Tropical Cyclone Movement and Surrounding Flow Relationships

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ABSTRACT

This paper presents results of a comprehensive study of the relationship between the movement of tropical cyclones and the large-scale circulation which surrounds them. Cyclones have been stratified by direction and speed of movement, latitude, intensity change and size (as determined by the radius of the outermost closed surface isobar) in three ocean basins: the northwest Pacific, the west Atlantic and the Australian-South Pacific region. Twenty-one different stratifications are available in the northwest Pacific, 13 in the west Atlantic and 6 in the Australian-South Pacific area. Cyclone movement and surrounding flow relationships were studied at different pressure levels and a variety of radii. Pressure-weighted layer-averages were also analyzed in search of such relationships.

Results show an important relationship between surrounding large-scale flow and tropical cyclone movement. For all stratifications, the winds in the mid-troposphere (500-700 mb) at 5-7° latitude radius from the cyclone center have the best correlation with cyclone movement. Tropical cyclones in the Northern Hemisphere move ~10-20° to the left of their surrounding mid-tropospheric flow at 5-7° latitude radius, and those in the Southern Hemisphere move ~10° to the right. It is also found that cyclones, in general, move ~1 m s⁻¹ faster than this flow. These general relationships appear to be modified by the vertical shear of the environmental wind, the zonal component of the cyclone velocity and other characteristics of the cyclone. The mean tropospheric flow (surface to 100 mb) at 5-7° latitude radius also correlates well with cyclone movement in most cases. For cyclones embedded in an environment with relatively small vertical wind shear, the mid-tropospheric flow is as good a descriptor of cyclone motion as the mean tropospheric flow. The average wind between the upper (200 mb) and lower (900 mb) troposphere also appears to correlate reasonably well with cyclone movement.

1. Introduction

It has long been observed that the movement of a tropical cyclone can be described, to a large extent, by the synoptic-scale flow surrounding the cyclone. These observations have led to the steering-flow theory of cyclone movement. It appears that a tropical cyclone can be considered as a point vortex embedded in an air current such that the direction and speed of the center can be approximated by those of its surrounding winds, or equivalently, the pressure or height gradients across the cyclone. The pressure level at which the speed and direction of the surrounding winds best correlate with those of the cyclone is called the steering level.

Based on this theory, a number of tropical cyclone track forecasting schemes have been developed, e.g., Riehl and Shafer (1944), Miller and Moore (1960), Tse (1966) and Renard et al. (1973). For a detailed description of these methods, the reader is referred to the WMO Tropical Cyclone Project Report (WMO, 1979). Although different forecast schemes employ different steering levels, it is generally accepted that the mid-tropospheric levels (700 and 500 mb) are the best for predicting tropical cyclone movement. Attempts to use winds and heights at upper tropospheric levels (see, e.g., Jordan, 1952; Miller, 1958) have not been as successful. No unified conclusion can be drawn from all these schemes on the location (relative to the cyclone center) at which one should measure the surrounding winds or height gradients to get the best description of cyclone movement for all classes of cyclones. This diversity exists because the data samples used in these studies have, in general, not been large and the variety of cyclone types have not been extensive.

A more comprehensive study on the steering flow problem is therefore necessary in order to determine:

1) Which level(s) is/are the best steering level(s);
2) How far from the center of the cyclone the surrounding flow best correlates with the movement of the cyclone; and
3) If this correlation varies among cyclones in different oceans, with different directions and speeds of movement, at different latitudes, of different intensities, intensity changes and sizes, etc.

George and Gray (1976) established the statistical relationship between the movement of northwest Pacific tropical cyclones and their surrounding winds averaged between 1-7° latitude radius from the cy-
TABLE 1. Description of stratifications of tropical cyclones in the northwest Pacific. All cyclones under study had a maximum sustained wind speed $V_{\text{max}} > 18$ m s$^{-1}$. The number of rawinsonde soundings in each group of stratifications within the $5^\circ$-$7^\circ$ latitude radial band is $\sim 1000$. CD is cyclone direction, CP is central pressure, ROCI is radius of outermost closed surface isobar averaged around the cyclone to the nearest whole degree latitude, and $V_c$ is cyclone speed.

<table>
<thead>
<tr>
<th>Stratification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude:</td>
<td></td>
</tr>
<tr>
<td>North cyclone</td>
<td>Latitude of cyclone $&gt;20^\circ$N</td>
</tr>
<tr>
<td>South cyclone</td>
<td>Latitude of cyclone $&lt;20^\circ$N</td>
</tr>
<tr>
<td>Speed:</td>
<td></td>
</tr>
<tr>
<td>Slow cyclone</td>
<td>Cyclone speed $V_c &lt; 3$ m s$^{-1}$</td>
</tr>
<tr>
<td>Moderate cyclone</td>
<td>$4$ m s$^{-1} &lt; V_c &lt; 7$ m s$^{-1}$</td>
</tr>
<tr>
<td>Fast cyclone</td>
<td>$V_c &gt; 7$ m s$^{-1}$</td>
</tr>
<tr>
<td>Direction:</td>
<td></td>
</tr>
<tr>
<td>Westward cyclone</td>
<td>$250^\circ &lt; CD &lt; 310^\circ$</td>
</tr>
<tr>
<td>Northward cyclone</td>
<td>$310^\circ &lt; CD &lt; 350^\circ$</td>
</tr>
<tr>
<td>Eastward cyclone</td>
<td>$350^\circ &lt; CD &lt; 60^\circ$</td>
</tr>
<tr>
<td>Intensity:</td>
<td></td>
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<tr>
<td>Weak cyclone</td>
<td>$980$ mb $&lt; CP &lt; 1000$ mb</td>
</tr>
<tr>
<td>Intense cyclone</td>
<td>$950$ mb $&lt; CP &lt; 980$ mb</td>
</tr>
<tr>
<td>Very Intense cyclone</td>
<td>$CP &lt; 950$ mb</td>
</tr>
<tr>
<td>Intensity change:</td>
<td></td>
</tr>
<tr>
<td>Deepening north cyclone</td>
<td>CP decreasing at time of observation; latitude of cyclone $&gt; 20^\circ$N</td>
</tr>
<tr>
<td>Deepening south cyclone</td>
<td>CP decreasing at time of observation; latitude of cyclone $&lt; 20^\circ$N</td>
</tr>
<tr>
<td>Filling north cyclone</td>
<td>CP increasing at time of observation; latitude of cyclone $&gt; 20^\circ$N</td>
</tr>
<tr>
<td>Filling south cyclone</td>
<td>CP increasing at time of observation; latitude of cyclone $&lt; 20^\circ$N</td>
</tr>
<tr>
<td>Size and intensity:</td>
<td></td>
</tr>
<tr>
<td>Small tropical storm</td>
<td>$980$ mb $&lt; CP &lt; 1000$ mb; $1^\circ &lt; \text{ROCI} &lt; 3^\circ$</td>
</tr>
<tr>
<td>Medium tropical storm</td>
<td>$980$ mb $&lt; CP &lt; 1000$ mb; $4^\circ &lt; \text{ROCI} &lt; 5^\circ$</td>
</tr>
<tr>
<td>Large tropical storm</td>
<td>$980$ mb $&lt; CP &lt; 1000$ mb; $\text{ROCI} &gt; 6^\circ$</td>
</tr>
<tr>
<td>Small typhoon</td>
<td>$CP &lt; 980$ mb; $1^\circ &lt; \text{ROCI} &lt; 3^\circ$</td>
</tr>
<tr>
<td>Medium typhoon</td>
<td>$CP &lt; 980$ mb; $4^\circ &lt; \text{ROCI} &lt; 5^\circ$</td>
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<tr>
<td>Large typhoon</td>
<td>$CP &lt; 980$ mb; $\text{ROCI} &gt; 6^\circ$</td>
</tr>
</tbody>
</table>

TABLE 2. As in Table 1, except for tropical cyclones in the west Atlantic. The number of rawinsonde soundings in each group of stratifications within the $5^\circ$-$7^\circ$ latitude radial band is $\sim 900$.

