

# **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 for 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  $5-7^{\circ}$  latitude radius from the cyclone center have the best correlation with cyclone movement. Tropical cyclones in the Northern Hemisphere move about  $10-20^{\circ}$  to the left of their surrounding mid-tropospheric flow at  $5-7^{\circ}$  latitude radius and those in the Southern Hemisphere move about  $10^{\circ}$  to the right. It is also found that cyclones, in general, move faster by about  $1 \text{ m s}^{-1}$  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  $5-7^{\circ}$  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.

TABLE OF CONTENTS

	Page
1. INTRODUCTION . . . . .	1
2. METHODOLOGY AND DATA STRATIFICATIONS . . . . .	4
a. Stratifications of the Cyclones . . . . .	4
b. Composite Technique . . . . .	4
3. RELATIONSHIP BETWEEN THE SURROUNDING FLOW AND THE DIRECTION OF TROPICAL CYCLONE MOVEMENT. . . . .	14
a. Radial Band Average . . . . .	16
b. Individual Octants. . . . .	36
4. RELATIONSHIP BETWEEN THE SURROUNDING FLOW AND THE SPEED OF TROPICAL CYCLONES . . . . .	42
a. Radial Band Average . . . . .	42
b. Individual Octants. . . . .	57
5. SUMMARY AND DISCUSSION . . . . .	62
ACKNOWLEDGEMENTS. . . . .	65
REFERENCES. . . . .	66

## 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 idea, a number of tropical cyclone track forecasting schemes have been developed, for example 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 Number WMO-528 (World Meteorological Organization, 1979). Although different forecast schemes employ different steering levels, it is generally accepted that the mid-tropospheric levels (700 mb and 500 mb) are the best in predicting tropical cyclone movement. Attempts to use winds and heights at upper tropospheric levels (see for example, E. 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.

The study by 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 cyclone 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 a large part of the area over which the winds were averaged is very close to the cyclone center, these data included both the cyclone circulation and part of the environmental flow as well. This radial belt, therefore, will not provide the best description of the relationships between the movement of a cyclone and its environmental 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 previous analyses. Composite wind data over an area ( $5^{\circ}$ - $7^{\circ}$  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 test more thoroughly 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 the papers by 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 ( $V_{\max}$ )  $\geq 18 \text{ m s}^{-1}$  in the northwest Pacific (time period: 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 Fig. 1 (northwest Pacific), 2 (west Atlantic) and 3 (Australian-south Pacific region) were composited around cyclones for the stratifications listed in Tables 1-3



TABLE 1

Description of stratifications of tropical cyclones in the northwest Pacific. All cyclones under study had a maximum sustained wind speed ( $V_{max}$ )  $> 18 \text{ m s}^{-1}$ . The number of rawinsonde soundings in each group of stratifications within the  $5-7^{\circ}$  latitude radial band is  $\sim 1000$ .

<u>STRATIFICATION</u>	<u>DESCRIPTION</u>
<u>By Latitude</u>	
North Cyclone	Latitude of cyclone $> 20^{\circ}\text{N}$
South Cyclone	Latitude of cyclone $\leq 20^{\circ}\text{N}$
<u>By Speed</u>	
Slow Cyclone	Cyclone speed ( $V_c$ ) $\leq 3 \text{ m s}^{-1}$
Moderate Cyclone	$4 \text{ m s}^{-1} \leq V_c \leq 7 \text{ m s}^{-1}$
Fast Cyclone	$V_c > 7 \text{ m s}^{-1}$
<u>By Direction</u>	
Westward Cyclone	$250^{\circ} < \text{Cyclone Direction (CD)} \leq 310^{\circ}$
Northward Cyclone	$310^{\circ} < \text{CD} \leq 350^{\circ}$
Eastward Cyclone	$350^{\circ} < \text{CD} \leq 60^{\circ}$
<u>By Intensity</u>	
Weak Cyclone	$980 \text{ mb} < \text{Central Pressure (CP)} \leq 1000 \text{ mb}$
Intense Cyclone	$950 \text{ mb} \leq \text{CP} \leq 980 \text{ mb}$
Very Intense Cyclone	$\text{CP} < 950 \text{ mb}$
<u>By Intensity Change</u>	
Deepening North Cyclone	CP was decreasing at the time of observation; latitude of cyclone $> 20^{\circ}\text{N}$
Deepening South Cyclone	CP was decreasing at the time of observation; latitude of cyclone $\leq 20^{\circ}\text{N}$
Filling North Cyclone	CP was increasing at the time of observation; latitude of cyclone $> 20^{\circ}\text{N}$
Filling South Cyclone	CP was increasing at the time of observation; latitude of cyclone $\leq 20^{\circ}$
<u>By Size and Intensity</u>	
Small Tropical Storm	$980 < \text{CP} < 1000 \text{ mb}$ ; $1^{\circ} < \text{ROCI}^1 < 3^{\circ}$
Medium Tropical Storm	$980 \text{ mb} < \text{CP} < 1000 \text{ mb}$ ; $4^{\circ} < \text{ROCI} < 5^{\circ}$
Large Tropical Storm	$980 \text{ mb} < \text{CP} < 1000 \text{ mb}$ ; $\text{ROCI} > 6^{\circ}$
Small Typhoon	$\text{CP} \leq 980 \text{ mb}$ ; $1^{\circ} \leq \text{ROCI} \leq 3^{\circ}$
Medium Typhoon	$\text{CP} \leq 980 \text{ mb}$ ; $4^{\circ} \leq \text{ROCI} \leq 5^{\circ}$
Large Typhoon	$\text{CP} \leq 980 \text{ mb}$ ; $\text{ROCI} \geq 6^{\circ}$

<sup>1</sup> ROCI - radius of outermost closed surface isobar averaged around the cyclone to the nearest whole degree latitude.

TABLE 2

Same as Table 1 except for tropical cyclones in the west Atlantic. The number of rawinsonde soundings in each group of stratifications within the 5-7° latitude radial band is ~ 900.

<u>STRATIFICATION</u>	<u>DESCRIPTION</u>
<u>By Latitude</u>	
Region I Cyclone <sup>2</sup>	Cyclone location: lat. $\leq 18^{\circ}\text{N}$ , long. $> 45^{\circ}\text{W}$ or lat. $< 22^{\circ}\text{N}$ , $75^{\circ}\text{W} \leq \text{long.} \leq 87^{\circ}\text{W}$ .
Region II Cyclone <sup>2</sup>	Cyclone location: $18^{\circ}\text{N} < \text{lat.} \leq 35^{\circ}\text{N}$ long. $\geq 45^{\circ}\text{W}$ except those already included in Region I.
<u>By Speed</u>	
Slow Cyclone	Cyclone speed $< 4 \text{ m s}^{-1}$
Fast Cyclone	Cyclone speed $\geq 4 \text{ m s}^{-1}$
<u>By Direction</u>	
Northward Cyclone	Direction of movement: $316^{\circ}-45^{\circ}$
Westward Cyclone	Direction of movement: $225^{\circ}-315^{\circ}$
<u>By Intensity</u>	
Hurricane	Maximum sustained wind ( $V_{\text{max}}$ ) $\geq 33 \text{ m s}^{-1}$
Tropical Storm	$18 \text{ m s}^{-1} \leq V_{\text{max}} < 33 \text{ m s}^{-1}$
<u>By Size and Intensity</u>	
Small Tropical Storm	$18 \text{ m s}^{-1} \leq V_{\text{max}} < 33 \text{ m s}^{-1}$ ; $1^{\circ} \leq \text{ROCI} \leq 3^{\circ}$
Large Tropical Storm	$18 \text{ m s}^{-1} \leq V_{\text{max}} < 33 \text{ m s}^{-1}$ ; $\text{ROCI} \geq 4^{\circ}$
Small Hurricane	$V_{\text{max}} \geq 33 \text{ m s}^{-1}$ ; $1^{\circ} \leq \text{ROCI} \leq 3^{\circ}$
Large Hurricane North	Latitude of cyclones $> 25^{\circ}\text{N}$ $V_{\text{max}} \geq 33 \text{ m s}^{-1}$ ; $\text{ROCI} \geq 4^{\circ}$
Large Hurricane South	Latitude of cyclones $\leq 25^{\circ}\text{N}$ $V_{\text{max}} \geq 33 \text{ m s}^{-1}$ ; $\text{ROCI} \geq 4^{\circ}$

<sup>2</sup>See Fig. 2 for a more detailed description of the regions.

TABLE 3

Same as Table 1 except for tropical cyclones in the Australian-south Pacific region. The number of rawinsonde soundings in each group of stratifications within the 5-7° latitude radial band is ~ 500.

<u>STRATIFICATION</u>	<u>DESCRIPTION</u>
<u>By Direction</u>	
Eastward Cyclone	CP $\leq$ 990 mb 40° $\leq$ CD $\leq$ 150°
Westward Cyclone	CP $\leq$ 990 mb 210° $\leq$ CD $\leq$ 320°
<u>By Intensity and Region</u>	
All Hurricanes	CP $\leq$ 990 mb
Coral Sea Hurricanes	Longitude east of 136°E CP $\leq$ 980 mb
Coral Sea Tropical Storm	Longitude east of 136°E 980 mb $<$ CP $<$ 995 mb
West Australian Hurricane	Longitude west of 136°E CP $\leq$ 980 mb

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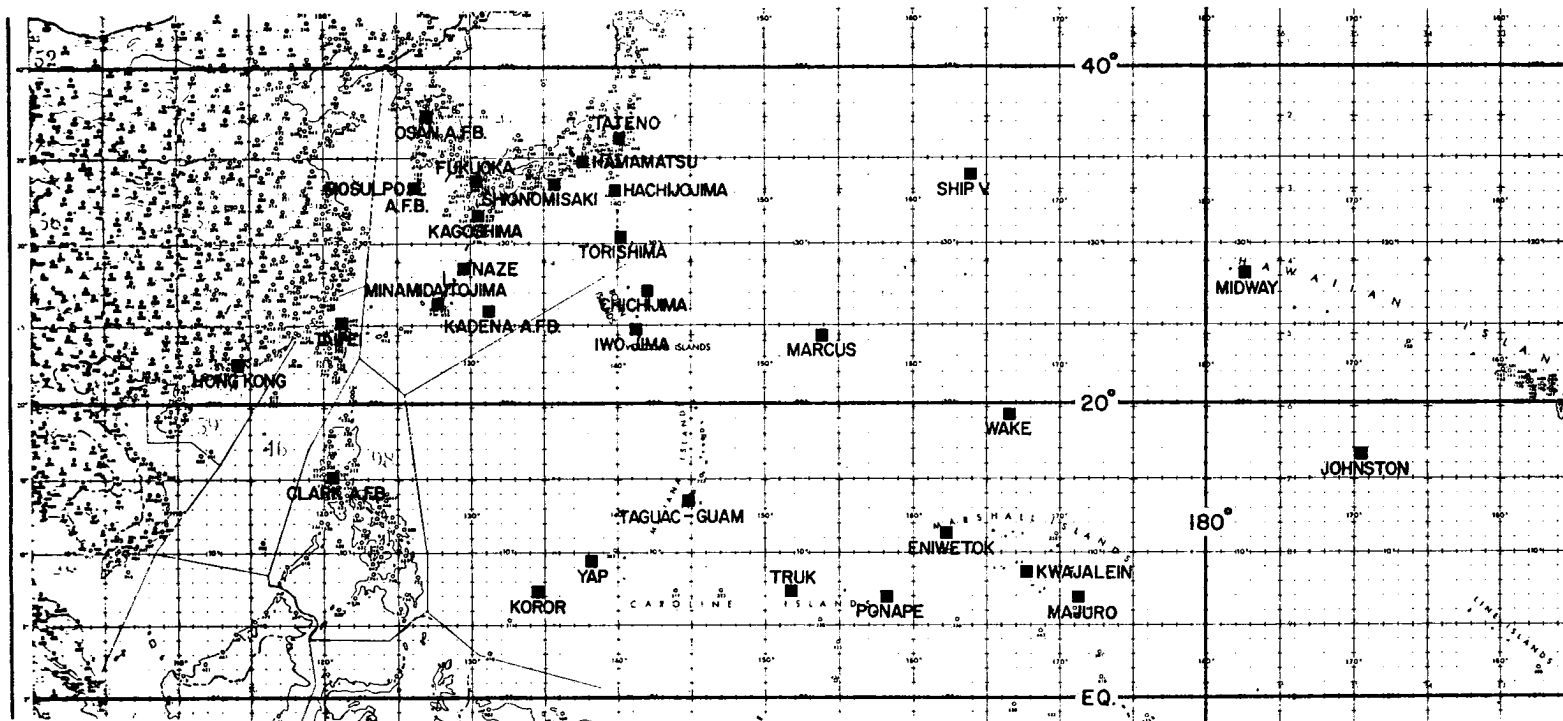


Figure 1. Northwest Pacific rawinsonde stations.

