-turning cyclones clearly have a maximum local change of relative vorticity to the right front quadrant.

Intuitively, one would think that the area of maximum vorticity tendency should form along the direction of the turn between turn time T and 12 h later. However, these results suggest that such a local change in vorticity actually occurs at the time when or even *before* a cyclone starts to turn. From a forecasting point of view, this means that by more accurately determining the vorticity tendency, it might be possible to

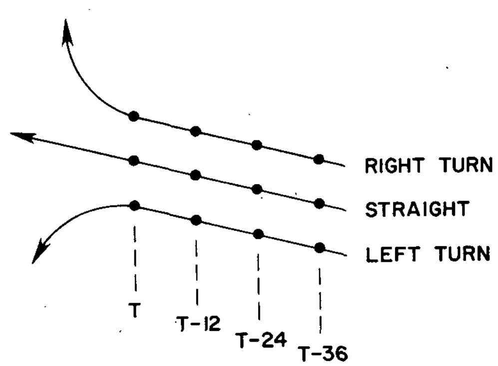


FIG. 10. Schematic of the tracks of the three classes of turning tropical cyclones at turn time T and 12 to 36 h prior to turn (After Chan *et al.*, 1980).

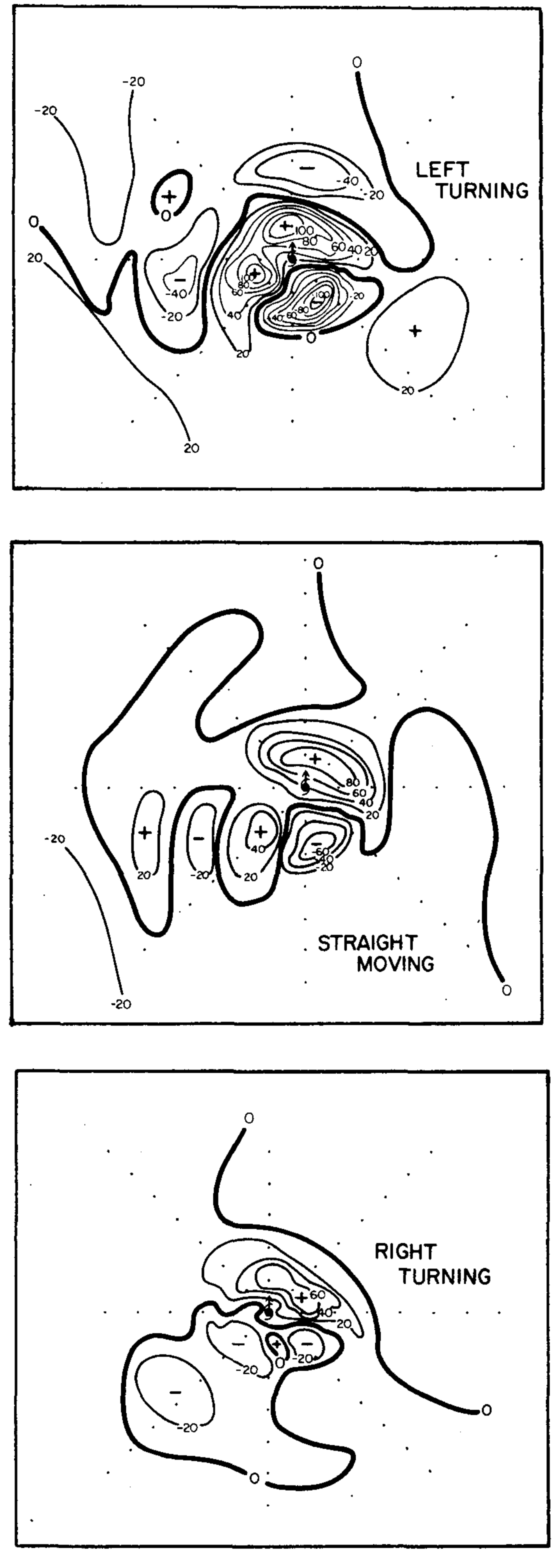


FIG. 11. The 12 h local change in relative vorticity (units of 10^{-6} s^{-1} day^{-1}) at 500 mb between turn time (T) and 12 h before turn time ($T - 12$) for turning and straight-moving cyclones in the west Atlantic. Arrow indicates direction of cyclone movement at time T. The grid spacing is 2° lat (222.2 km).

improve the 12 h prediction of the directional movement of the cyclone.