<table>
<thead>
<tr>
<th>Stratification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude:</td>
<td></td>
</tr>
<tr>
<td>Region I cyclone*</td>
<td>Location: latitude $&lt; 18^\circ$N, longitude $&gt; 45^\circ$W; or latitude $&lt; 22^\circ$N, $75^\circ$W $\leq$ longitude $&lt; 87^\circ$W</td>
</tr>
<tr>
<td>Region II cyclone*</td>
<td>Location: $18^\circ$N $&lt;$ latitude $&lt; 35^\circ$N, longitude $&gt; 45^\circ$W except those already included in Region I</td>
</tr>
<tr>
<td>Speed:</td>
<td></td>
</tr>
<tr>
<td>Slow cyclone</td>
<td>$V_c &lt; 4$ m s$^{-1}$</td>
</tr>
<tr>
<td>Fast cyclone</td>
<td>$V_c &gt; 4$ m s$^{-1}$</td>
</tr>
<tr>
<td>Direction:</td>
<td></td>
</tr>
<tr>
<td>Northward cyclone</td>
<td>CD $316^\circ$-$45^\circ$</td>
</tr>
<tr>
<td>Westward cyclone</td>
<td>CD $225^\circ$-$315^\circ$</td>
</tr>
<tr>
<td>Intensity:</td>
<td></td>
</tr>
<tr>
<td>Hurricane</td>
<td>$V_{\text{max}} &gt; 33$ m s$^{-1}$</td>
</tr>
<tr>
<td>Tropical storm</td>
<td>$18$ m s$^{-1} &lt; V_{\text{max}} &lt; 33$ m s$^{-1}$</td>
</tr>
<tr>
<td>Size and intensity:</td>
<td></td>
</tr>
<tr>
<td>Small tropical storm</td>
<td>$18$ m s$^{-1} &lt; V_{\text{max}} &lt; 33$ m s$^{-1}$; $1^\circ &lt; \text{ROCI} &lt; 3^\circ$</td>
</tr>
<tr>
<td>Large tropical storm</td>
<td>$18$ m s$^{-1} &lt; V_{\text{max}} &lt; 33$ m s$^{-1}$; $\text{ROCI} &gt; 4^\circ$</td>
</tr>
<tr>
<td>Small hurricane</td>
<td>$V_{\text{max}} &gt; 33$ m s$^{-1}$; $1^\circ &lt; \text{ROCI} &lt; 3^\circ$</td>
</tr>
<tr>
<td>Large hurricane north</td>
<td>Latitude of cyclones $&gt; 25^\circ$N; $V_{\text{max}} &gt; 33$ m s$^{-1}$; $\text{ROCI} &gt; 4^\circ$</td>
</tr>
<tr>
<td>Large hurricane south</td>
<td>Latitude of cyclones $&lt; 25^\circ$N; $V_{\text{max}} &gt; 33$ m s$^{-1}$; $\text{ROCI} &gt; 4^\circ$</td>
</tr>
</tbody>
</table>

* See Fig. 2 for a more detailed description of the regions.

winds. Furthermore, due to the usual lack of upper air data around the cyclone center, it is typically impossible to apply these results to describe the movement of an individual cyclone.

The present study is an extension of these two pre-

TABLE 3. As in Table 1, except for tropical cyclones in the Australian–South Pacific region. The number of rawinsonde soundings in each group of stratifications within the $5^\circ$-$7^\circ$ latitude radial band is $\sim 500$.

<table>
<thead>
<tr>
<th>Stratification</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Direction:</td>
<td></td>
</tr>
<tr>
<td>Eastward cyclone</td>
<td>CP $&lt; 990$ mb; $40^\circ &lt; \text{CD} &lt; 150^\circ$</td>
</tr>
<tr>
<td>Westward cyclone</td>
<td>CP $&lt; 990$ mb; $210^\circ &lt; \text{CD} &lt; 320^\circ$</td>
</tr>
<tr>
<td>Intensity and region:</td>
<td></td>
</tr>
<tr>
<td>All hurricanes</td>
<td>CP $&lt; 990$ mb</td>
</tr>
<tr>
<td>Coral Sea hurricanes</td>
<td>East of $136^\circ$E; CP $&lt; 980$ mb</td>
</tr>
<tr>
<td>Coral Sea tropical storm</td>
<td>East of $136^\circ$E; 980 mb $&lt; CP &lt; 995$ mb</td>
</tr>
<tr>
<td>West Australian hurricane</td>
<td>West of $136^\circ$E; CP $&lt; 980$ mb</td>
</tr>
</tbody>
</table>

clone center. They found that over this broad radial belt, the 500 mb winds have the strongest correlation with the direction of cyclone movement, while the 700 mb winds best correlate with cyclone speed. Gray (1977) presented a similar composite analysis of the winds at 1–7° radius around west Atlantic tropical cyclones. The results were in general agreement with those obtained by George and Gray (1976). Since the area over which the winds were averaged includes both the cyclone circulation and part of the environmental flow, this radial belt, therefore, will not provide the best description of the relationship between the movement of a cyclone and its environmental
vious analyses. Composite wind data over an area (5–7° latitude radius from the cyclone center) outside the strong inner circulation of the cyclone were correlated with cyclone movement in the west Atlantic, northwest Pacific and Australian–South Pacific regions. More stratifications for both west Atlantic and northwest Pacific cyclones have been included to test the validity of the conclusions in the two previous studies. Data at individual levels, as well as mean layer averages, were studied and compared for data sets with different characteristics. A combination of the winds in the lower (900 mb) and upper (200 mb) troposphere was also analyzed to more thoroughly test the idea of using upper and lower tropospheric winds to describe and predict cyclone movement as suggested by Chan et al. (1980). It is important to test this relationship because satellite-derived wind data at lower and upper tropospheric levels have become increasingly available.

2. Methodology and data stratifications

Because of the scarcity of data over the oceans where tropical cyclones spend most of their lifetime, the only way to obtain quantitative and representative results is to composite data around cyclones with similar characteristics so that a more even coverage of data can be obtained. Although such a procedure undoubtedly smooths out features particular to individual cyclones, those characteristics that are common to all cyclones in the same stratification should be isolated. In addition, random noise from the data will be largely eliminated through the process of averaging. A more detailed description of this compositing philosophy can be found in Williams and Gray (1973), Frank (1977), Gray (1981) and other Colorado State University tropical cyclone research reports. Corrections for balloon drift and mass-balance were made in the same way as described in these papers and reports.

a. Stratification of the cyclones

Tropical cyclones with maximum sustained wind speed \( V_{\text{max}} \geq 18 \text{ m s}^{-1} \) in the northwest Pacific (1961–1970), west Atlantic (1961–1974), and Australian–South Pacific (1961–1970) oceans were studied. The cyclones were stratified according to their direction and speed of movement, latitude, intensity, intensity change and size. These stratifications are listed in Tables 1, 2 and 3.

b. Compositing technique

Wind data from rawinsonde stations shown in Figs. 1 (northwest Pacific), 2 (west Atlantic) and 3 (Australian–South Pacific region) were composited around cyclones for the stratifications listed in Tables 1–3 using the circular grid shown in Fig. 4. The center of the grid coincides with the cyclone center. The grid has a radius of 15° latitude with eight radial bands. Each radial band is divided into eight equal segments (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. Each parameter (in this case

\(^1\) Hereafter all distances will be referred to in degrees latitude (1° latitude = 111.1 km).
the wind components), for all soundings, falling within any given grid box for a stratification is then averaged. This average value is assigned to the midpoint of the grid box giving 64 values of each parameter at each pressure level.

The wind vectors were resolved in two coordinate systems. The first system involves resolving each wind observation into a parallel component \( V_p \) along the direction of cyclone movement and a component normal \( V_N \) to this direction, as shown in Fig. 5. This will be referred to as the ROTated (ROT) system. In order to study the environmental flow relative to the cyclone, a second coordinate system is used in which the speed of the cyclone \( V_C \) was subtracted from the parallel wind component \( V_p \) for each sounding. The composite method was then applied to the difference \( V_p - V_C \) which is labeled as \( V_{PM} \) (see Fig. 6). This will be referred to as the MOTROT (for MOTion-ROTated) system. The normal component \( V_N \) is the same as in the ROT system. See George and Gray (1976) or Chan et al. (1980) for a more detailed description of these two coordinate systems.