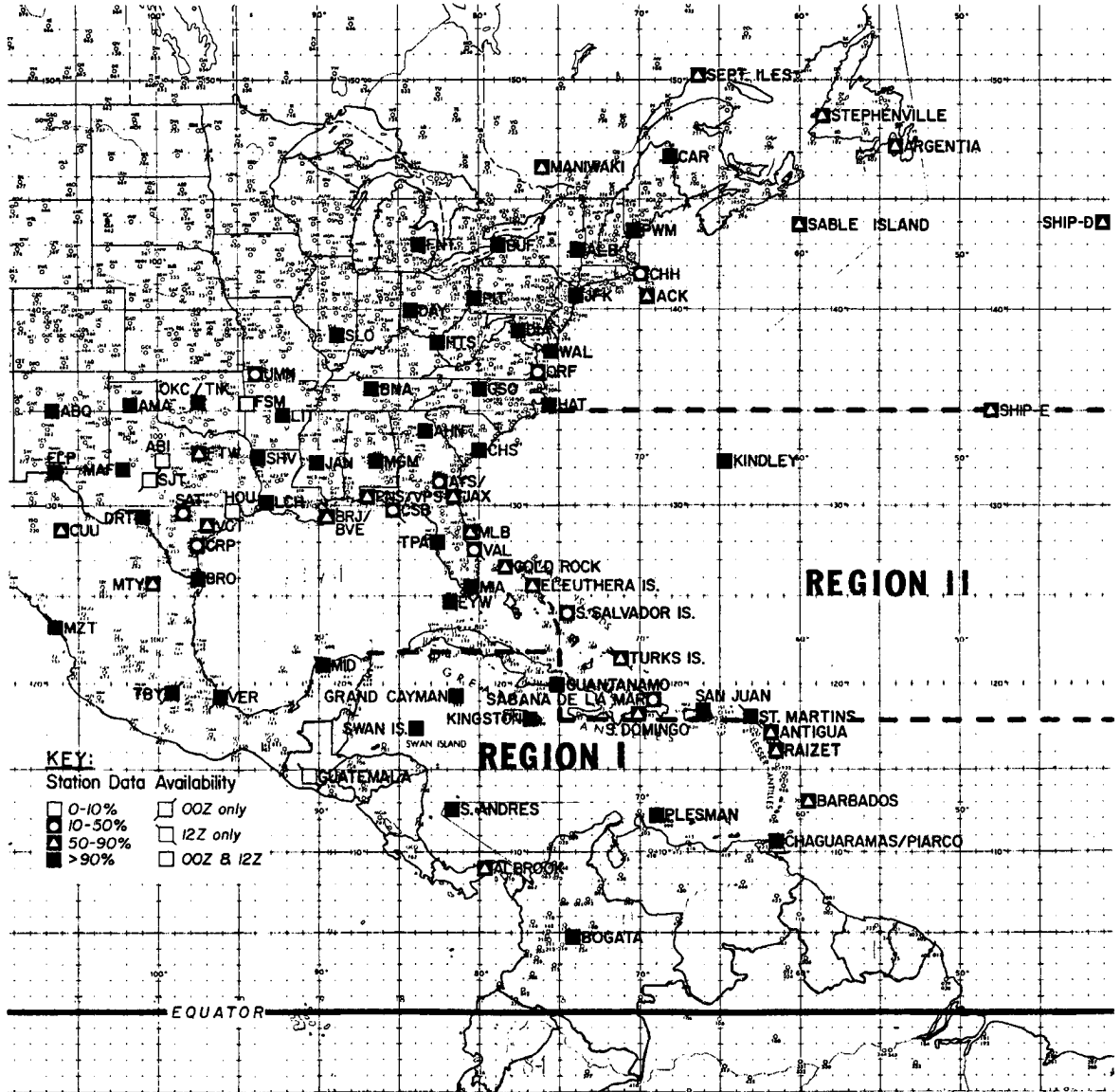


Figure 2. West Atlantic rawinsonde stations.

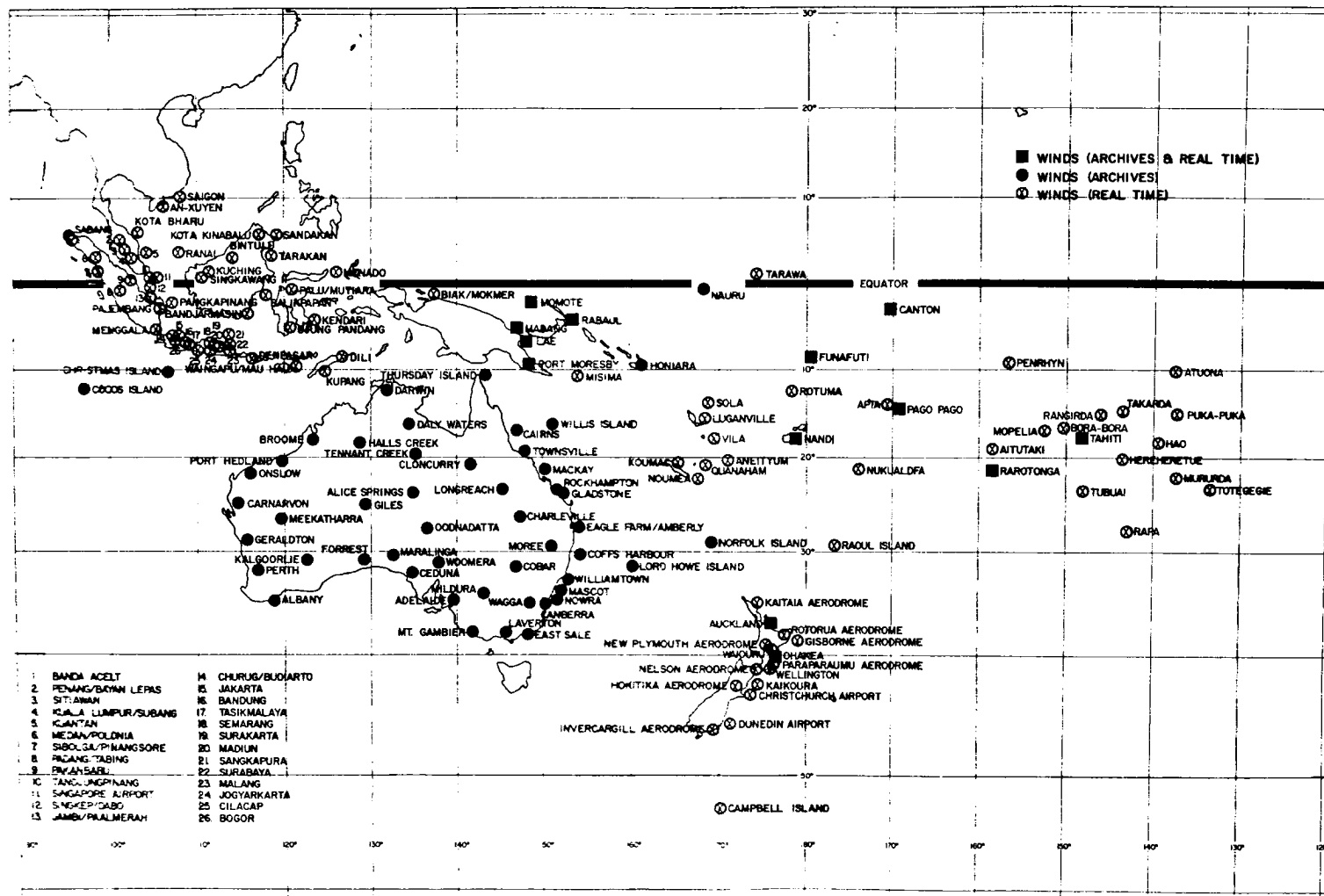


Figure 3. Australian-south Pacific region rawinsonde stations.

using the circular grid shown in Fig. 4. The center of the grid coincides with the cyclone center. The grid has a radius of  $15^\circ$  latitude<sup>3</sup> with eight radial bands. Each radial band is divided into eight equal segments or octants and numbered from 1 to 8 in a counterclockwise fashion, with Octant 1 always being in front of the cyclone.

The  $\pm 6$ h (from current position) best-track positions were used to determine the direction and speed of cyclone movement. Each parameter (in this case the wind components) for all soundings falling within any given grid box for a stratification are then averaged. This average value is assigned to the mid-point 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 out of 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.

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<sup>3</sup> Hereafter all distances will be referred to in degrees latitude ( $1^\circ$  latitude = 111.1 km).

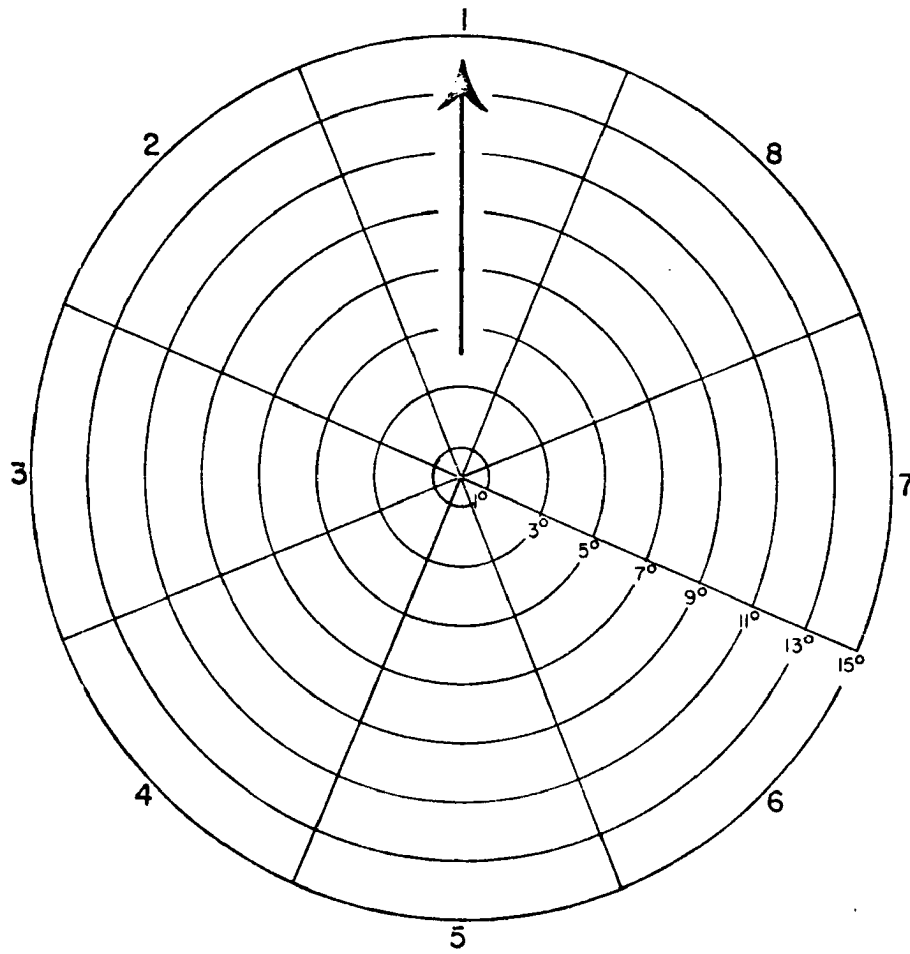


Figure 4. Grid used for compositing rawinsonde data. The arrow points in the direction of storm motion. Outer numbers denote octants. Numbers inside grid indicate distances from the center in degrees latitude.