To determine the relative importance of the various processes in producing this local change in relative vorticity, one would need to know the flow field at some intermediate time between T and $T - 12$. Since this is not possible, the best alternative is to analyze the flow field at time T. Such a procedure would tend to overestimate the local change because the $\partial\zeta/\partial t$ derived from the graphical subtraction of the relative vorticity fields can be considered only as the time average during those 12 h whereas that calculated from the flow field at turn time is the instantaneous, and probably maximum, value.

Plan views of the horizontal advection of absolute vorticity at 500 mb and turn time T for the three classes of cyclones are shown in Fig. 12. Within 4° latitude radius from the cyclone center, left-turning cyclones have maximum horizontal vorticity advection to the left front, while such a maximum occurs on the right-front side for right-turning cyclones. Straight-moving cyclones have two positive maxima, one on each front side of the cyclone as well as a large positive area in front of the cyclone. The positive area in the turning cases is much smaller and more concentrated. The advection of the earth's vorticity was found to be much smaller than that of the relative vorticity at both 2° and 4° latitude radii.

The other term that might contribute significantly to the local change in relative vorticity is the divergence term. Plan views of this term at 500 mb are shown in Fig. 13. For left-turning cyclones, this term is negative to the left-front but weaker than the advection term. Therefore, the net effect would still be positive, giving the local change pattern in Fig. 11. Right-turning cyclones have positive values to the right front and thus cooperate with the advection term to produce a maximum positive local change in this area. For straight-moving cyclones, the divergence term is generally negative, with a magnitude that almost equalizes the positive contribution of the advection term in front and to the right front of the cyclone. However, to the left front, the advection term is larger than the divergence term, giving a net positive contribution. Therefore, straight-moving cyclones appear to have a tendency to move slightly to the left of the present direction.

These results again point to the importance in computing the horizontal advection of relative (and thus, absolute) vorticity in estimating a change in the direction of cyclone movement. The divergence term appears to play a secondary, though not necessarily insignificant, role.