3. Relationship between the surrounding flow and the direction of tropical cyclone movement

A convenient parameter to describe the relationship between the surrounding flow and the direction of movement of tropical cyclones is the difference between the direction of the surrounding wind and that of the cyclone. If the ROT system is used, this Directional Difference (DD) is given by

\[
DD = \begin{cases} 
\text{arctan} \left( \frac{V_N}{V_p} \right), & V_p > 0 \\
\text{arctan} \left( \frac{V_N}{V_p} \right) + 180^\circ, & V_N > 0, V_p < 0 \\
\text{arctan} \left( \frac{V_N}{V_p} \right) - 180^\circ, & V_N < 0, V_p < 0 
\end{cases}
\]

where \( V_N \) and \( V_p \) are the components of the composite wind normal and parallel to the direction of cyclone movement. The parameter DD therefore represents the deviation of the composite wind in a particular octant and radial band from the direction of movement of all tropical cyclones in a particular
stratification. A positive value of DD means that the
cyclone is moving to the left of the composite wind.

The basic assumption in the steering-flow theory
is that the vortex and its environmental circulations
do not interact. If this is the case, the directional
difference at the steering level should be approximately
the same for cyclones with different characteristics.
Under this assumption, the steering level can be
determined by studying the scatter of the values of DD
for data sets in the same ocean at each pressure level.
The level and radius with the least amount of scatter
is then assumed to be the steering level. Mid-tropo-
spheric (700–500 mb) data 5–7° from the cyclone
center appear to best satisfy this criterion. This is not
surprising, since forecasters have traditionally found
these to be the best steering levels.

To make use of this information in practice, re-
connaissance flights will have to be made to measure
winds at these levels because most of the time, few
or no rawinsonde observations are available around
a cyclone. Such flights, however, are not routinely
flown. A plausible alternative may be to use 200 and/
or 900 mb winds which can often be derived from
satellite pictures. An examination of the rawinsonde
data shows that the values of DD at these two levels

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**Fig. 3.** Australian-South Pacific region rawinsonde stations.

**Fig. 4.** Grid used for composing rawinsonde data. Arrow points
in the direction of storm motion. Outer numbers denote octants.
Numbers inside grid indicate distances from the center in degrees
latitude.
vary significantly between the different stratifications. However, if the $V_N$'s and $V_P$'s at these two levels are averaged and substituted into Eq. (1), the values of DD are quite consistent among data sets. This may prove to be rather useful in areas where only satellite-derived winds are available.

In some of the track forecast schemes, layer-averaged winds are used to represent the steering current (see, e.g., Riehl and Burgner, 1950; Jordan, 1952; Miller, 1958; Sanders and Burpee, 1968). To see if this idea would yield better results than "single-level steering," layer-averaged deviations (pressure-weighted) have also been computed.

One problem in steering flow studies is that the environmental flow around the cyclone might not be uniform. That is, each part of the cyclone may be subjected to a different current. The best way to avoid this problem is to consider the mean surrounding flow, i.e., by relating cyclone movement to the average flow around a radial band. To calculate the radial band average of DD, the values of $V_N$ and $V_P$ in each of the eight octants are averaged to obtain mean $V_N$ (or $\bar{V}_N$) and mean $V_P$ (or $\bar{V}_P$) values. Eq. (1) is then applied using $\bar{V}_N$ and $\bar{V}_P$ to give the radial band average of DD (or DD). The value DD therefore represents the difference between the direction of the mean wind in a particular radial band and that of the cyclone. This was done for all radial bands at each individual pressure level. As mentioned above, the smallest scatter in the values of DD appears 5–7° from the cyclone center. Therefore, only data at this radius will be presented.

a. Variation with height

1) NORTHWEST PACIFIC

Fig. 7 shows a plot of the 5–7° belt average winds in the ROT coordinate system at different levels for all data sets in the northwest Pacific. These winds were plotted using the values of $\bar{V}_N$ and $\bar{V}_P$. The direction of cyclone movement is towards the top of the figure. This figure shows that for all data sets, the cyclone is moving to the left of the mean wind direction at all cyclonic levels (below 300 mb) except near the boundary layer (below 900 mb). The least variability between data sets appears to be in the mid-troposphere. More variability exists both at the anticyclonic levels (above 300 mb) and in the boundary layer.

The actual variations of the belt average deviation of (DD) with height for all the data sets in the northwest Pacific are shown in Fig. 8. A positive number means that the cyclone is moving to the left of the mean wind. It can be seen that for most of the data sets, the values of DD do not vary much throughout a large portion of the troposphere. This suggests that the average flow around most of these cyclones does not have much directional wind shear in the vertical.

If the values of DD at different levels are compared among all the data sets, the ones in the mid-troposphere (500–700 mb) show the least amount of variation. This is apparent from Fig. 8. For a detailed, quantitative comparison, the reader is referred to Chan and Gray (1982).

Focusing at the middle levels, some variations within each category of cyclones can be seen in Fig. 8. Cyclones at latitudes north of 20°N seem to move more to the left of the mean wind than those south of 20°N. Similar results have also been obtained by Brand et al. (1981). DD values of slow-moving cyclones appear to be the largest among the speed composites. Westward-moving cyclones appear to move less to the left of the mean wind than northward- and eastward-moving cyclones. As a cyclone increases in intensity, it seems to move more to the left of the mean wind. The value of DD also appears to increase with the size of the cyclone.

Although variations exist, a general consistency between data sets (which have widely different characteristics) in the mid-troposphere is still remarkable. These results might suggest the general applicability of the steering flow theory at the middle levels. How-
ever, if such a theory is correct, one would expect the value of DD to be near zero. While this is true in a few stratifications, a systematic difference of $\sim 20^\circ$ exists between the mean 5–7° mid-tropospheric wind direction and the direction of cyclone movement. This suggests that the large-scale flow, though the dominant factor, is not totally responsible for the directional movement of the tropical cyclone. Other factors, which still need to be identified, must be present to provide such a systematic directional deviation.

The vertical variability in the values of DD for most data sets is also not very significant. Therefore,
it appears that winds at a single-level in the mid-troposphere might be used to describe the directional movement of a tropical cyclone equally as well as layer-averaged winds. More discussion of this will follow.

2) WEST ATLANTIC

Fig. 9 shows the 5–7° belt average winds in the ROT coordinate system for west Atlantic tropical cyclones. The portion of the atmosphere in which the

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**Fig. 8.** Variation with height of the 5–7° belt average wind deviation (DD, solid line) for all data sets in the northwest Pacific. The zero (dashed) line represents the direction of cyclone movement. A positive value means that the cyclone is moving to the left of the 5–7° belt average wind direction.
variability between data sets is small, seems to be
confined only to the mid-troposphere between 700
and 500 mb. For each data set, the variation in the
vertical is slightly larger, when compared with north-
west Pacific tropical cyclones. Most cyclones move
either in the same direction or to the right of the
mean winds below 800 mb. In the mid- to upper
troposphere, however, west Atlantic cyclones move
to the left of the mean wind, as in the northwest
Pacific. In the mid-troposphere the winds are, in gen-
eral, weaker than those in the northwest Pacific and
the values of DD are also smaller.
These observations are more clearly shown in Fig.
10. For all data sets except the westward-moving
cyclones, the values of DD appear to increase with
height from the surface up to ~150 mb. Westward-
moving cyclones tend to move in the same direction or even slightly to the right of the mean wind direction. Values of DD above 300 mb for this data set were not plotted because the winds are very weak, as shown in Fig. 9, and directional deviations are, therefore, less well defined. Again, if the values of DD at various levels are compared among the data sets, they are most consistent at the middle levels. More quantitative discussion of these observations can be found in the report of Chan and Gray (1982).

However, slight variations within each category of cyclones in the mid-troposphere are still discernible from Fig. 10. Region I (~south of 18°N) cyclones move less to the left of the mean winds than cyclones in Region II (~north of 18°N). Westward-moving cyclones have quite different values of DD than northward-moving cyclones. This is the same as the northwest Pacific, except it is more obvious for west Atlantic cyclones. The values of DD also appear to increase slightly with the size of the cyclones. However, from a practical point of view, the differences in the values of DD between cyclones of different sizes may not be distinguishable. Therefore, it might be safe to say that the direction of cyclone movement can be described adequately using the 5–7° mean mid-tropospheric wind, irrespective of the size of the cyclone. This is true in both the northwest Pacific and west Atlantic.