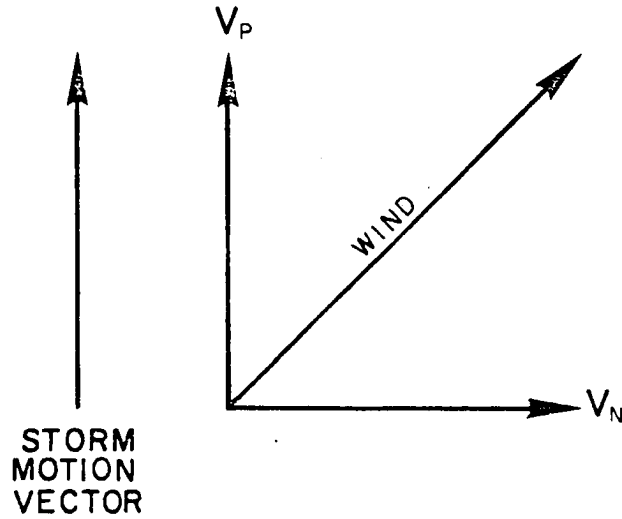


Figure 5. Parallel ( $V_P$ ) and perpendicular ( $V_N$ ) component of a wind vector showing their relation to the storm motion vector in the ROT system.

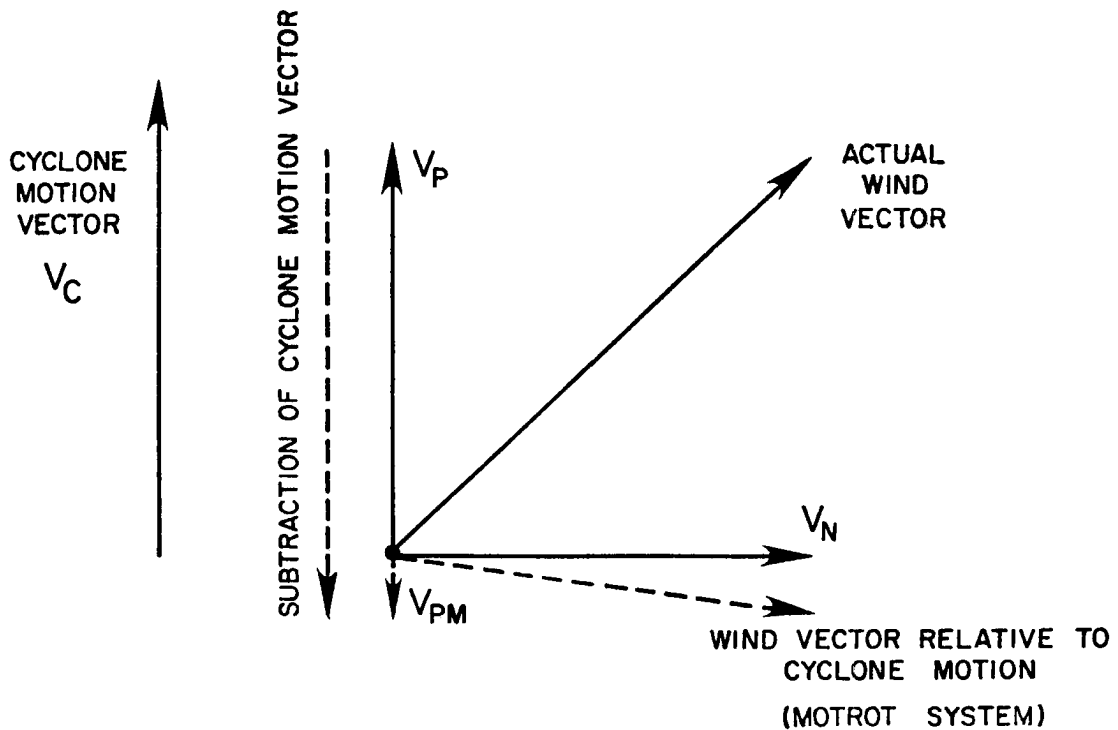


Figure 6. Illustration of the MOTion-ROTated (MOTROT) coordinate system.

### 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 described in section 2b is used, this Directional Difference (DD) is given by

$$DD = \begin{cases} \arctan (V_N/V_P) & V_P > 0 \\ \arctan (V_N/V_P) + 180^\circ & V_N > 0, V_P < 0 \\ \arctan (V_N/V_P) - 180^\circ & V_N < 0, V_P < 0 \end{cases} \quad (1)$$

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 about 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 scatter S is

$$S = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2}$$

where  $N$  = number of data sets

$x_i$  = value of the parameter  $x$  for data set  $i$

$\bar{x}$  = mean value of the parameter  $x$  for all data sets.

In a sense, the scatter is analogous to the standard deviation of a data sample. However, it cannot be interpreted in the same way because the values of  $x_i$  in this case are not all independent from one another. Furthermore, the  $x_i$ 's are population means. Nevertheless, the value of  $S$  should provide an idea as to the spread of the parameter  $x$  among different data sets. The level and radius with the least amount of scatter is then assumed to be the steering level. Mid-tropospheric (700-500 mb) data 5-7<sup>0</sup> from the cyclone center appear to satisfy this criterion the best. This is not surprising since forecasters have traditionally found these to be the best steering levels.

To make use of this information in practice, reconnaissance 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 mb 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 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, for example, Riehl and Burgner, 1950; E. 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.

In the following sections, two sets of DD values will be presented: the radial band averages and those at individual octants.

a. Radial Band Average

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  $\overline{DD}$ ). The value  $\overline{DD}$  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  $\overline{DD}$  appears 5-7° from the cyclone center. Therefore, only data at this radius will be presented.

(i) Variation With Height

Northwest Pacific. Figure 7 shows a plot of the 5-7° belt average winds in the ROT coordinate system (see section 2b) 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 the data sets, the cyclone is moving to the left of the direction of the mean wind at all the cyclonic levels (below 300 mb) except near the boundary layer (below 900 mb). The least variability between data sets

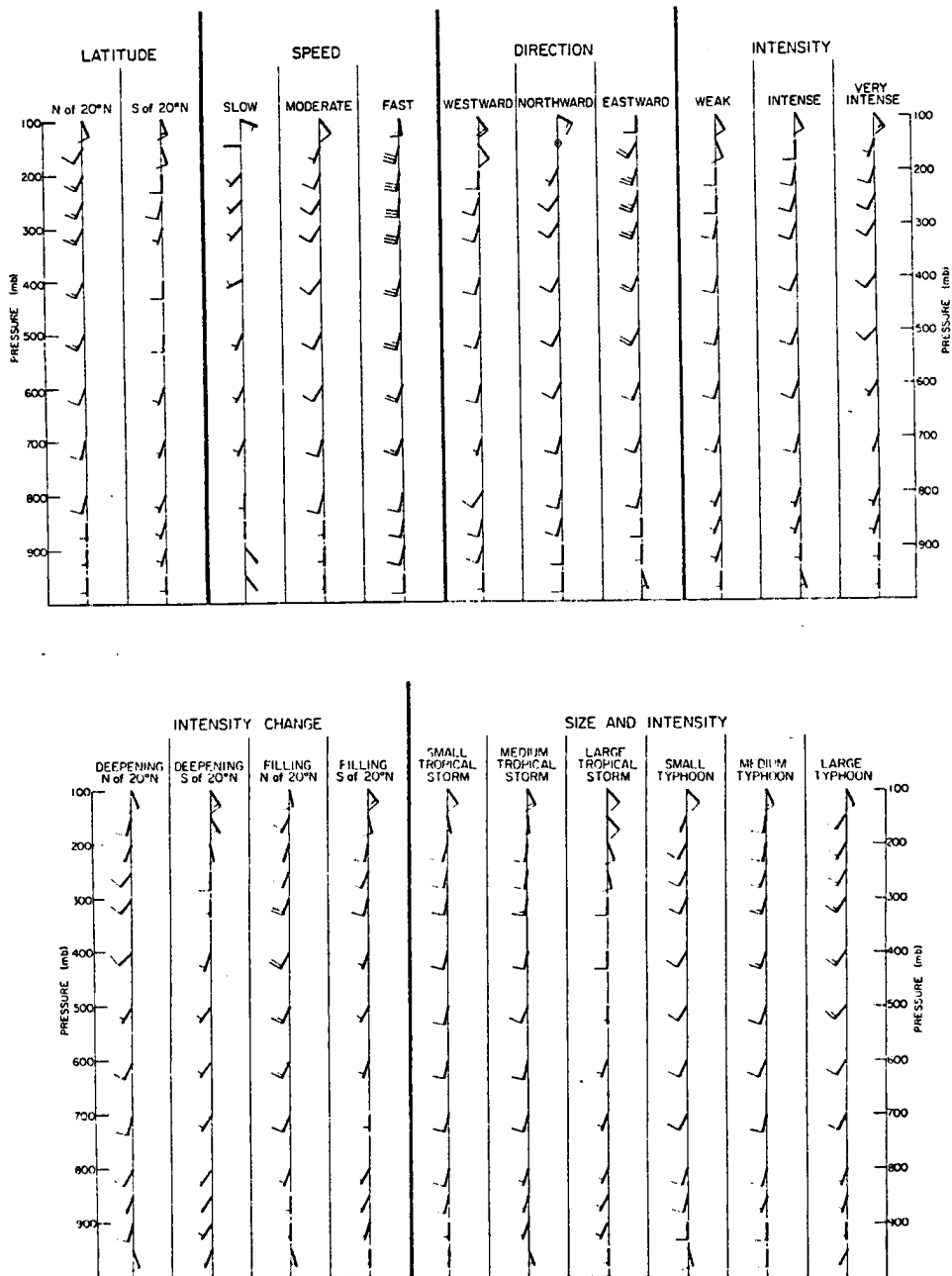


Figure 7. 5-7° belt average winds in the ROT coordinate system at different pressure levels for all data sets in the northwest Pacific. The direction of cyclone movement is towards the top of the figure. Wind barbs were plotted in the usual meteorological convention, one full barb being equivalent to  $5 \text{ m s}^{-1}$ .

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  $\overline{DD}$  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  $\overline{DD}$  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.

Some variations within each category of cyclones can also be seen in Fig. 8. Cyclones at latitudes north of  $20^{\circ}\text{N}$  seem to move more to the left of the mean wind than those south of  $20^{\circ}\text{N}$ . Similar results have also been obtained by Brand *et al.* (1981). In the speed category, slow-moving cyclones appear to have a much larger variation of  $\overline{DD}$  values in the vertical. Northward-moving cyclones have  $\overline{DD}$  values increasing with height while the opposite is true for westward-moving cyclones. As a cyclone increases in intensity it seems to move more to the left of the mean wind. The values of  $\overline{DD}$  also appear to increase slightly with the size of a cyclone.

Since not much variability in the values of  $\overline{DD}$  in the vertical exists, 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.