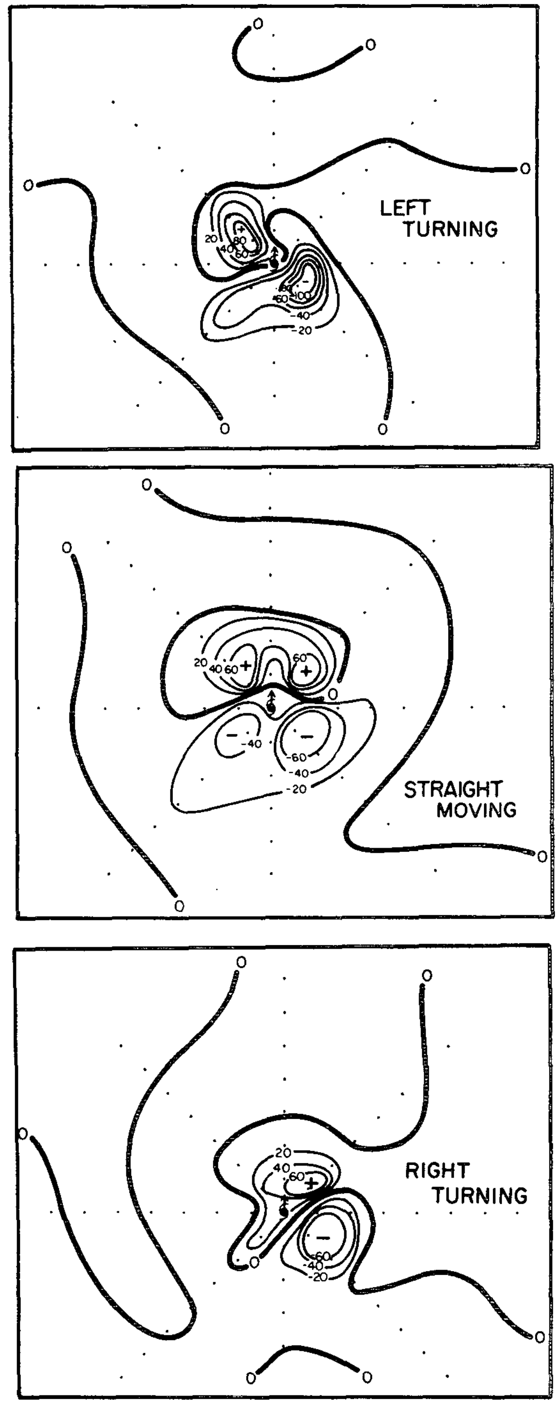


FIG. 12. Horizontal advection of absolute vorticity (units of 10^{-6} s^{-1} day^{-1}) at 500 mb and turn time (T) for turning and straight-moving cyclones in the west Atlantic. Arrow indicates the instantaneous direction of cyclone movement; grid spacing is 2° lat (222.2 km).

5. Discussion and conclusions

The results of the previous sections all point to the fact that the future movement of a tropical cyclone can be estimated from an analysis of the vorticity budget. These observations, therefore, justify the assumption used in numerical track prediction models—that the future position of the cyclone coincides with the predicted position of maximum vorticity. Of the

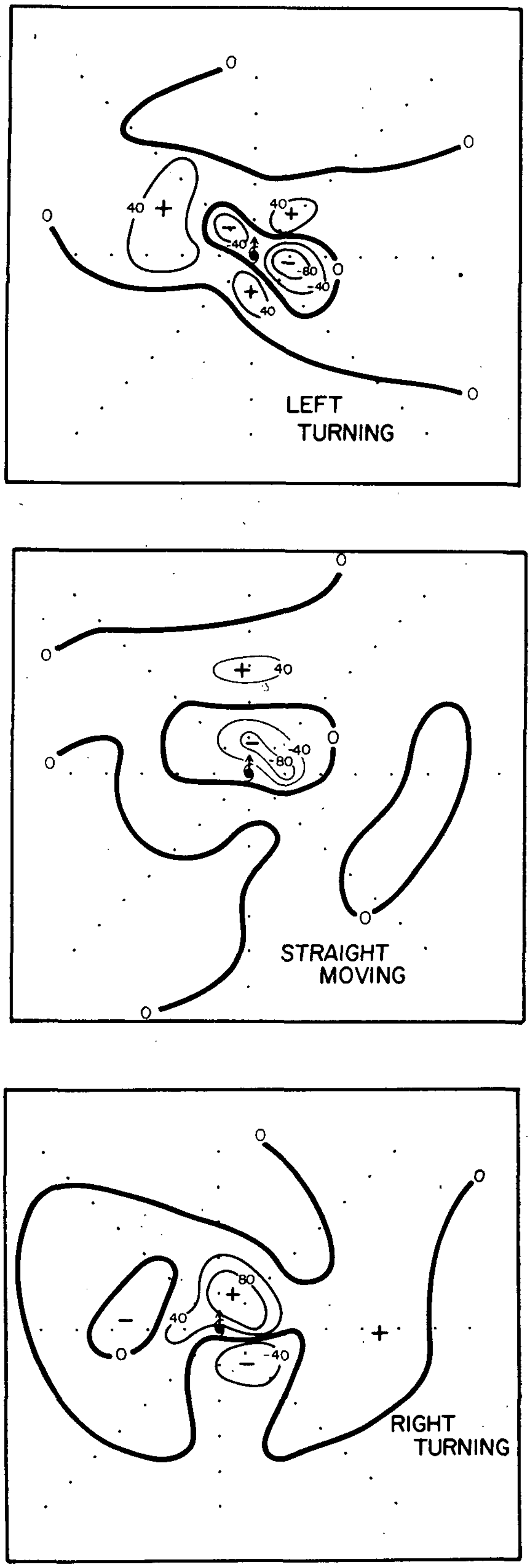


FIG. 13. As in Fig. 12, except for the divergence term in the vorticity equation.