The general increase in the values of DD with height for west Atlantic tropical cyclones, suggests that the cyclones are in an environment with a stronger average directional vertical wind shear than northwest Pacific cyclones. This type of shear profile would imply that using layer-averaged steering might be superior to using single-level steering. This will be discussed in greater detail later.

3) AUSTRALIAN-SOUTH PACIFIC

Fig. 11 gives the 5–7° belt-averaged winds in the ROT coordinate system for tropical cyclones in the Australian–South Pacific region. At first glance, the data appear to be very noisy. However, a closer examination shows that for data sets classified under “intensity and region,” the variability among the data sets in the mid- to upper-troposphere is actually very small, with the cyclone moving to the right of the mean wind direction above 700 mb. This is also the case for eastward-moving cyclones. Westward-moving cyclones appear to move to the left of the mean wind at levels up to 400 mb.

These variations are better illustrated in Fig. 12, which gives the 5–7° belt-average deviations (DD) at different levels. The values of DD generally decrease with height, the exact opposite of the west Atlantic. These profiles again demonstrate the existence of an average directional wind shear profile in the vertical. This shear appears to be stronger in the lower troposphere (below ~600 mb). With the exception of eastward-moving cyclones, the values of DD in the mid-troposphere are fairly constant among all data sets.

The same type of difference in the DD profiles between westward and eastward-moving cyclones exists in this region as in the two Northern Hemisphere ocean basins (see Figs. 8 and 10). It appears that when directional vertical wind shear is present (as in the west Atlantic and Australian–South Pacific regions), this difference in directional deviations (between cyclones moving in different directions) is more obvious. One must conclude that the deviation of the cyclone direction from that of the mean wind at a
given level is related to the zonal and meridional
direction of cyclone motion.

4) SUMMARY

The results in this subsection show that the vertical
variation of the deviation of the cyclone direction
from the 5–7° belt average wind direction for all three
tropical regions depends on the directional vertical
wind shear of the environmental winds. The least
variability among data sets in a given ocean basin
appears to be in the mid-troposphere. Most cyclones
in the Northern Hemisphere move to the left of the
5–7° belt average wind (at least in the mid-tropo-
sphere) while cyclones in the Southern Hemisphere,
in general, move to the right of mid-tropospheric
winds at this radius. The direction of movement of
west Atlantic cyclones tends to deviate less to the left
of the mid-tropospheric mean wind (~10°) than those
in the northwest Pacific (~20°). In opposite
direction but probably with similar physical agree-
ment, cyclones in the Southern Hemisphere move to
the right of the mean winds at 600 and 500 mb. Parts
of these results are consistent with those obtained by
George and Gray (1976) and Brand et al. (1981) for
the northwest Pacific and those of Gray (1977) for
the west Atlantic. Such deviations appear to be
slightly modified by latitude, intensity and size of the
cyclone. Also, cyclones with different zonal compo-
nents of motion have large differences in their DD
values. The fact that consistent differences occur for
cyclones with east and west directions of movement
suggests the possible presence of other factors in de-
termining the direction of cyclone movement besides
the large-scale mean surrounding flow.

b. Level and layer-averages

Five averages were calculated: surface to 100, 300
and 500 mb; 700 to 500 mb; and the average between
the 200 and 900 mb levels. The first four layer in-
tegrations involve pressure-weighted averages and the
last is the arithmetic mean between the two levels.
The radial band averages of the two component winds
\( \bar{V}_N \), \( \bar{V}_P \) were integrated or averaged to get the layer-
average \( \langle \bar{V}_N \rangle \) and \( \langle \bar{V}_P \rangle \). That is, for the pressure-
weighted averages,

\[
\langle \bar{V}_N \rangle = \left( \int_{p_1}^{p_2} \bar{V}_N \, dp \right) / (p_2 - p_1),
\]

\[
\langle \bar{V}_P \rangle = \left( \int_{p_1}^{p_2} \bar{V}_P \, dp \right) / (p_2 - p_1),
\]

where \( p_1 \) and \( p_2 \) are the lower and upper pressure
levels of the layer. The 200 and 900 mb arithmetic
averages are defined by

\[
[\bar{V}_N] = \frac{1}{2} [\bar{V}_N(200 \text{ mb}) + \bar{V}_N(900 \text{ mb})].
\]

The layer- or level-averaged directional deviation is
then calculated by substituting \( \langle \bar{V}_N \rangle \), \( \langle \bar{V}_P \rangle \) or \( [\bar{V}_N] \),
\( [\bar{V}_P] \) into Eq. (1).

The reason for choosing the surface to 100 mb
layer-average is to test the validity of the suggestion
by Sanders and Burpee (1968) that the integrated tro-
ospheric flow is the most applicable “steering” cur-
rent. Richl and Burgner (1950) and Jordan (1952)
used the surface to 300 mb mean flow as their pre-
dictor. The surface to 500 mb mean flow is calculated
for comparison with the deeper surface to 300 mb
mean flow pattern. The results in the previous sub-
section indicate the importance of mid-tropospheric
flow and hence the 700 to 500 mb mean flow was also
calculated.

To compare different layer-averages, the scatter \( S \)
among the data sets is calculated. This is defined as

\[
S = \left[ \frac{1}{N} \sum_{i=1}^{N} (\overline{\text{DD}}_i - \overline{\text{DD}})^2 \right]^{1/2},
\]

where \( N \) is the total number of data sets, \( \overline{\text{DD}}_i \) is the
value of DD for the data set \( i \) and \( \overline{\text{DD}} \) is the mean
value of DD for all data sets. In a sense, the value of
\( S \) is similar to the standard deviation of a sample.
However, it cannot be interpreted in the same way
because the data sets are not all independent and the
values of DD are population means. Nevertheless,
this calculation will provide a measure of the spread
of the values of DD. The larger the value of \( S \), the
less “useful” will be the type of layer-average.

1) NORTHWEST PACIFIC

Table 4 shows the layer-averaged values of \( \overline{\text{DD}} \) for
northwest Pacific tropical cyclones. Not much vari-
ation exists between the different pressure-weighted
averages. This small variation is also reflected in the
mean for all the data sets. However, within each cat-
egory, slight differences exist between data sets. These
differences are consistent with those discussed in Sec-
tion 3a. Cyclones south of 20°N move less to the left
of all the layer-averaged flow than those north of
20°N. Slow-moving cyclones have the largest devia-
tions in the speed category. An increase in the direc-
tional deviation is also found to correlate very well
with an increase in cyclone intensity. The deviation
also increases with cyclone size. The different layer-
averages have approximately the same scatter among
the data sets. The mean flow corresponding to the
layer of cyclonic flow (surface to 300 mb or surface
to 500 mb) is slightly better than the other levels.
These results again demonstrate the absence of ap-
preciable directional wind shear in the vertical.

The 200 and 900 mb average directional deviations
also relate in a reasonable way to cyclone motion.
With the exception of the large tropical storm data
TABLE 4. Directional deviations between cyclone direction and direction of level- or layer-averaged 5–7° mean winds for different combinations of levels for northwest Pacific tropical cyclones. See text for a description of how these averages and the scatter were calculated.