West Atlantic. Figure 9 shows the  $5-7^{\circ}$  belt average winds in the ROT coordinate system for west Atlantic tropical cyclones. The portion of the atmosphere in which the variability between data sets is small seems to be confined only to the mid-troposphere between 700 mb and 500

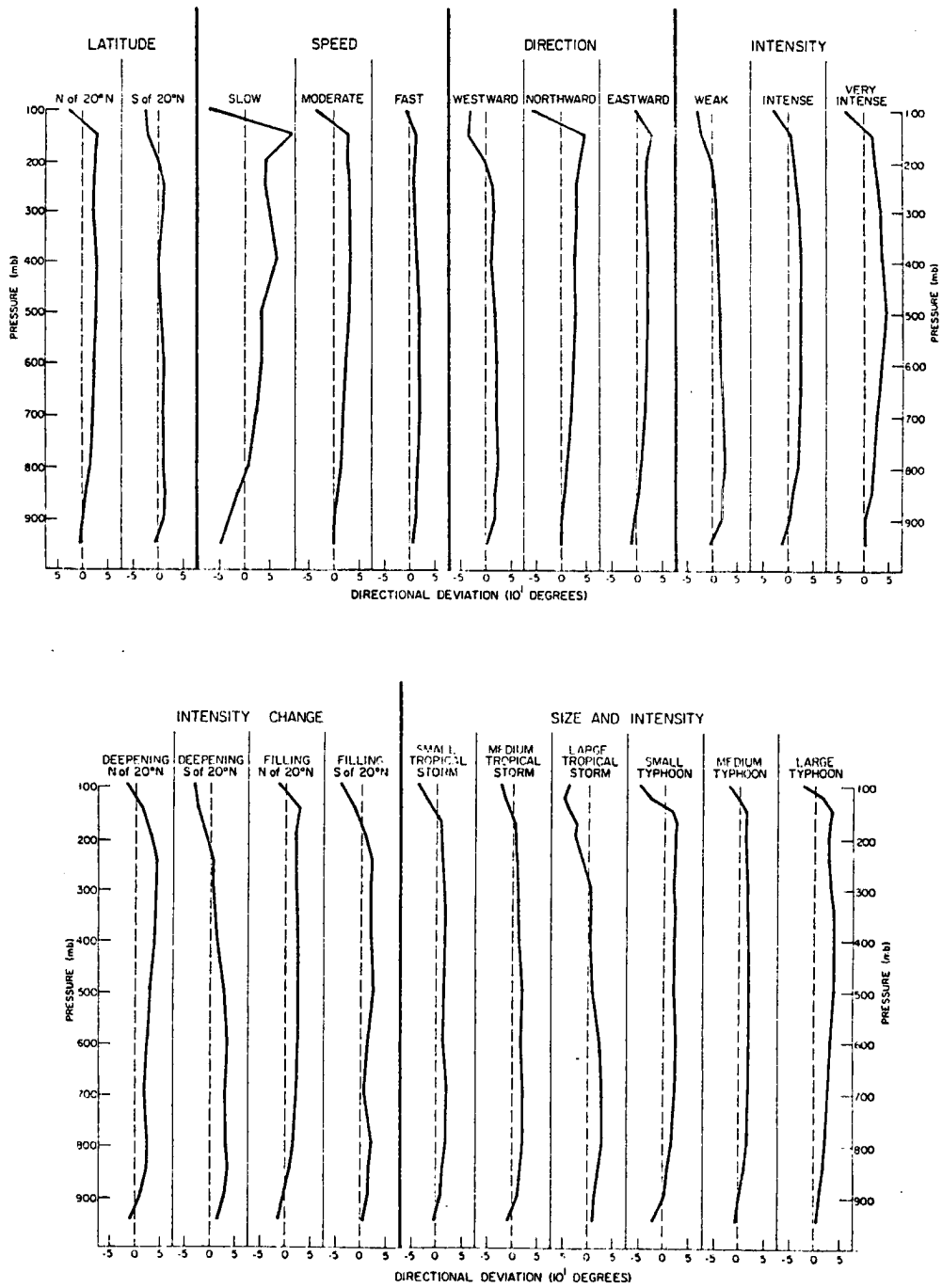


Figure 8. Variation with height of the 5-7° belt average wind deviation (DD - solid line) for all data sets in the northwest Pacific. The zero (dashed) line represents the direction of cyclone movement. A positive value means that the cyclone is moving to the left of the 5-7° belt average wind direction.

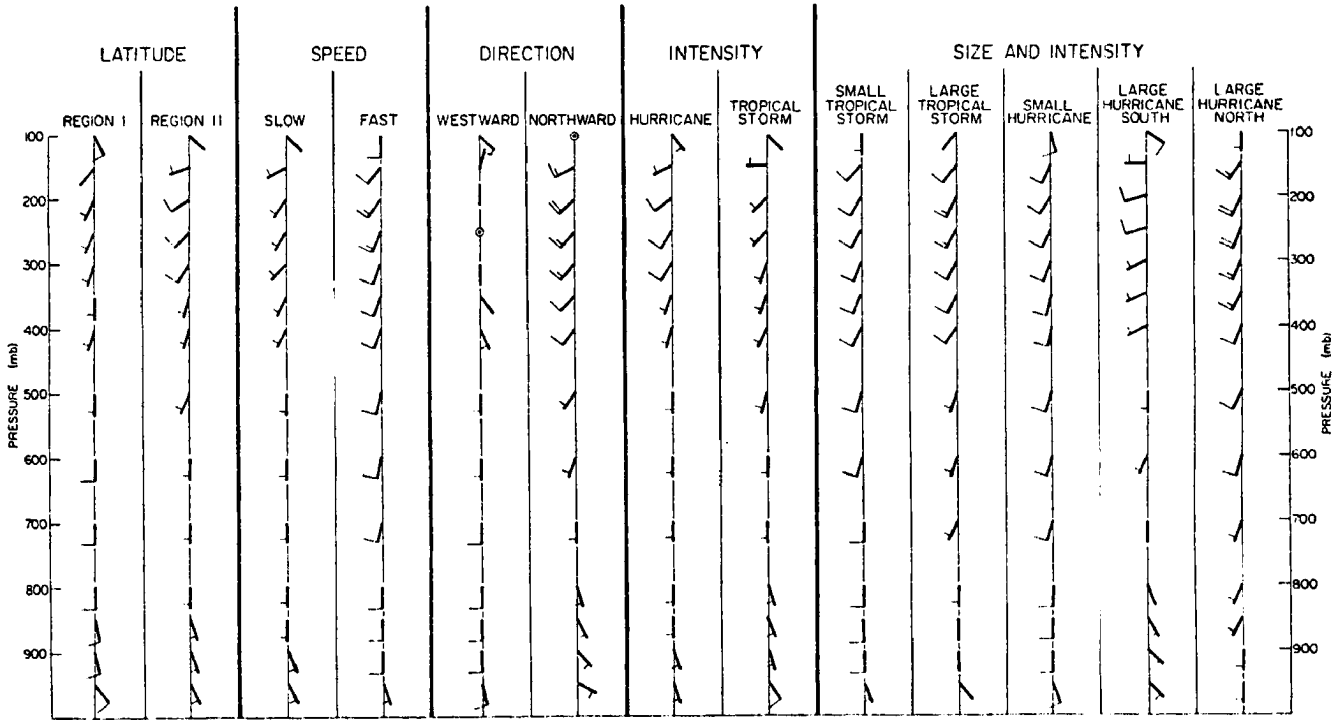


Figure 9. Same as Fig. 7 except for west Atlantic tropical cyclones.

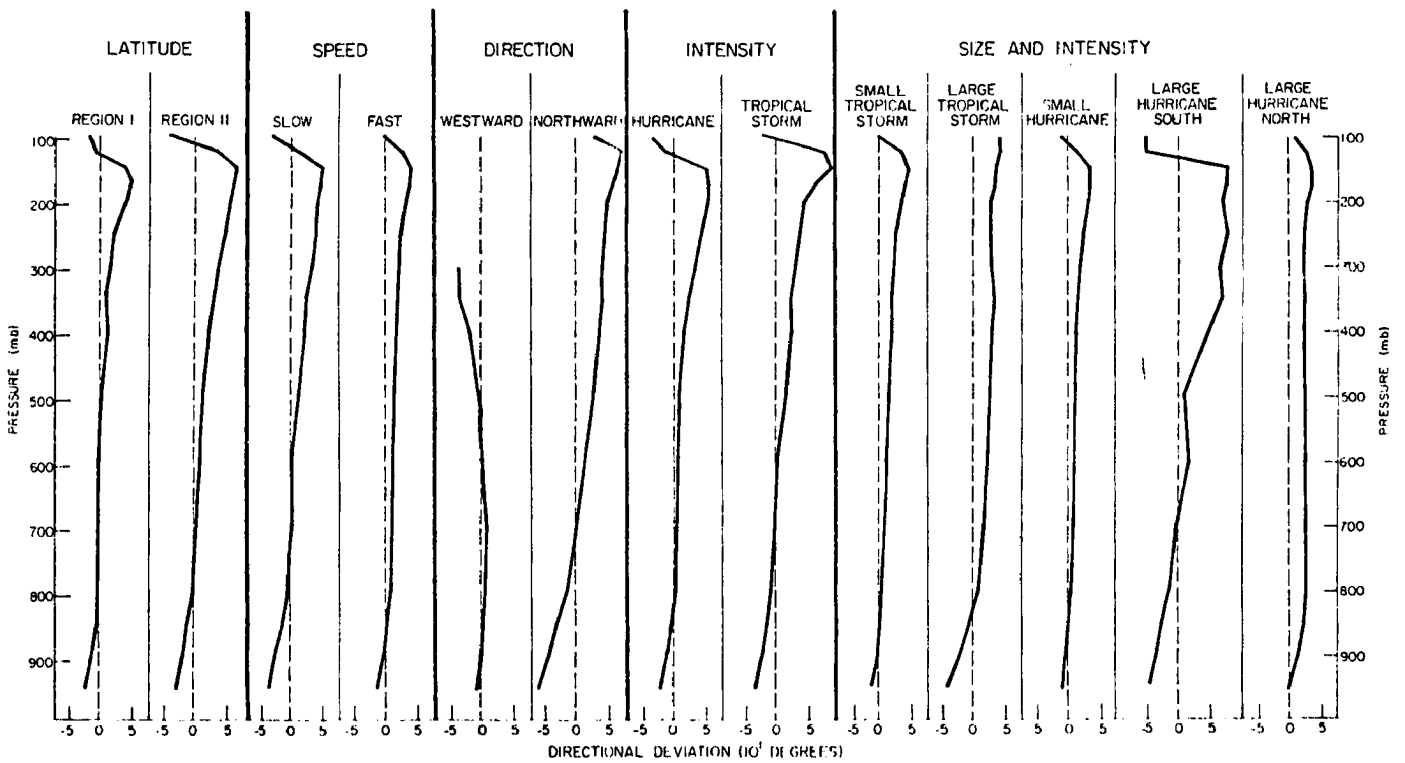


Figure 10. Same as Fig. 8 except for west Atlantic tropical cyclones.



mb. For each data set, the variation in the vertical is slightly larger when compared with northwest 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 general, weaker than those in the northwest Pacific and the values of  $\overline{DD}$  are also smaller.

These observations are more clearly shown in Fig. 10. There seems to be an increase in the values of  $\overline{DD}$  with height from the surface up to  $\sim 150$  mb for all the data sets with the exception of the westward-moving data set. Westward-moving cyclones appear to move in the same direction or even slightly to the right of the mean wind direction. Values of  $\overline{DD}$  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.

Variations within each category of cyclones can also be seen in Fig. 10. Region I ( $\sim$  south of  $18^{\circ}\text{N}$ ) cyclones move less to the left of the mean winds than cyclones in Region II ( $\sim$  north of  $18^{\circ}\text{N}$ ). Westward-moving cyclones have different  $\overline{DD}$  values than northward-moving cyclones. This is the same as the northwest Pacific except it is more obvious for west Atlantic cyclones. Bigger cyclones tend to move more to the left of the mean wind than smaller cyclones. However, the difference is probably not large enough to be detected in practice. Therefore, it might be safe to say that the direction of cyclone movement can be described adequately using the  $5-7^{\circ}$  mean wind irrespective of the size of the cyclone, at least in the mid-troposphere. This is true for both west Atlantic and northwest Pacific

cyclones.

The general increase in the values of  $\overline{DD}$  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.

Australian-south Pacific region. Figure 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, however, 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 ( $\overline{DD}$ ) at different levels. The values of  $\overline{DD}$  generally decrease with height, in 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).