terms in the vorticity equation, the most dominant throughout the middle troposphere appears to be the horizontal advection of absolute vorticity. This conclusion thus seems to confirm the assertion that as far as tropical cyclone motion is concerned, the atmosphere may be, to a first approximation, considered to be barotropic and hence barotropic track prediction models can be used. However, it must be emphasized that the divergence term can play an important role in determining the vorticity tendency, especially in the lower and upper troposphere (see Figs. 7 and 8). Therefore, barotropic models should use only the mid-tropospheric flow in their prediction of cyclone tracks.

In fact, the divergence term may be one important factor which causes the cyclone to move in a slightly different manner (both in direction and speed) from its surrounding flow. This difference has been reported in observational studies by George and Gray (1976), Gray (1977), Brand *et al.* (1981) and Chan and Gray (1982). In two similar theoretical studies, Chan (1982) and Holland (1983) discussed the contributions of the divergence term to the vorticity tendency. The effect of the divergence term in the movement of a cyclone may be physically interpreted as follows.

The surrounding flow advects the vorticity associated with the cyclone towards the front of (looking downstream), and thus "steers," the cyclone forward along the direction of this "steering" flow. If one assumes the cyclone to be in steady state, then in analogy to Petterson's (1956) discussion of the speed of movement of pressure centers, the cyclone speed can be shown to be equal to that of the steering flow. However, because of the divergence/convergence associated with the flow and/or the vortex, the vorticity tendency will be modified so that the maximum local change in vorticity might no longer be along the direction of the steering flow and the speed of the cyclone (as computed from Petterson's formula) might not be the same as that of the cyclone. Therefore, a deviation between the cyclone motion vector and the steering flow wind vector results.

Hence, although the steering concept (which has been interpreted as the advection of absolute vorticity) is valid to a large extent in explaining tropical cyclone motion, an extra component of motion appears to be present. This component, largely a result of the divergence term in the vorticity equation, may be termed the "propagation" of the cyclone, to distinguish it from the steering component.

The presence of this extra component suggests that the use of one-layer barotropic dynamics to describe or predict tropical cyclone motion can only be considered as approximately valid. However, a better understanding or forecast of the movement of tropical cyclones may come only from employing at least a two-layer model.

The increase in vorticity due to a combination of these two components will produce a wind-pressure imbalance. Such an imbalance can be offset by an advection of temperature or mass. It is also possible that vertical motion may contribute to the total warming of the column of air which has this imbalance. An example of this is shown in Fig. 14 which depicts the vertical variations of *p*-velocity at turn time *T* for turning cyclones studied in Section 4. It is seen that at both 2° and 4° latitude radius from the cyclone center, the *p*-velocity in the area where the cyclone is turning into [octant 2 (left-front) for left-turning cyclones and octant 8 (right-front) for right-turning cyclones] is positive; i.e., air is subsiding. Such a subsidence will warm the column, lowering (increasing) pressure in the lower (upper) troposphere, thus partly balancing (the other part being provided by thermal advection) the change in relative vorticity in the column. Gray and Shea (1973) also speculated the formation of the eye of a tropical cyclone as a continual process of ventilation of air within the eye and the subsequent sinking and warming of air in the direction of cyclone motion. Thus, it appears that although steering (which can be broadly interpreted as the concomitant advection of vorticity and mass) is largely responsible for tropical cyclone motion, other physical processes (stretching of vortex tubes, sinking motion) do contribute to a certain extent.