<table>
<thead>
<tr>
<th>Stratification</th>
<th>100 mb surface</th>
<th>300 mb surface</th>
<th>500 mb surface</th>
<th>700 mb surface</th>
<th>200 mb + 900 mb Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North of 20°N</td>
<td>19</td>
<td>19</td>
<td>15</td>
<td>23</td>
<td>16</td>
</tr>
<tr>
<td>South of 20°N</td>
<td>2</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Speed:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow (1–3 m s⁻¹)</td>
<td>29</td>
<td>27</td>
<td>10</td>
<td>30</td>
<td>22</td>
</tr>
<tr>
<td>Moderate (4–7 m s⁻¹)</td>
<td>20</td>
<td>20</td>
<td>14</td>
<td>23</td>
<td>16</td>
</tr>
<tr>
<td>Fast (&gt;7 m s⁻¹)</td>
<td>12</td>
<td>14</td>
<td>15</td>
<td>18</td>
<td>9</td>
</tr>
<tr>
<td>Direction:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Westward (250–310°)</td>
<td>9</td>
<td>17</td>
<td>18</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>Northward (310–350°)</td>
<td>16</td>
<td>17</td>
<td>13</td>
<td>23</td>
<td>13</td>
</tr>
<tr>
<td>Eastward (350–60°)</td>
<td>17</td>
<td>16</td>
<td>13</td>
<td>19</td>
<td>15</td>
</tr>
<tr>
<td>Intensity:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weak (1000–980 mb)</td>
<td>8</td>
<td>14</td>
<td>16</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>Intense (950–980 mb)</td>
<td>16</td>
<td>20</td>
<td>18</td>
<td>25</td>
<td>9</td>
</tr>
<tr>
<td>Very intense (&lt;950 mb)</td>
<td>23</td>
<td>26</td>
<td>22</td>
<td>34</td>
<td>13</td>
</tr>
<tr>
<td>Intensity change:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deepening north of 20°N</td>
<td>23</td>
<td>23</td>
<td>17</td>
<td>23</td>
<td>21</td>
</tr>
<tr>
<td>Deepening south of 20°N</td>
<td>14</td>
<td>24</td>
<td>30</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>Filling north of 20°N</td>
<td>19</td>
<td>20</td>
<td>17</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>Filling south of 20°N</td>
<td>8</td>
<td>13</td>
<td>10</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Size and intensity:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small tropical storm</td>
<td>9</td>
<td>12</td>
<td>11</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>Medium tropical storm</td>
<td>9</td>
<td>14</td>
<td>16</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>Large tropical storm</td>
<td>1</td>
<td>14</td>
<td>19</td>
<td>19</td>
<td>-15</td>
</tr>
<tr>
<td>Small typhoon</td>
<td>15</td>
<td>16</td>
<td>15</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>Medium typhoon</td>
<td>12</td>
<td>15</td>
<td>14</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>Large typhoon</td>
<td>27</td>
<td>29</td>
<td>26</td>
<td>31</td>
<td>22</td>
</tr>
<tr>
<td>Mean</td>
<td>15</td>
<td>18</td>
<td>16</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>Scatter</td>
<td>7.5</td>
<td>5.6</td>
<td>5.2</td>
<td>6.4</td>
<td>8.1</td>
</tr>
</tbody>
</table>

set, the variation between data sets is not large. The negative value for the large tropical storm data set is a result of the large negative deviation at 200 mb (see Fig. 8). The reason for this is unknown. These results suggest that it might be possible to use winds at these levels (derivable from satellite pictures) to describe the directional movement of tropical cyclones when other information is not available.

2) WEST ATLANTIC

Table 5 indicates that the directional variability between data sets in the west Atlantic is larger than in the northwest Pacific. The smallest variation appears to be for the surface to 300 mb and 700–500 mb averages. These results again point to the existence of directional wind shear in the vertical. When integrated over the lower troposphere (surface to 500 mb), the shear near the boundary layer gives a large variability among data sets. However, when the integration is made up to 300 mb or just in the midtroposphere (700–500 mb), the effect of the boundary layer is quite small. If the upper tropospheric flow is included (surface to 100 mb), a large variability exists because of the strong shear at the upper levels. Therefore, it appears that in the west Atlantic, where directional wind shear is present in the upper and lower troposphere, winds in either the mid-troposphere or a deep layer corresponding to the cyclonic rotation of the storm is a better descriptor of cyclone direction.

As in the northwest Pacific, small variations between data sets exist within each category. North cyclones move more to the left of the layer-averaged winds than south cyclones. In fact, south cyclones move slightly to the right of the mean flow. This is also the case for westward-moving cyclones. These two data sets (south and westward-moving) probably include almost the same cyclones since cyclones south of 20°N usually move west-northwestward. Northward-moving cyclones, on the other hand, are usually at higher latitudes. Therefore, consistent with north cyclones, they move more to the left of the mean wind. These results suggest the importance of the latitude (which relates to the Coriolis parameter) in cyclone motion. This question has been addressed in some theoretical studies (e.g., Holland, 1982;
Table 5. As in Table 4, except for west Atlantic tropical cyclones.

<table>
<thead>
<tr>
<th>Stratification</th>
<th>100 mb surface</th>
<th>100 mb 500 mb</th>
<th>200 mb + 900 mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Region I (South)</td>
<td>-1</td>
<td>-3</td>
<td>-7</td>
</tr>
<tr>
<td>Region II (North)</td>
<td>16</td>
<td>5</td>
<td>-4</td>
</tr>
<tr>
<td>Speed:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow (&lt;1-3 m s⁻¹)</td>
<td>11</td>
<td>3</td>
<td>-7</td>
</tr>
<tr>
<td>Fast (&gt;3 m s⁻¹)</td>
<td>14</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Direction:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northward (316–45°)</td>
<td>27</td>
<td>13</td>
<td>-5</td>
</tr>
<tr>
<td>Westward (225–315°)</td>
<td>-9</td>
<td>-5</td>
<td>-2</td>
</tr>
<tr>
<td>Intensity:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hurricane</td>
<td>10</td>
<td>3</td>
<td>-3</td>
</tr>
<tr>
<td>Tropical storm</td>
<td>6</td>
<td>-1</td>
<td>-8</td>
</tr>
<tr>
<td>Size and intensity:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small tropical storm</td>
<td>14</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Large tropical storm</td>
<td>22</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>Small hurricane</td>
<td>12</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Large hurricane north</td>
<td>22</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Large hurricane south</td>
<td>18</td>
<td>4</td>
<td>-12</td>
</tr>
<tr>
<td>Mean</td>
<td>13</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Scatter</td>
<td>9.7</td>
<td>7.7</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Chan, 1982). Anthes (1982) also presented a review of this topic. In the intensity category, hurricanes generally move more to the left of the layer-averaged flow than tropical storms. The deviation also appears to increase with cyclone size. The small (or even negative) deviation for the large hurricane south-moving data set is probably a result of the latitude of the cyclones.

Because of the shear between the upper and lower troposphere, the 200 and 900 mb average directional deviations do not give as small a variability as their counterparts in the northwest Pacific.

3) AUSTRALIAN-SOUTH PACIFIC REGION

Table 6 gives the layer-averaged DD values for tropical cyclones in the Australian–South Pacific region. The striking result is the consistency among data sets for the surface to 100 mb layer-average. It shows the Australian cyclones move to the right of the 5–7° mean tropospheric wind. Because of the large directional vertical wind shear, a relatively large variability exists among the different layer-averages for a given data set, with the exception of eastward-moving hurricanes (see Fig. 12). Again, because of the strong vertical directional shear, these layer-averages show a larger variability than those in the Northern Hemisphere ocean basins. This is also the case for the 200 and 900 mb average directional deviation.

4) SUMMARY

The mean DD values for all data sets for each level or layer-average for the three ocean basins are shown in Table 7. They show that the mean tropospheric

Table 6. As in Table 4, except for tropical cyclones in the Australian–South Pacific region.

<table>
<thead>
<tr>
<th>Stratification</th>
<th>100 mb surface</th>
<th>100 mb 500 mb</th>
<th>200 mb + 900 mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eastward (40–150°)</td>
<td>-10</td>
<td>-13</td>
<td>-14</td>
</tr>
<tr>
<td>Westward (210–320°)</td>
<td>-9</td>
<td>14</td>
<td>22</td>
</tr>
<tr>
<td>Intensity and region:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hurricane</td>
<td>-20</td>
<td>-12</td>
<td>3</td>
</tr>
<tr>
<td>Coral Sea hurricane</td>
<td>-15</td>
<td>-7</td>
<td>12</td>
</tr>
<tr>
<td>Coral Sea tropical storm</td>
<td>-13</td>
<td>-2</td>
<td>5</td>
</tr>
<tr>
<td>West Australian hurricane</td>
<td>-22</td>
<td>-8</td>
<td>10</td>
</tr>
<tr>
<td>Mean</td>
<td>-15</td>
<td>-5</td>
<td>6</td>
</tr>
<tr>
<td>Scatter</td>
<td>5.3</td>
<td>10.0</td>
<td>12.0</td>
</tr>
</tbody>
</table>

* Such a large directional difference is due to weak 900 mb winds (see Fig. 11). This value is therefore not well defined.
flow (surface to 100 mb) gives almost the same results for all the three ocean basins. It seems that the mean
tropospheric flow, on the average, would be the best
descriptor or predictor for direction of cyclone move-
m ent, with cyclones in the Northern Hemisphere
moving to the left of this flow by \( \sim 15^\circ \) and those in
the Southern Hemisphere moving to the right by app-
ximately the same amount. However, it appears that,
for individual ocean basins, the best layer de-
 pends on the directional vertical shear of the envi-
 ronmental wind in that region. In general, the more
directional shear there is with height, the deeper the
steering layer. When little directional shear is present,
mid-tropospheric and deep layer steering are com-
parable. The magnitude of vertical directional shear
also affects the degree of applicability of winds at 900
and 200 mb in describing the directional movement of
the cyclone.