Another important feature in Fig. 12 is the difference in the  $\overline{DD}$  profiles between westward and eastward-moving cyclones. This same type of difference between cyclones moving in different directions also shows up in the two northern hemisphere ocean basins (see Figs. 8 and 10). It

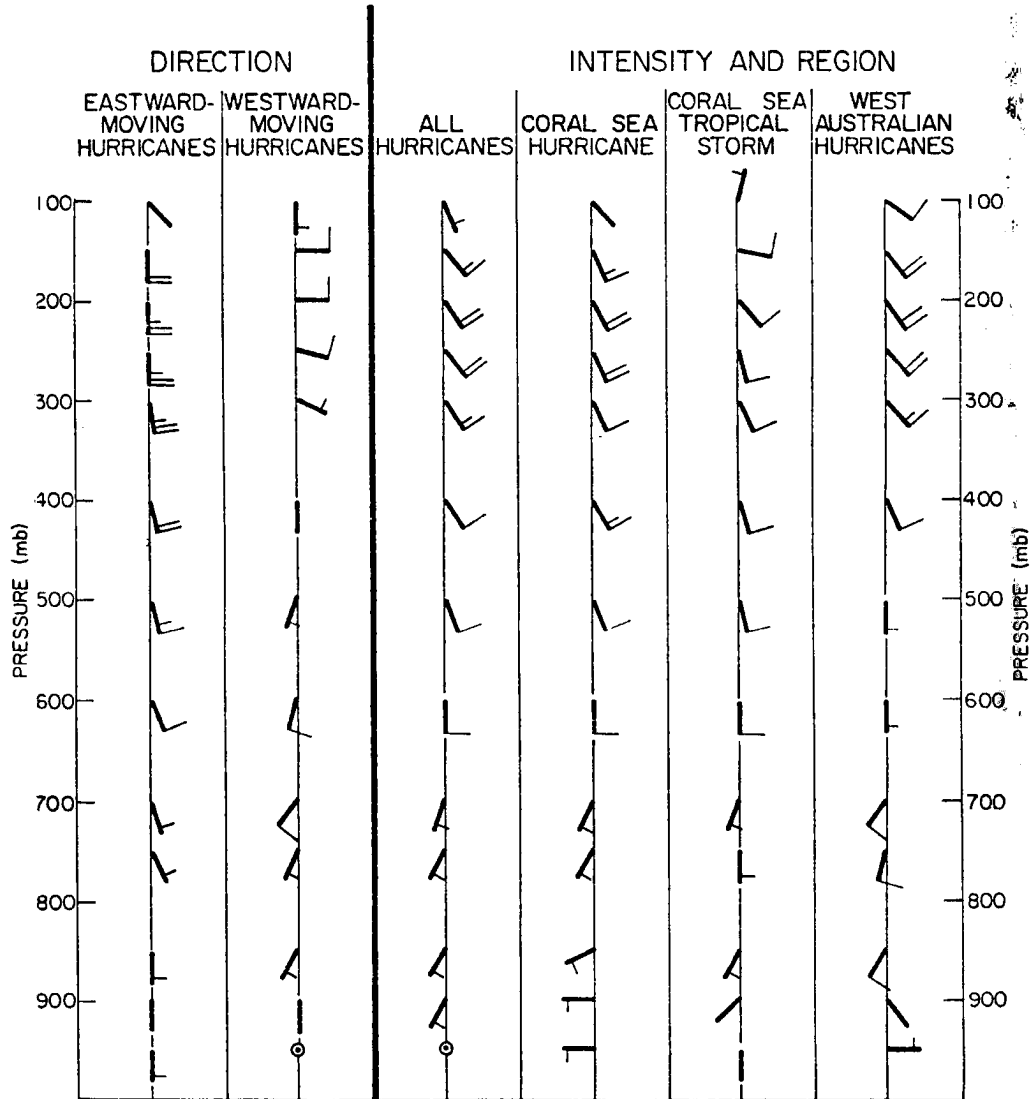


Figure 11. Same as Fig. 7 except for tropical cyclones in the Australian-south Pacific region.

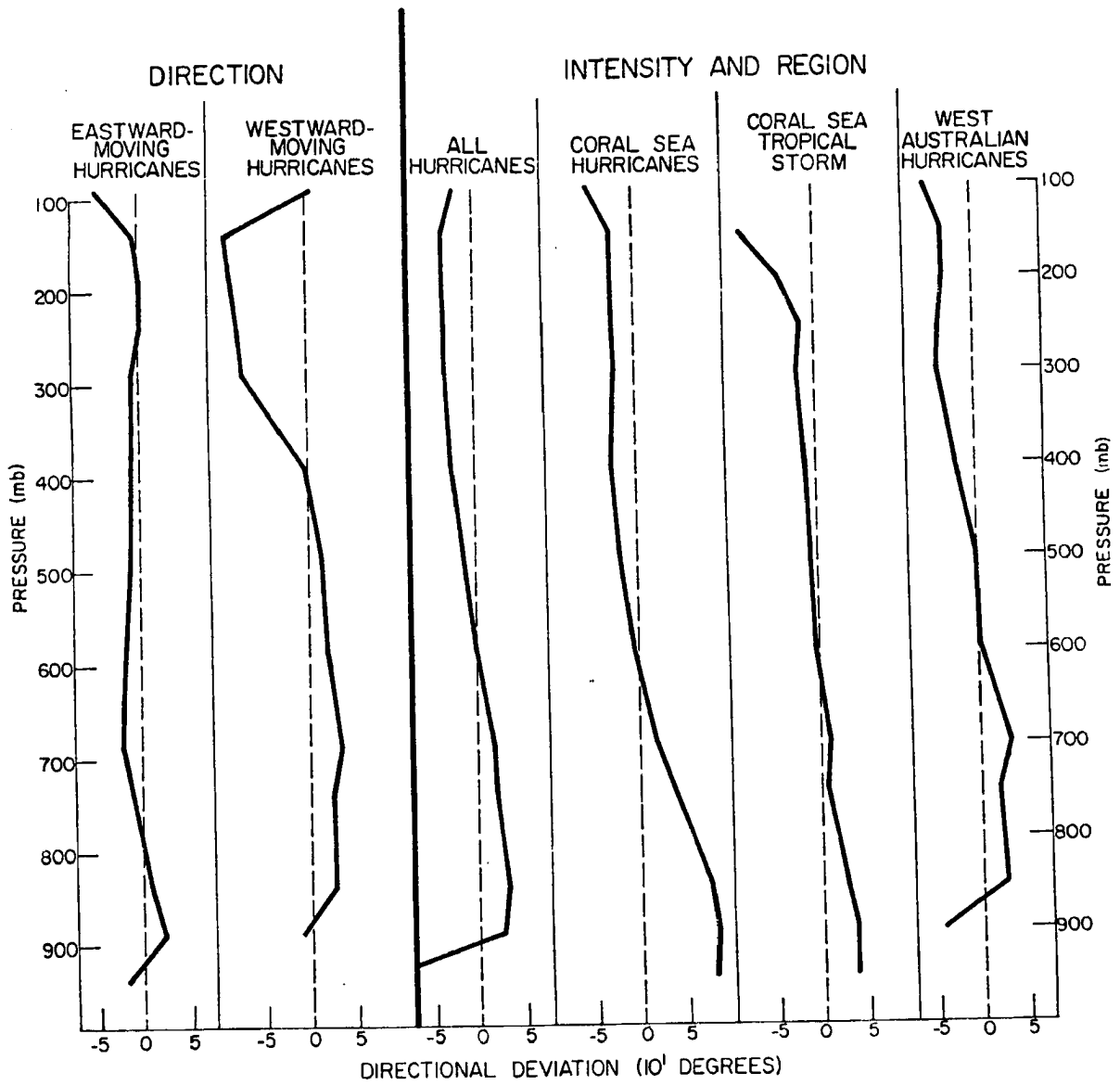


Figure 12. Same as Fig. 8 except for tropical cyclones in the Australian-south Pacific region.

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.

Summary. The results in this subsection show that the vertical variation of the deviation of the cyclone direction from the  $5-7^{\circ}$  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  $5-7^{\circ}$  belt average wind (at least in the mid-troposphere) while cyclones in the Southern Hemisphere, in general, move to the right of mid-tropospheric winds at this radius. Such deviations appear to be only slightly modified by latitude, intensity, and size of the cyclone. However, cyclones with different zonal components of motion have large differences in the  $\overline{DD}$  values.

(ii) Individual level

As the mid-tropospheric wind data at  $5-7^{\circ}$  radius give the least amount of difference in the directional deviations between data sets, these levels will now be more closely examined. The actual values of  $\overline{DD}$  for all data sets at 700, 600, and 500 mb and the corresponding scatter are presented.

Northwest Pacific. Table 4 shows the  $5-7^{\circ}$   $\overline{DD}$  values for northwest Pacific tropical cyclones at 700, 600, and 500 mb. All cyclones move to the left of the  $5-7^{\circ}$  mean wind by about the same

TABLE 4

Directional Difference (DD) between the  $5^{\circ}$ - $7^{\circ}$  radial band average wind and the direction of cyclone movement for northwest Pacific tropical cyclones. (See text for a description of how the averages and the scatter were calculated.) A positive number indicates the cyclone is moving to the left of the mean wind. Unit: degrees.

<u>STRATIFICATION</u>	<u>700 mb</u>	<u>600 mb</u>	<u>500 mb</u>
<u>By Latitude</u>			
North of $20^{\circ}\text{N}$	19	22	26
South of $20^{\circ}\text{N}$	9	10	4
<u>By Speed</u>			
Slow ( $1-3 \text{ m s}^{-1}$ )	23	32	34
Moderate ( $4-7 \text{ m s}^{-1}$ )	16	22	29
Fast ( $> 7 \text{ m s}^{-1}$ )	19	17	17
<u>By Direction</u>			
Westward ( $250^{\circ}$ - $310^{\circ}$ )	21	21	17
Northward ( $310^{\circ}$ - $350^{\circ}$ )	18	23	28
Eastward ( $350^{\circ}$ - $60^{\circ}$ )	16	18	22
<u>By Intensity</u>			
Weak (1000-980 mb)	21	16	14
Intense (950-980 mb)	23	25	26
Very Intense ( $< 950 \text{ mb}$ )	24	34	42
<u>By Intensity Change</u>			
Deepening North of $20^{\circ}\text{N}$	19	23	29
Deepening South of $20^{\circ}\text{N}$	29	33	25
Filling North of $20^{\circ}\text{N}$	22	24	24
Filling South of $20^{\circ}\text{N}$	3	13	23
<u>By Size and Intensity</u>			
Small Tropical Storm	17	11	13
Medium Tropical Storm	19	15	19
Large Tropical Storm	28	22	8
Small Typhoon	22	24	21
Medium Typhoon	17	18	19
Large Typhoon	24	30	36
Mean	19	22	23
Scatter	5.8	6.8	9.1

amount, an indication of the relatively small vertical wind shear in this ocean basin (see Fig. 8). Since such a consistency exists between data sets with widely different characteristics, one might conclude that the steering flow theory appears quite applicable, particularly in the mid-tropospheric levels. However, if such a theory is correct, one would expect the value of  $\overline{DD}$  to be near zero. While this is true in a few stratifications, a systematic difference of  $\sim 20^\circ$  exists between the mean  $5-7^\circ$  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.

West Atlantic. Table 5 gives the values of  $\overline{DD}$  for west Atlantic tropical cyclones. Similar results are found. Cyclones generally move to the left of the  $5-7^\circ$  mean wind. A few stratifications, however, show different results, particularly the westward-moving tropical cyclones which move slightly to the right of the 500 mb environmental flow.

Australian-south Pacific region. The  $5-7^\circ$   $\overline{DD}$  values for tropical cyclones in the Australian-south Pacific region are shown in Table 6. As discussed earlier, because of the large directional shear of the wind in the lower to mid-troposphere,  $\overline{DD}$  values are noisier than those in the other two ocean basins. On the average, cyclones in this region move to the left of the  $5-7^\circ$  700 mb wind and to the right of the  $5-7^\circ$  600 mb and 500 mb wind. This is not true for cyclones having a large zonal component. Westward-moving cyclones move consistently to the left of the  $5-7^\circ$  mean wind at all three levels while the opposite is true for eastward-moving cyclones.

TABLE 5

Same as Table 4 except for west Atlantic tropical cyclones.