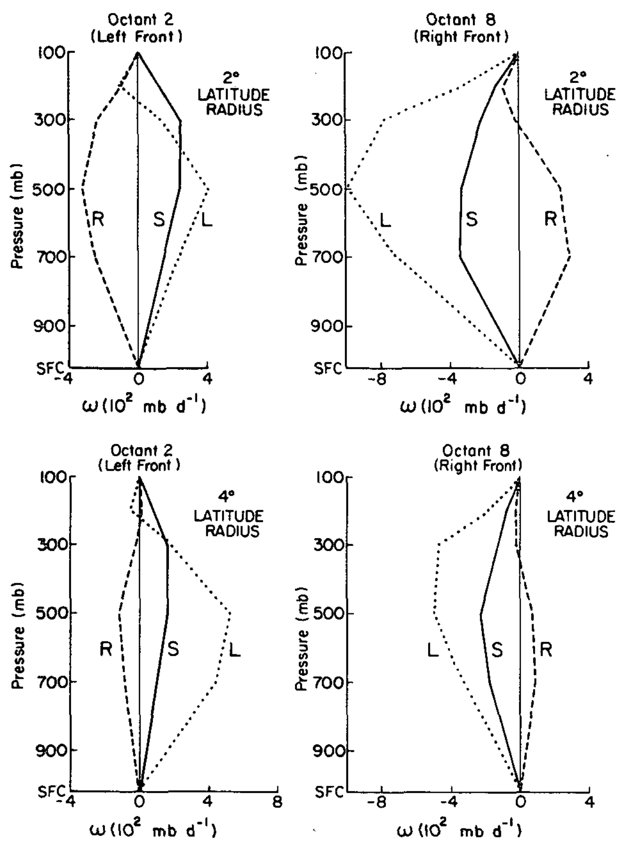


FIG. 14. Vertical motion (*p*-velocity) profiles of left-turning (*L*), straight-moving (*S*) and right-turning (*R*) cyclones at turn time and 2° and 4° lat radius in octants 2 (left-front) and 8 (right-front). The unit is 10^2 mb day^{-1}. Positive values indicate downward motion.

The vertical motion profiles in Fig. 14 also bring up another interesting point. On the side which the cyclone is *not* turning into, upward motion exists. This implies convection is probably more prevalent in this area. On the other hand, the side into which the cyclone is turning has subsidence, suggesting a reduction in convective cloudiness. Therefore, a comparison of the amount of convection between the left and right sides of a cyclone might provide some clues as to the future direction of movement of the cyclone. This, in fact, has been proposed by Lajoie (1976) from analyses of satellite pictures.

One major disadvantage of the present study is that the entire study is based on composite data. Although this is inevitable due to the sparseness of observations around tropical cyclones, limitations do exist in the interpretation of the results derived from the composites. The question of how representative the composite data are in individual cases often arises. The fact that results from two ocean basins (Section 3) agree with each other and appear to be physically reasonable provides some confidence that the rawinsonde composites are representative of individual cases. Nevertheless, efforts should still be made to verify the proposed hypothesis using individual cases. Attempts along this line should be possible with the data obtained from the proposal by R. Burpee of the National Hurricane Research Laboratory (American Meteorological Society, 1982) to fly research aircrafts around the periphery of individual cyclones and obtain dropwindsonde measurements at closely-spaced intervals. Data from these flights and the dropwindsondes may make it possible to perform computations for individual cyclones. Results can then be compared with those from the composites. The physical ideas presented in this paper can also be tested.

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APPENDIX

List of Symbols

- p pressure
- r radial distance from center of a cyclone
- R residual in the vorticity equation as defined in Eq. (1)
- t time
- u radial wind
- v tangential wind
- V vector horizontal wind velocity
- ω vertical p-velocity
- ζ relative vorticity
- ∇ horizontal del operator

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