It is important to note that the means in Tables
4–7 are meant to provide an idea of the average de-
viation of the cyclone direction and that of its envi-
r onmental flow. The deviation in individual cases will
differ from the mean, although in most cases not sig-
nificantly. The amount of this difference depends on
the various characteristics of the cyclone, as discussed
in the previous subsection.

4. Relationship between the surrounding flow and the
speed of tropical cyclones

In both coordinate systems described in Section
2b, the winds are resolved into two components, one
normal \( (V_N) \) and one parallel \( (V_P) \) to the direction of
 cyclone movement. The normal component \( V_N \) ob-
viously does not contribute to the scalar speed of the
cyclone. The study of the relation between the sur-
rounding flow and the speed \( V_C \) of a cyclone therefore
reduces to relating the parallel component of the wind
\( V_P \) to \( V_C \). If the large-scale surrounding flow is the
determining factor in cyclone speed, as is the case
with cyclone direction, then values of \( V_P \) relative to
cyclone movement, should be approximately the
same for different data sets. The MOTROT coordi-
nate system described in Section 2b is used for this
purpose. That is, for every wind observation, the
value of \( V_P \) relative to the cyclone \( (V_{PM}) \) is calculated
from

\[
V_{PM} = V_P - V_C.
\]

See Fig. 6 for an illustration of how this is done. A
 composite was then made using the individual values
of \( V_P - V_C \). The parameter \( V_{PM} \) therefore represents
the composite relative to the cyclone wind com-
ponent parallel to the cyclone direction. A negative
value of \( V_{PM} \) means that the cyclone is moving faster
than the composite wind.

As in the last section, the azimuthally-averaged
flow will be analyzed. The radial band average at each
pressure level and each radius is the average of the
\( V_{PM} \) for all eight octants in that radial band, denoted
by \( \bar{V}_{PM} \). To find the “best” steering level and radius
for cyclone speed, the scatter of \( \bar{V}_{PM} \) for data sets at
various levels and radii were calculated in the same
way described in the last section. Again, the 5–7°
radial band at the mid-tropospheric levels (700 and
500 mb) have the smallest scatter among data sets for
all three ocean basins. Following the procedure used
in Section 3, the variation of 5–7° \( V_{PM} \) with height
will be presented, followed by level- or layer-averaged
winds.

a. Variation with height

1) NORTHWEST PACIFIC

Fig. 13 shows the vertical profile of \( \bar{V}_{PM} \) at 5–7°
for northwest Pacific tropical cyclones. Not much
variation in the vertical exists for most data sets ex-
cept for the data set north of 20°N, the fast-moving,
eastward-moving, filling north of 20°N and large
typhoon data sets. This means that, with the excep-
tion of these five stratifications, the other cyclones are
gen erally embedded in an environment with relatively
small vertical speed shear.

The variation among data sets in the mid-tropo-
sphere is generally small, with \( \bar{V}_{PM} \approx -1 \) \( \text{m s}^{-1} \). However,
within each category, slight variations are still present.
Cyclones north of 20°N tend to move with the same speed as the mean mid-tropospheric
wind. Fast cyclones move slower than the 500 mb
**Fig. 13.** Variation with height of the 5–7° belt average relative component of the wind parallel to cyclone direction $v_{PM}$ for northwest Pacific tropical cyclones (solid line). The zero (dashed) line represents the cyclone speed. A negative value of $v_{PM}$ means that the cyclone is moving faster than the 5–7° surrounding wind.

Mean wind while both slow and moderate speed cyclones move faster than their environmental flow ($v_{PM} < 0$). Eastward-moving cyclones and those filling at latitudes north of 20°N move slower than the midtropospheric wind. All these cyclones have a strong northward and/or eastward component of motion. It seems, therefore, that the zonal and meridional components of cyclone motion have some effect on the speed of the cyclone relative to its surrounding wind.
2) West Atlantic

The vertical profiles of 5–7° $\bar{V}_{PM}$ values for west Atlantic tropical cyclones are shown in Fig. 14. The variation with height for most data sets is not very large. Noticeable exceptions are westward- and northward-moving cyclones, large tropical storms and large hurricanes north of 25°N. Again, all cyclones move faster than the lower and mid-tropospheric winds ($\bar{V}_{PM} < 0$). Between data sets, very little difference between the values of $\bar{V}_{PM}$ can be noticed, especially in the mid-troposphere. It is also of interest to note that a similar relationship between the 5–7° wind speed and the cyclone speed holds for cyclones of different sizes in both the northwest Pacific and the west Atlantic. It therefore appears that, despite the difference in the sizes of cyclones, the 5–7° surrounding flow can be used to describe the cyclone movement.

3) Australian-South Pacific

Fig. 15 shows the vertical profiles of 5–7° $\bar{V}_{PM}$ values for tropical cyclones in this region. Considerable variation of $\bar{V}_{PM}$ with height exists for most data sets, indicating a large speed shear in the vertical. Similar to those in the Northern Hemisphere, all cyclones move faster than the mean wind in the lower troposphere (below ~600 mb). Although strong shear is present, the values of $\bar{V}_{PM}$ in the mid-troposphere are approximately the same among different data sets. The main exception is the eastward-moving stratification, again pointing to the importance of the zonal component of cyclone motion.

4) Summary

The vertical profiles of $\bar{V}_{PM}$ at 5–7° do not show much variation among cyclones in the three ocean basins, when compared to the vertical profiles of directional deviations. Exceptions arise when the cyclone is in an environment with strong vertical speed shear. All the data sets indicate that cyclones, in general, tend to move faster than the 5–7° mean wind at the mid-troposphere. This is consistent with the results obtained by George and Gray (1976) and Gray (1977). Slight modifications to this rule could arise when cyclones have a large eastward component of motion. If the steering flow is totally responsible for the movement of a cyclone, one would expect $\bar{V}_{PM}$ to be near zero. The fact that $\bar{V}_{PM}$ is mostly negative, at least in the mid-troposphere, points out the existence of other factors in the determination of the speed of a cyclone.

b. Level- or layer-averages

To calculate the pressure-weighted averages of $\bar{V}_{PM}$, Eq. (2b) was used with $\bar{V}_{PM}$ in the integrand of the numerator instead of $\bar{V}_p$. Similarly, the 200 and 900 mb arithmetic average of $\bar{V}_{PM}$ can be computed using $\bar{V}_{PM}$ instead of $\bar{V}_p$ in Eq. (3b). Similar pressure-
weighted averages were calculated: surface to 100, 300 and 500 mb, and 700 to 500 mb. The scatter among data sets is also computed in the way described in the last section.