<u>STRATIFICATION</u>	<u>700 mb</u>	<u>600 mb</u>	<u>500 mb</u>
<u>By Latitude</u>			
Region I (South)	-5	-3	1
Region II (North)	3	7	12
<u>By Speed</u>			
Slow ( $1-3 \text{ m s}^{-1}$ )	-1	0	11
Fast ( $> 3 \text{ m s}^{-1}$ )	9	11	13
<u>By Direction</u>			
Northward ( $316^{\circ}-45^{\circ}$ )	0	12	25
Westward ( $225^{\circ}-315^{\circ}$ )	5	-2	-8
<u>By Intensity</u>			
Hurricane	2	3	5
Tropical Storm	-5	0	12
<u>By Size and Intensity</u>			
Small Tropical Storm	7	10	14
Large Tropical Storm	16	20	23
Small Hurricane	8	8	10
Large Hurricane North	23	22	24
Large Hurricane South	-3	15	7
Mean	5	8	11
Scatter	8.2	8.1	9.3

TABLE 6

Same as Table 4 except for tropical cyclones in the Australian-south Pacific region.

<u>STRATIFICATION</u>	<u>700 mb</u>	<u>600 mb</u>	<u>500 mb</u>
<u>By Direction</u>			
Eastward ( $40^{\circ}-150^{\circ}$ )	-24	-20	-13
Westward ( $210^{\circ}-320^{\circ}$ )	33	19	12
<u>By Intensity and Region</u>			
Hurricane	15	-3	-16
Coral Sea Hurricane	16	-7	-22
Coral Sea Tropical Storm	9	-5	-9
West Australian Hurricane	32	1	-2
Mean	14	-3	-8
Scatter	20.8	12.7	12.0



The fact that consistent differences occur for the east and west direction of movement suggests the possible presence of other factors in determining the direction of cyclone movement besides the large-scale mean surrounding flow. Apart from these differences, these results suggest that in exact opposite to the Northern Hemisphere, cyclones in the South Hemisphere generally move to the right (rather than to the left) of the mid-tropospheric flow. This should be expected if the same physical processes are involved.

Summary. Although some variations exist in  $\overline{DD}$  values between different composite data sets, a general consistency is found. Table 7 summarizes the mean values and the corresponding scatter for each of the three ocean basins. It can be seen that cyclones in the northwest Pacific have the smallest variability, a reflection of the small directional vertical wind shear. The direction of movement of west Atlantic cyclones tends to deviate less to the left of the mid-tropospheric mean wind ( $\sim 10^\circ$ ) than those in the northwest Pacific ( $\sim 20^\circ$ ). In opposite direction but with similar physical agreement, 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.

(iii) Level and layer-averages

Five averages were calculated: surface to 100 mb, surface to 300 mb, surface to 500 mb, 700 mb to 500 mb and the average between the 200 mb and 900 mb levels. The first four layer integrations involve pressure-weighted averages and the last is just the arithmetic mean between the two levels. The radial band averages of the two component

TABLE 7

Summary of the mean directional differences between cyclone motion and the 5-7° radial band mean wind averaged for all data sets in each ocean basin. The corresponding scatter within each ocean basin is given in parentheses.

<u>Ocean Basin</u>	<u>700 mb</u>	<u>600 mb</u>	<u>500 mb</u>
Northwest Pacific	19 (5.8)	22 (6.8)	23 (9.1)
West Atlantic	5 (8.2)	8 (8.1)	11 (9.3)
Australian- south Pacific Region	14 (20.8)	-3 (12.7)	-8 (12.0)

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,

$$\langle \bar{V}_N \rangle = \frac{\int_{p_1}^{p_2} \bar{V}_N dp}{p_2 - p_1} \quad (2a)$$

and

$$\langle \bar{V}_P \rangle = \frac{\int_{p_1}^{p_2} \bar{V}_P dp}{p_2 - p_1} \quad (2b)$$

where  $p_1$  and  $p_2$  are the lower and upper pressure levels of the layer.

The 200 mb and 900 mb arithmetic averages are defined by

$$[\bar{V}_N] = [\bar{V}_N(200\text{mb}) + \bar{V}_N(900\text{mb})]/2 \quad (3a)$$

and

$$[\bar{V}_P] = [\bar{V}_P(200\text{mb}) + \bar{V}_P(900\text{mb})]/2 \quad (3b)$$

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 tropospheric flow is the most applicable 'steering' current. Riehl and Burgner (1950) and E. Jordan (1952) used the surface to 300 mb mean flow as their predictor. 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 subsection indicate the importance of mid-tropospheric flow and hence the 700 mb to 500 mb mean flow was also calculated.

Northwest Pacific. Table 8 shows the layer-averaged values of  $\overline{DD}$  for northwest Pacific tropical cyclones. Not much variation exists between the different pressure-weighted averages. This small variation is also reflected in the mean for all the data sets. The scatter among the data sets is about the same for the different layer-averages. 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 appreciable directional wind shear in the vertical.

The 200 mb and 900 mb average directional deviations also relate in a reasonable way to cyclone motion. With the exception of the large tropical storm data set, the variation between data sets is not large. This suggests 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.

West Atlantic. Table 9 indicates that the directional variability between data sets in the west Atlantic is larger than in the northwest

TABLE 8

Directional deviations between cyclone direction and direction of level- or layer-averaged  $5^{\circ}$ - $7^{\circ}$  mean winds for different combination of levels for northwest Pacific tropical cyclones. See text for a description of how these averages were calculated.

	$\int_{\text{surface}}^{100\text{mb}}$	$\int_{\text{surface}}^{300\text{mb}}$	$\int_{\text{surface}}^{500\text{mb}}$	$\int_{700\text{mb}}^{500\text{mb}}$	200mb+900mb Average
<u>By Latitude</u>					
North of $20^{\circ}\text{N}$	19	19	15	23	16
South of $20^{\circ}\text{N}$	2	6	8	8	3
<u>By Speed</u>					
Slow ( $1-3 \text{ m s}^{-1}$ )	29	27	10	30	22
Moderate ( $4-7 \text{ m s}^{-1}$ )	20	20	14	23	16
Fast ( $> 7 \text{ m s}^{-1}$ )	12	14	15	18	9
<u>By Direction</u>					
Westward ( $250^{\circ}$ - $310^{\circ}$ )	9	17	18	20	5
Northward ( $310^{\circ}$ - $350^{\circ}$ )	16	17	13	23	13
Eastward ( $350^{\circ}$ - $60^{\circ}$ )	17	16	13	19	15
<u>By Intensity</u>					
Weak (1000-980 mb)	8	14	16	16	4
Intense (950-980 mb)	16	20	18	25	9
Very Intense ( $< 950 \text{ mb}$ )	23	26	22	34	13
<u>By Intensity Change</u>					
Deepening North of $20^{\circ}\text{N}$	23	23	17	23	21
Deepening South of $20^{\circ}\text{N}$	14	24	30	30	8
Filling North of $20^{\circ}\text{N}$	19	20	17	23	14
Filling South of $20^{\circ}\text{N}$	8	13	10	13	9
<u>By Size and Intensity</u>					
Small Tropical Storm	9	12	11	13	8
Medium Tropical Storm	9	14	16	18	6
Large Tropical Storm	1	14	19	19	-15
Small Typhoon	15	16	15	22	13
Medium Typhoon	12	15	14	18	7
Large Typhoon	27	29	26	31	22
Mean	15	18	16	21	10
Scatter	7.5	5.6	5.2	6.4	8.1

TABLE 9

Same as Table 8 except for west Atlantic tropical cyclones.

	$\int_{\text{surface}}^{100 \text{ mb}}$	$\int_{\text{surface}}^{300 \text{ mb}}$	$\int_{\text{surface}}^{500 \text{ mb}}$	$\int_{700 \text{ mb}}^{500 \text{ mb}}$	200mb+900mb Average
<u>By Latitude</u>					
Region I (South)	-1	-3	-7	-3	10
Region II (North)	16	5	-4	7	27
<u>By Speed</u>					
Slow ( $1-3 \text{ m s}^{-1}$ )	11	3	-7	4	16
Fast ( $> 3 \text{ m s}^{-1}$ )	14	10	7	11	18
<u>By Direction</u>					
Northward ( $316^{\circ}-045^{\circ}$ )	27	13	-5	13	34
Westward ( $225^{\circ}-315^{\circ}$ )	-9	-5	-2	-1	1
<u>By Intensity</u>					
Hurricane	10	3	-3	3	24
Tropical Storm	6	-1	-8	2	6
<u>By Size and Intensity</u>					
Small Tropical Storm	14	9	5	10	19
Large Tropical Storm	22	18	11	20	19
Small Hurricane	12	8	5	9	16
Large Hurricane North	22	21	21	23	24
Large Hurricane South	18	4	-12	6	34
Mean	13	7	0	8	19
Scatter	9.7	7.7	9.2	7.6	9.8

Pacific. The smallest variation appears to be for the surface to 300 mb average and the 700-500 mb average. 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 mid-troposphere (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, either the mid-troposphere or a deep layer corresponding to the cyclonic rotation of the storm is a better predictor of cyclone direction. Because of the shear between the upper and lower troposphere, the 200 mb and 900 mb average directional deviations do not give as small a variability as their counterparts in the northwest Pacific.

Australian-South Pacific region. Table 10 gives the layer-averaged  $\overline{DD}$  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 that Australian cyclones move to the right of the  $5-7^{\circ}$  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 relatively strong directional shear in the vertical, these layer-averages show a larger variability than those in the Northern Hemisphere ocean basins. This is also the case for the 200 mb and 900

TABLE 10

Same as Table 8 except for tropical cyclones in the Australian-south Pacific region.

	$\int_{\text{surface}}^{100\text{mb}}$	$\int_{\text{surface}}^{300\text{mb}}$	$\int_{\text{surface}}^{500\text{mb}}$	$\int_{700\text{mb}}^{500\text{mb}}$	200mb+900mb Average
<u>By Direction</u>					
Eastward ( $40^{\circ}$ - $150^{\circ}$ )	-10	-13	-14	-17	2
Westward ( $210^{\circ}$ - $320^{\circ}$ )	-9	14	22	22	-72*
<u>By Intensity and Region</u>					
Hurricane	-20	-12	3	-5	-29
Coral Sea Hurricane	-15	-7	12	-12	-15
Coral Sea Tropical Storm	-13	-2	5	-4	-23
West Australian Hurricane	-22	-8	10	14	-36
Mean	-15	-5	6	0	-29
Scatter	5.3	10.0	12.0	15.2	24.9

\*Such a large directional difference is due to weak 900 mb winds (see Fig. 11). This value is therefore not well defined.

TABLE 11

Same as Table 7 except for level- or layer-averaged winds.

Ocean Basin	$\int_{\text{surface}}^{100\text{mb}}$	$\int_{\text{surface}}^{300\text{mb}}$	$\int_{\text{surface}}^{500\text{mb}}$	$\int_{700\text{mb}}^{500\text{mb}}$	200mb+900mb Average
Northwest Pacific	15 (7.5)	18 (5.6)	16 (5.2)	21 (6.4)	10 (8.1)
West Atlantic	13 (9.7)	7 (7.7)	0 (9.2)	8 (7.6)	19 (9.8)
Australian- south Pacific Region	-15 (5.3)	-5 (10.0)	6 (12.0)	0 (15.2)	-29 (24.9)

mb average directional deviation.

Summary. The mean  $\overline{DD}$  values for all data sets for each level- or layer-average for the three ocean basins are shown in Table 11. It shows that the mean tropospheric 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 movement, 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 about the same amount. However, it appears that, for individual ocean basins, the best layer depends on the directional vertical shear of the environmental 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 comparable. The magnitude of vertical directional shear also affects the degree of applicability of winds at 900 mb and 200 mb in describing the directional movement of the cyclone.