1) NORTHWEST PACIFIC

Table 8 shows the four pressure-weighted layer averages and the 200 and 900 mb average $\overline{V}_{PM}$ for all northwest Pacific cyclones. As with the layer-averaged directional deviations, not much variation exists among the different averages. This is also evident from the mean for all the data sets. Slight variations within each category are also apparent. Cyclones south of 20°N move faster than the layer-averaged flow by a larger amount than those north of 20°N. The values of the integrated $\overline{V}_{PM}$ for eastward-moving cyclones are generally the least negative among the direction data sets. Very intense cyclones tend to move faster than the mean wind by the largest amount within the intensity category. For the same intensity change, north cyclones have $\overline{V}_{PM}$ values less

<table>
<thead>
<tr>
<th>Stratification</th>
<th>$\int_{100\ mb}^{\ surface}$</th>
<th>$\int_{300\ mb}^{\ surface}$</th>
<th>$\int_{500\ mb}^{\ surface}$</th>
<th>$\int_{500\ mb}^{\ 700\ mb}$</th>
<th>$200\ mb + 900\ mb$</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude: North of 20°N</td>
<td>-0.6</td>
<td>-1.0</td>
<td>-1.7</td>
<td>-0.6</td>
<td>-0.6</td>
<td></td>
</tr>
<tr>
<td>South of 20°N</td>
<td>-1.3</td>
<td>-1.6</td>
<td>-1.7</td>
<td>-1.5</td>
<td>-0.8</td>
<td></td>
</tr>
<tr>
<td>Speed: Slow (1-3 m s$^{-1}$)</td>
<td>-0.9</td>
<td>-0.9</td>
<td>-0.9</td>
<td>-0.6</td>
<td>-0.7</td>
<td></td>
</tr>
<tr>
<td>Moderate (4-7 m s$^{-1}$)</td>
<td>-1.1</td>
<td>-1.1</td>
<td>-1.3</td>
<td>-0.9</td>
<td>-1.1</td>
<td></td>
</tr>
<tr>
<td>Fast (&gt;7 m s$^{-1}$)</td>
<td>-0.1</td>
<td>-1.3</td>
<td>-3.0</td>
<td>-0.6</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Direction: Westward (250-310°)</td>
<td>-2.2</td>
<td>-2.3</td>
<td>-2.4</td>
<td>-2.4</td>
<td>-1.7</td>
<td></td>
</tr>
<tr>
<td>Northward (310-350°)</td>
<td>-1.5</td>
<td>-1.0</td>
<td>-0.8</td>
<td>-0.9</td>
<td>-2.0</td>
<td></td>
</tr>
<tr>
<td>Eastward (350-60°)</td>
<td>0.2</td>
<td>-0.5</td>
<td>-1.8</td>
<td>0.2</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Intensity: Weak (1000-980 mb)</td>
<td>-0.8</td>
<td>-1.1</td>
<td>-1.6</td>
<td>-0.9</td>
<td>-0.9</td>
<td></td>
</tr>
<tr>
<td>Intense (950-980 mb)</td>
<td>-0.7</td>
<td>-1.1</td>
<td>-1.6</td>
<td>-0.6</td>
<td>-0.7</td>
<td></td>
</tr>
<tr>
<td>Very intense (&lt;950 mb)</td>
<td>-1.4</td>
<td>-1.7</td>
<td>-1.9</td>
<td>-2.0</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>Intensity change: Deepening north of 20°N</td>
<td>-1.0</td>
<td>-1.1</td>
<td>-1.1</td>
<td>-1.1</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>Deepening south of 20°N</td>
<td>-1.5</td>
<td>-1.7</td>
<td>-1.7</td>
<td>-1.5</td>
<td>-1.1</td>
<td></td>
</tr>
<tr>
<td>Filling north of 20°N</td>
<td>0.2</td>
<td>-0.7</td>
<td>-1.9</td>
<td>-0.1</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Filling south of 20°N</td>
<td>-1.9</td>
<td>-2.3</td>
<td>-2.5</td>
<td>-2.4</td>
<td>-1.2</td>
<td></td>
</tr>
<tr>
<td>Size and intensity: Small tropical storm</td>
<td>-1.3</td>
<td>-1.2</td>
<td>-1.5</td>
<td>-1.1</td>
<td>-1.5</td>
<td></td>
</tr>
<tr>
<td>Medium tropical storm</td>
<td>-0.2</td>
<td>-0.7</td>
<td>-1.4</td>
<td>-0.6</td>
<td>-0.1</td>
<td></td>
</tr>
<tr>
<td>Large tropical storm</td>
<td>-1.7</td>
<td>-1.9</td>
<td>-2.3</td>
<td>-1.9</td>
<td>-1.5</td>
<td></td>
</tr>
<tr>
<td>Small typhoon</td>
<td>-1.2</td>
<td>-1.0</td>
<td>-1.0</td>
<td>-0.8</td>
<td>-1.4</td>
<td></td>
</tr>
<tr>
<td>Medium typhoon</td>
<td>-0.1</td>
<td>-0.4</td>
<td>-1.0</td>
<td>-0.3</td>
<td>-0.2</td>
<td></td>
</tr>
<tr>
<td>Large typhoon</td>
<td>-0.7</td>
<td>-1.0</td>
<td>-1.7</td>
<td>-1.0</td>
<td>-0.3</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>-0.9</td>
<td>-1.2</td>
<td>-1.7</td>
<td>-1.0</td>
<td>-0.7</td>
<td></td>
</tr>
<tr>
<td>Scatter</td>
<td>0.7</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>
than those of south cyclones. This is consistent with
the results for cyclones in the latitude category.

Apart from such small variations, these results
seem to suggest that a relatively shallow layer would
be nearly as representative of cyclone speed as a deep
layer average. This is of course a reflection of the
relatively small speed shear of the environmental
wind.

The values of 200 and 900 mb average $\bar{V}_{PM}$ are
also very consistent. This suggests that it may be possible
to use the 200 and 900 mb winds to describe
tropical cyclone movement in the northwest Pacific
with some degree of confidence.

2) WEST ATLANTIC

The layer-averaged 5–7° $\bar{V}_{PM}$ values for west
Atlantic tropical cyclones are shown in Table 9. The
variations among different averages is also small for
most data sets. The scatter among data sets is
approximately the same for all four layer-averages.

The 200 and 900 mb average $\bar{V}_{PM}$ has a much
larger scatter. This might restrict the use of this type
of data for describing the cyclone speed more in the
west Atlantic than in the northwest Pacific. Vertical
wind shears in the west Atlantic are generally larger,
probably due to the higher latitude of these storms.

3) AUSTRALIAN–SOUTH PACIFIC

Table 10 shows the level- and layer-averaged $\bar{V}_{PM}$
5–7° for tropical cyclones in this region. As men-
tioned before, the vertical speed shear in this region
is relatively large (see Fig. 15). Therefore, a large
variation among different layer-averages exists for a given
data set, as seen in Table 10. Both the surface to 500
mb and the 700 to 500 mb layer-averages give
extremely good consistency. The deep layer averages
have a larger spread. This is different than the layer-
average directional deviations discussed in Section 3
in which the mean tropospheric flow best describe the
directional movement of a cyclone. It appears from
Fig. 15 that the speed shear is too variable among
data sets to give a consistent $\bar{V}_{PM}$ when integrated
over a deep layer. However, if the integration is
through a shallower layer, the effect of the shear
would not be felt as much.

Because of this large spread in vertical wind
shear, the 200 and 900 mb average $\bar{V}_{PM}$ has a wide
scatter among data sets in this region. The possibility
of using 200 and 900 mb information for cyclone
steering in the Australian–South Pacific region is thus
more doubtful than in the northwest Pacific or the
west Atlantic.

4) SUMMARY

Layer-averaged $\bar{V}_{PM}$ for all data sets in each of the
three ocean basins is shown in Table 11. It can be
seen that in the three ocean basins, cyclones generally
move faster than the mean 5–7° level- or layer-av-
eraged winds. The most consistent layer-average ap-
pears to be the surface to 300 mb average. The mid-
tropospheric average is also approximately the same
between the three oceans. Therefore, it seems that

<table>
<thead>
<tr>
<th>Stratification</th>
<th>$\bar{V}_{PM}$ (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude:</td>
<td></td>
</tr>
<tr>
<td>Region I (south)</td>
<td>-1.3  -0.9  -0.7  -0.7  -1.7</td>
</tr>
<tr>
<td>Region II (north)</td>
<td>-1.4  -1.3  -1.3  -1.3  -1.2</td>
</tr>
<tr>
<td>Speed:</td>
<td></td>
</tr>
<tr>
<td>Slow (1–3 m s$^{-1}$)</td>
<td>-0.5  -0.5  -0.6  -0.6  -0.3</td>
</tr>
<tr>
<td>Fast (&gt;3 m s$^{-1}$)</td>
<td>-1.7  -1.8  -2.2  -1.7  -2.0</td>
</tr>
<tr>
<td>Direction:</td>
<td></td>
</tr>
<tr>
<td>Northward (316–45°)</td>
<td>-1.4  -1.6  -2.0  -1.5  -0.8</td>
</tr>
<tr>
<td>Westward (225–315°)</td>
<td>-2.2  -1.4  -0.7  -1.3  -2.8</td>
</tr>
<tr>
<td>Intensity:</td>
<td></td>
</tr>
<tr>
<td>Hurricane</td>
<td>1.3</td>
</tr>
<tr>
<td>Tropical storm</td>
<td>-1.6</td>
</tr>
<tr>
<td>Size and intensity</td>
<td></td>
</tr>
<tr>
<td>Small tropical storm</td>
<td>-1.4  -1.3  -1.4  -1.2  -1.2</td>
</tr>
<tr>
<td>Large tropical storm</td>
<td>-1.4  -1.8  -2.3  -1.7  -0.6</td>
</tr>
<tr>
<td>Small hurricane</td>
<td>-1.3  -1.3  -1.5  -1.4  -1.0</td>
</tr>
<tr>
<td>Large hurricane north</td>
<td>-0.6  -1.3  -2.2  -1.5  0.2</td>
</tr>
<tr>
<td>Large hurricane south</td>
<td>-1.7  -1.5  -1.2  -1.3  -1.5</td>
</tr>
<tr>
<td>Mean</td>
<td>-1.4  -1.3  -1.4  -1.3  -1.2</td>
</tr>
<tr>
<td>Scatter</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 9. As Table 8, except for west Atlantic tropical cyclones.
TABLE 10. As in Table 8, except for tropical cyclones in the Australian–South Pacific region.

<table>
<thead>
<tr>
<th>Stratification</th>
<th>100 mb</th>
<th>500 mb</th>
<th>200 mb + 900 mb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>surface</td>
<td>surface</td>
<td>Average</td>
</tr>
<tr>
<td>Direction:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eastward (40–150°)</td>
<td>0.2</td>
<td>-0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Westward (210–320°)</td>
<td>-2.2</td>
<td>-1.9</td>
<td>-3.3</td>
</tr>
<tr>
<td>Intensity and region:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hurricane</td>
<td>-0.7</td>
<td>-1.3</td>
<td>-0.4</td>
</tr>
<tr>
<td>Coral Sea hurricane</td>
<td>-0.8</td>
<td>-1.5</td>
<td>-0.7</td>
</tr>
<tr>
<td>Coral Sea tropical storm</td>
<td>-2.4</td>
<td>-2.1</td>
<td>-2.4</td>
</tr>
<tr>
<td>West Australian hurricane</td>
<td>-0.1</td>
<td>-1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Mean</td>
<td>-1.0</td>
<td>-1.4</td>
<td>-0.8</td>
</tr>
<tr>
<td>Scatter</td>
<td>1.1</td>
<td>0.5</td>
<td>1.8</td>
</tr>
</tbody>
</table>

what layer-average is best, depends very much on the vertical wind shear profile in the environment. The 200 and 900 mb average $V_p$ appears not to be nearly as useful as the mean layer information.

5. Summary and discussion

The main conclusions of this study are:

1) The large-scale circulation is a key factor in determining the movement of tropical cyclones.

2) Wind data at the mid-troposphere (700, 600 and 500 mb) correlate best with both the direction and speed of cyclone movement.

3) On the average, tropical cyclones in the Northern Hemisphere moves $\sim$10–20° to the left of the surrounding mid-tropospheric winds at $\sim$6° radius from the cyclone center; an approximate opposite directional deviation occurs for cyclones in the Southern Hemisphere.

4) On the average, tropical cyclones move faster by $\sim$1 m s$^{-1}$ than the surrounding mid-tropospheric winds at $\sim$6° radius from the cyclone center.

5) Cyclones having different zonal directions of motion have different relationships with their 5–7° surrounding flow.

6) Deep tropospheric flow appears to be a good descriptor of cyclone movement; for cyclones in a relatively weak shear environment a shallow layer-average flow is equally suitable.

7) The average wind data between the upper (200 mb) and lower (900 mb) troposphere also correlate relatively well with the direction of movement and speed but less well than the wind data at the mid-troposphere or the mean layer data.

Some of these same conclusions were also made by George and Gray (1976), Gray (1977) and Brand et al. (1981). Bell and Lam (1980) found that northwest Pacific tropical cyclones move, on the average, 0.9 m s$^{-1}$ more northward and 3.4 m s$^{-1}$ more westward compared to the geostrophic steering flow. This means that cyclones having a westward component of motion, which is normally the case, move faster than and to the left of the geostrophic flow, in qualitative agreement with the present study.

From a forecasting point of view, these results imply that a forecasting scheme based on steering flow alone would tend to predict a cyclone to move to the right of and slower than the observed track. This, in fact, was found to be the case by Kasahara (1957) using a barotropic non-divergent model. Since then, other numerical forecasts of tropical cyclone movement based primarily on steering flow also produced a systematic rightward deflection of the predicted trajectory relative to the actual path and a predicted speed slower than the observed speed. See, for example, Kasahara (1959, 1960), Birchfield (1960), Jones (1961, 1977), Sanders and Burpee (1968), Anthes and Hoke (1975), Sanders et al. (1975), Har-

TABLE 11. As in Table 7, except for level- or layer-averaged $V_p$.

<table>
<thead>
<tr>
<th>Ocean basin</th>
<th>100 mb</th>
<th>500 mb</th>
<th>200 mb + 900 mb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>surface</td>
<td>surface</td>
<td>Average</td>
</tr>
<tr>
<td>Northwest Pacific</td>
<td>-0.9</td>
<td>-1.2</td>
<td>-0.7</td>
</tr>
<tr>
<td></td>
<td>(0.7)</td>
<td>(0.5)</td>
<td>(0.7)</td>
</tr>
<tr>
<td>West Atlantic</td>
<td>-1.4</td>
<td>-1.3</td>
<td>-1.2</td>
</tr>
<tr>
<td></td>
<td>(0.4)</td>
<td>(0.4)</td>
<td>(0.8)</td>
</tr>
<tr>
<td>Australian–South Pacific region</td>
<td>-1.0</td>
<td>-1.4</td>
<td>-0.8</td>
</tr>
<tr>
<td></td>
<td>(1.1)</td>
<td>(0.5)</td>
<td>(1.8)</td>
</tr>
</tbody>
</table>
rison (1981). Such systematic direction and speed biases have also been discussed by Neumann and Pelissier (1981) in the analyses of operational track forecast errors.

Some of the authors have attributed such biased rightward deflection in the predicted track to the influence of the Coriolis acceleration as discussed by Rossby (1948). Birchfield (1961) managed to reduce the rightward bias in his model by implicitly including an interaction between the storm vortex and its surrounding flow. He gave no physical explanation, however. Kasahara and Platzman (1963) solved a modified barotropic potential-vorticity equation which included an interaction between the vortex and the steering flow and obtained predicted directional tracks closer to the observed ones.

Theoretical studies by Rossby (1949), Adem (1956) and Kasahara and Platzman (1963) all suggest the importance of the zonal direction of cyclone motion in determining the relation between the environmental flow and cyclone movement. Their results imply a slight slow-down of vortex movement, relative to the surrounding flow for eastward-moving cyclones, while the opposite is true for westward- and northward-moving cyclones. The findings in this paper are consistent with these theoretical analyses. Recent studies by Chan (1982) and Holland (1982) also arrive at the same conclusion. They explained both the directional deviation and the difference between cyclone speed and environmental wind speed in terms of the variation of the Coriolis parameter across the cyclone.

All these theoretical and observational results point to the fact that although the environmental flow is important in the determination of cyclone motion, the steering flow theory cannot completely explain the physical processes involved in the movement of tropical cyclones. The interaction between the vortex and the environmental circulations must also be considered.

More detailed observational information on the relations between tropical cyclone movement and its environmental flow at individual levels and octants are contained in Chan and Gray (1982).

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