#### b. Individual Octants

Although the above results might be used to make good estimates of cyclone motion, such information is usually not available for individual cyclone situations. Typically, only a few observations are available. Therefore, for practical purposes, it would be useful if only one sector of the cyclone radial band shows similar directional differences as the azimuthally-averaged data. To determine if this is possible, the scatter of the DD values at  $5-7^{\circ}$  at each octant were calculated. For simplicity only single-level values will be considered. Because belt-average winds at the mid-tropospheric levels prove to be the 'best'



steering current, DD values at 700, 600, and 500 mb were investigated. In addition, the 200 mb and 900 mb average winds were investigated because of their potential applications using satellite winds. The analyses indicate that for cyclones in the northwest Pacific and west Atlantic, the octants to the right (octants 6, 7, 8 in Fig. 4) of the cyclone at 700 mb have the smallest scatter among data sets. For cyclones in the Australian region, it is the exact opposite - the smallest standard deviations of DD values occur in octants to the left of the cyclone (octants 2, 3, 4 in Fig. 4).

For the mean upper (200 mb) and lower (900 mb) tropospheric winds, the directional difference DD is calculated using Eq. 1 with  $V_N = [V_N(200) + V_N(900)]/2$  and  $V_P = [V_P(200) + V_P(900)]/2$ . As such, it represents the difference between the direction of the mean 200 mb and 900 mb wind in a particular grid box and that of the cyclone. The resulting values, denoted by [DD] are significantly noisier.

Northwest Pacific. Table 12 shows the 700 mb DD values at 5-7° in octants 6 (right-rear), 7 (right) and 8 (right front) for northwest Pacific tropical cyclones. The average of the three octants is also shown. This is simply the arithmetic average of the DD values in octants 6, 7 and 8. The consistency between data sets is very good, especially for the three-octant average. For the mean 200 mb and 900 mb winds, the best consistency shows up if the [DD] values in octants 6, 7 and 8 are averaged.

West Atlantic. Table 13 gives the same information as Table 12 for west Atlantic cyclones. The consistency among data sets is quite good. The smallest scatter in the DD values occurs in the right octant (7). This is the octant with the strongest wind, and hence, the largest  $V_P$

TABLE 12

Values of DD at  $5^{\circ}$ - $7^{\circ}$  for the 700 mb wind and the mean 200 mb and 900 mb wind in the octants indicated. Ocean basin: northwest Pacific.

STRATIFICATION	700mb				200mb+900mb
	OCTANT			OCTANT	OCTANT
	6 right rear	7 right	8 right front	6 7 8 Ave.	6 7 8 Ave.
<u>By Latitude</u>					
North of $20^{\circ}$ N	25	7	-17	5	12
South of $20^{\circ}$ N	25	5	-42	-4	16
<u>By Speed</u>					
Slow ( $1-3 \text{ m s}^{-1}$ )	33	4	-28	3	21
Moderate ( $4-7 \text{ m s}^{-1}$ )	27	9	-16	7	15
Fast ( $> 7 \text{ m s}^{-1}$ )	13	4	-14	1	5
<u>By Direction</u>					
Westward ( $250^{\circ}$ - $310^{\circ}$ )	28	11	-22	6	15
Northward ( $310^{\circ}$ - $350^{\circ}$ )	24	10	-15	6	12
Eastward ( $350^{\circ}$ - $60^{\circ}$ )	17	1	-12	2	6
<u>By Intensity</u>					
Weak (1000-980 mb)	34	-2	-15	6	-2
Intense (950-980 mb)	30	7	-17	7	16
Very Intense ( $< 950$ mb)	24	13	-16	7	13
<u>By Intensity Change</u>					
Deepening North of $20^{\circ}$ N	35	15	-9	14	15
Deepening South of $20^{\circ}$ N	32	12	-23	7	23
Filling North of $20^{\circ}$ N	20	6	-14	4	13
Filling South of $20^{\circ}$ N	22	15	-22	5	36
<u>By Size and Intensity</u>					
Small Tropical Storm	35	-4	-3	9	2
Medium Tropical Storm	28	-2	-14	4	5
Large Tropical Storm	35	-6	-27	1	-6
Small Typhoon	23	5	6	11	21
Medium Typhoon	26	4	-26	1	8
Large Typhoon	26	5	-20	4	14
Mean	27	6	-17	5	12
Scatter	6.0	6.0	9.7	3.9	9.2

TABLE 13

Same as Table 12 except for west Atlantic tropical cyclones.

STRATIFICATION	700mb				200mb+900mb Ave.
	6 right rear	OCTANT 7 right	8 right front	OCTANT 6 7 8 Ave.	OCTANT 7 8 Ave.
<u>By Latitude</u>					
Region I (South)	13	-7	-19	-4	29
Region II (North)	31	-4	-23	1	33
<u>By Speed</u>					
Slow ( $1-3 \text{ m s}^{-1}$ )	30	-1	-26	1	28
Fast ( $> 3 \text{ m s}^{-1}$ )	22	-9	-15	-1	23
<u>By Direction</u>					
Northward ( $316^{\circ}-45^{\circ}$ )	17	-7	-22	-4	42
Westward ( $225^{\circ}-315^{\circ}$ )	28	-2	-20	2	28
<u>By Intensity</u>					
Hurricane	27	-3	-24	0	34
Tropical Storm	16	-9	-10	-1	26
<u>By Size and Intensity</u>					
Small Tropical Storm	9	-6	-15	-4	38
Large Tropical Storm	25	-4	-31	-3	9
Small Hurricane	19	-7	-15	1	32
Large Hurricane North	31	1	-30	1	21
Large Hurricane South	38	-8	-31	0	43
Mean	24	-5	-22	-1	30
Scatter	8.4	3.2	6.8	2.2	9.1

component. Variations in the normal component of the wind in this octant are small.

For the mean 200 mb and 900 mb wind, the data in octant 6 are very noisy. But if the [DD] values in octants 7 and 8 are averaged, they give a good consistency between data sets.

Australian-south Pacific region. For tropical cyclones in this region, the best steering consistency at 700 mb occurs in octants 2 (front-left), 3 (left), and 4 (left-rear) (see Table 14). For the mean 200 mb and 900 mb wind, the [DD] values are very noisy for most octants. The best consistency is in octant 5 (to the back of the cyclone).

TABLE 14

Same as Table 12 except for tropical cyclones in the Australian-South Pacific region.

STRATIFICATION	700mb				200mb+900mb
				Ave.	
	OCTANT 2 Left Front	OCTANT 3 Left	OCTANT 4 Left Rear	OCTANT 2 3 4 Ave.	OCTANT 5
<u>By Direction</u>					
Eastward ( $40^{\circ}$ - $150^{\circ}$ )	35	14	-25	8	-42
Westward ( $210^{\circ}$ - $320^{\circ}$ )	34	11	-25	7	-39
<u>By Intensity and Region</u>					
Hurricane	31	16	-23	8	-45
Coral Sea Hurricane	30	0	-27	1	-37
Coral Sea Tropical Storm	26	7	-28	2	-32
West Australian Hurricane	32	27	-17	14	-30
Mean	31	13	-24	7	-38
Scatter	3.2	9.1	3.9	4.7	5.8

Summary. In situations where an estimate of the  $5-7^{\circ}$  radial band average wind is not possible, individual octant information appears to

be almost as useful. The best data appear to be in the region of strongest winds - right-hand-side, or octants 6, 7 and 8, for cyclones in the Northern Hemisphere and left-hand-side, or octants 2, 3 and 4, for cyclones in the Southern Hemisphere.

Although the 200 mb and 900 mb winds tend to be noisier, they do give consistent directional differences around some part of the cyclone. This might prove to be useful in situations where the tracking of clouds is only possible in one sector of the cyclone.

#### 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  $V_N$  obviously does not contribute to the scalar speed of the cyclone. The study of the relation between the surrounding 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 about the same for different data sets. The MOTROT coordinate 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 component 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 results will be presented in terms of the radial band average and individual octant values.

##### a. Radial Band Average

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 as described in the last section. Again, the 5-7° radial band at the three mid-tropospheric levels (700, 600 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°  $\bar{V}_{PM}$  with height will be presented, followed by individual levels and then level- or layer-averaged winds.

(i) Variation with height

Northwest Pacific. Figure 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 except 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 exception of these five stratifications, the other cyclones are generally embedded in an environment with relatively small vertical speed shear. The variation among different data sets, if those five stratifications are excluded, is very small. These data sets all have a strong northward and/or eastward component of motion. Therefore, it appears that the zonal and meridional movement of a cyclone have some effect on the cyclone speed relative to the surrounding winds. However, for all data sets, the values of  $\bar{V}_{PM}$  are negative below ~ 600 mb. This means that tropical cyclones in the northwest Pacific generally move faster than their surrounding mean 5-7° winds in the lower to mid-troposphere.

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

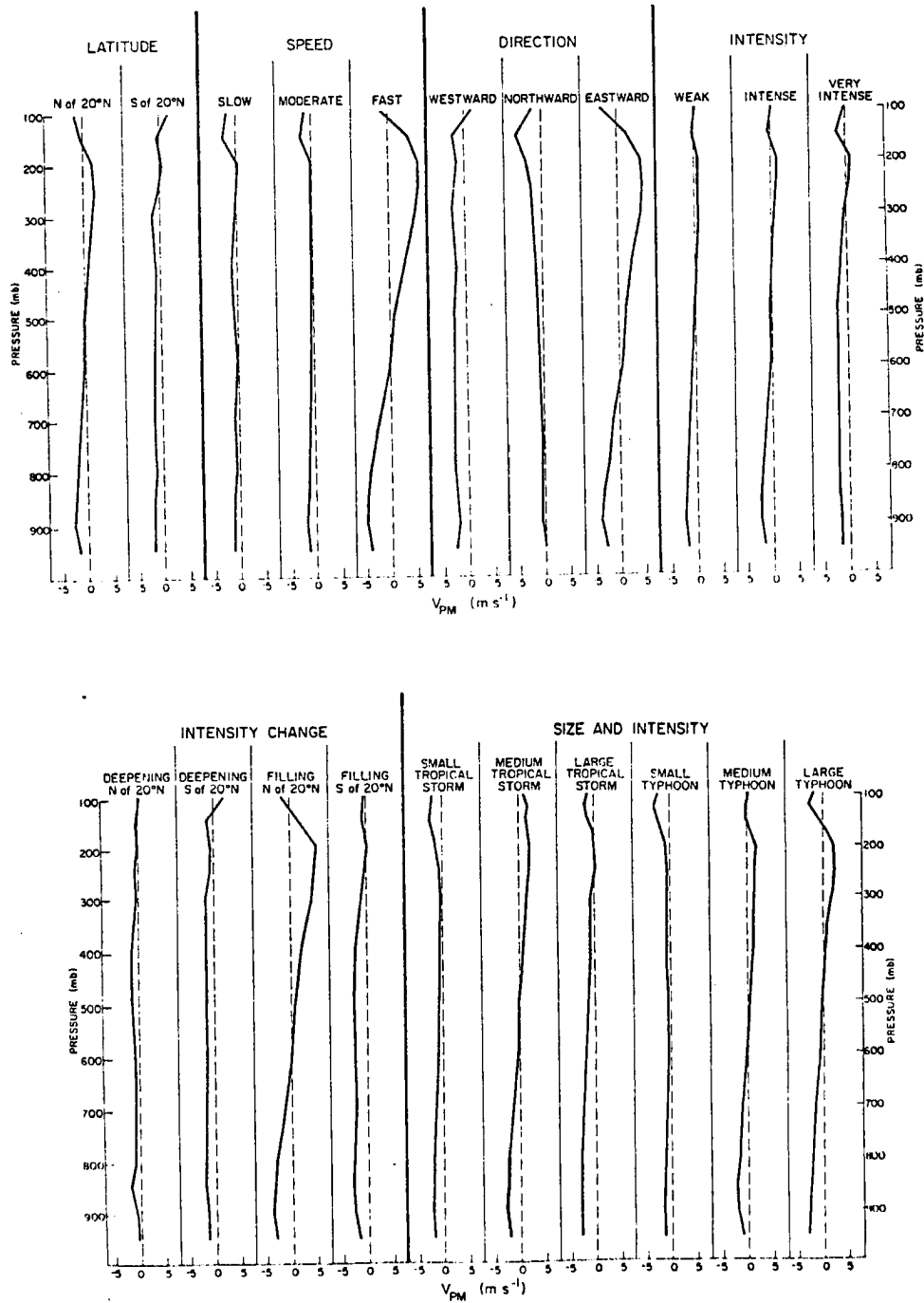


Figure 13. Variation with height of the 5-7° belt average relative component of the wind parallel to cyclone direction  $V_{PM}$  for northwest Pacific tropical cyclones (solid line). The zero (dashed) line represents the cyclone speed. A negative value of  $V_{PM}$  means that the cyclone is moving faster than the 5-7° surrounding wind.



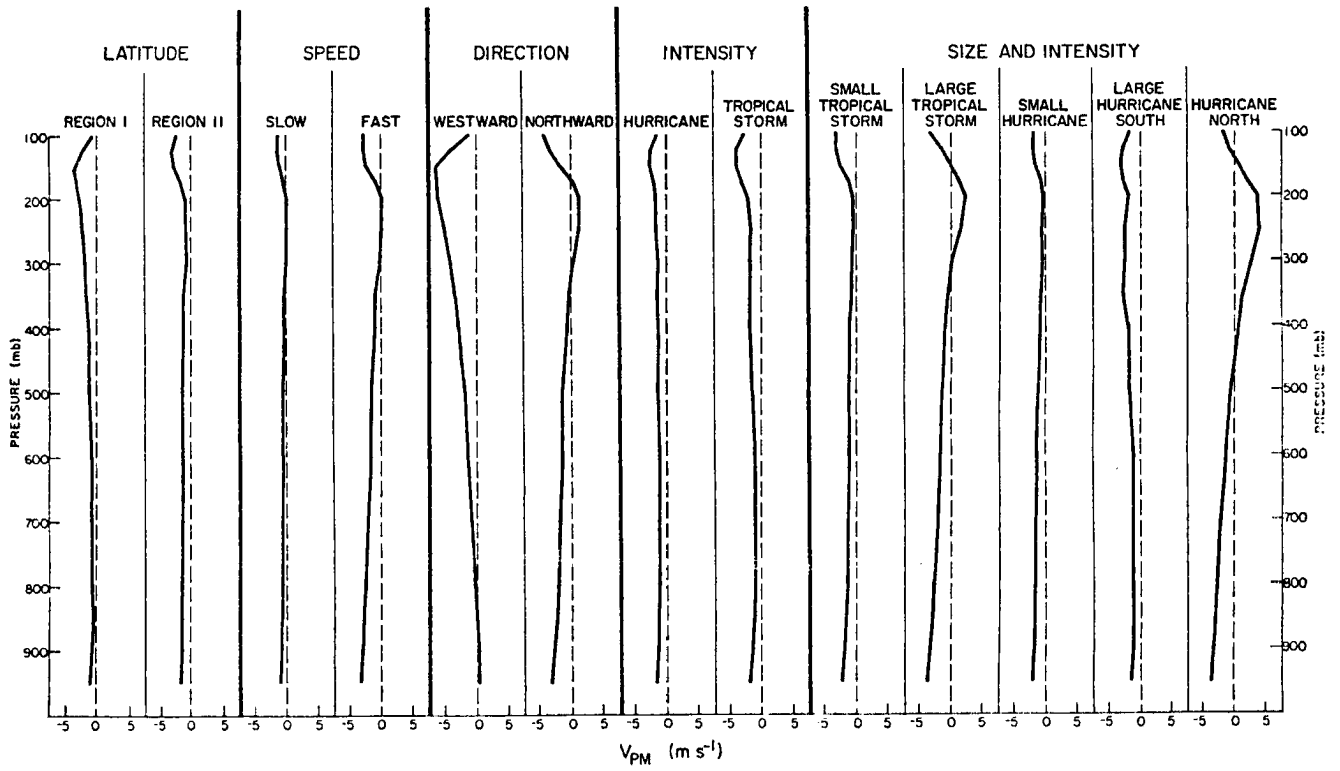


Figure 14. Same as Fig. 13 except for west Atlantic tropical cyclones.

hurricanes north of  $25^{\circ}\text{N}$ . Again, all cyclones move faster than the lower and mid-tropospheric winds ( $\bar{V}_{\text{PM}} < 0$ ). Between data sets, very little difference between the values of  $\bar{V}_{\text{PM}}$  can be noticed, especially in the mid-troposphere. It is also of interest to note that similar relationships between the  $5-7^{\circ}$  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  $5-7^{\circ}$  surrounding flow can be used to describe cyclone movement satisfactorily.

Australian-south Pacific region. Figure 15 shows the vertical profiles of  $5-7^{\circ}$   $\bar{V}_{\text{PM}}$  values for tropical cyclones in this region. Considerable variation of  $\bar{V}_{\text{PM}}$  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  $\sim 600$  mb). Although strong shear is present, the values of  $\bar{V}_{\text{PM}}$  in the mid-troposphere are about the same among different data sets.

Summary. The vertical profiles of  $\bar{V}_{\text{PM}}$  at  $5-7^{\circ}$  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. However, all the data sets indicate that cyclones tend to move faster than the  $5-7^{\circ}$  mean wind at the mid-troposphere. This is consistent with the results obtained by George and Gray (1976) and Gray (1977). If the steering flow is totally responsible for the movement of a cyclone, one would expect  $\bar{V}_{\text{PM}}$  to be near zero. The fact that  $\bar{V}_{\text{PM}}$  is always negative, at least in the mid-troposphere, points out the existence of

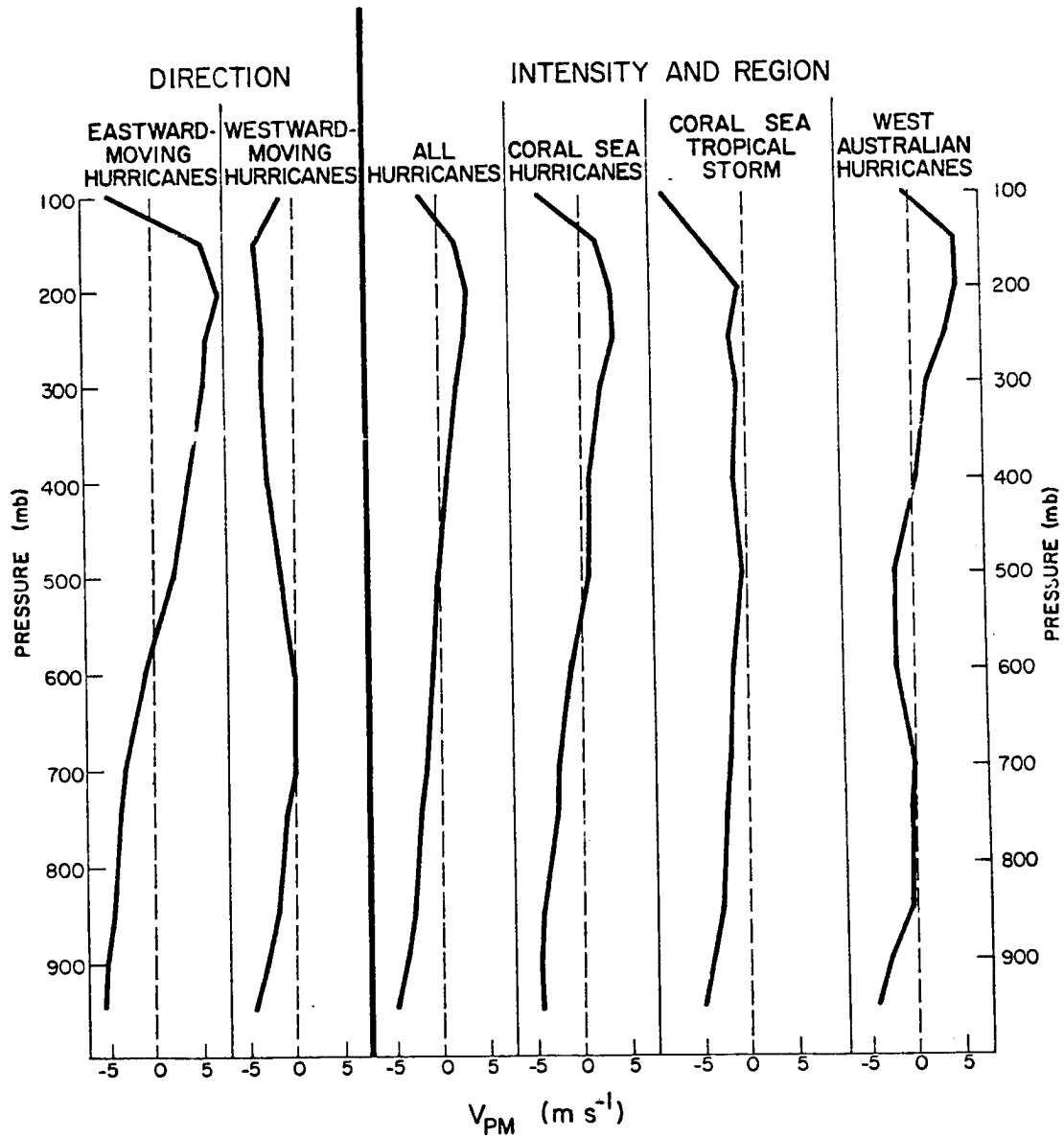


Figure 15. Same as Fig. 13 except for Australian-south Pacific region tropical cyclones.

other factors in the determination of the speed of a cyclone.

(ii) Individual levels

The results in the last subsection suggest that mid-tropospheric data correlate best with cyclone speed. To quantify these results, the values of  $\bar{V}_{PM}$  at 700, 600 and 500 mb and the corresponding standard deviations between data sets are specifically portrayed.

Northwest Pacific. Table 15 gives the values of  $\bar{V}_{PM}$  at 5-7° for three mid-tropospheric levels for northwest Pacific tropical cyclones. It can be seen that the  $\bar{V}_{PM}$  values at 700 mb have the least spread among data sets. Notice that all data sets show a negative  $\bar{V}_{PM}$ , meaning that a tropical cyclone travels faster than its 6° mean 700 mb wind. Similar observations can be made about the 600 and 500 mb data with the exception of eastward-moving, fast and filling north of 20°N cyclones. This again points to the importance of the zonal and meridional directions of cyclone motion.

West Atlantic. The values of 5-7°  $\bar{V}_{PM}$  at 700, 600 and 500 mb for west Atlantic tropical cyclones are shown in Table 16. Very little scatter exists in the data sets for all three mid-tropospheric levels, as evidenced from the standard deviations. The results also show that a cyclone travels faster than its surrounding 6° mid-tropospheric winds.

Australian-south Pacific region. Table 17 presents the mid-tropospheric 5-7° values of  $\bar{V}_{PM}$  for tropical cyclones in the Australian-south Pacific region. As mentioned in the last sub-section, although large vertical speed shear exists in this region, the values of  $\bar{V}_{PM}$  do not differ very much between data sets. Again, cyclones travel  $\sim 1 \text{ m s}^{-1}$  faster than their surrounding mid-tropospheric winds.

TABLE 15

Radial band average of the relative (to the cyclone) component of the wind parallel to the direction of cyclone movement ( $V_{PM}$ ) at  $5^{\circ}$ - $7^{\circ}$  radius for northwest Pacific tropical cyclones. A negative value of  $V_{PM}$  means the cyclone moves faster than the mean wind. Units:  $m s^{-1}$ .

<u>STRATIFICATION</u>	<u>700 mb</u>	<u>600 mb</u>	<u>500 mb</u>
<u>By Latitude</u>			
North of $20^{\circ}N$	-1.4	-0.5	-0.2
South of $20^{\circ}N$	-1.7	-1.5	-1.3
<u>By Speed</u>			
Slow ( $1-3 m s^{-1}$ )	-0.9	-0.3	-0.9
Moderate ( $4-7 m s^{-1}$ )	-1.2	-0.8	-0.8
Fast ( $> 7 m s^{-1}$ )	-2.4	-0.4	0.7
<u>By Direction</u>			
Westward ( $250^{\circ}-310^{\circ}$ )	-2.6	-2.3	-2.3
Northward ( $310^{\circ}-350^{\circ}$ )	-0.6	-0.9	-1.3
Eastward ( $350^{\circ}-60^{\circ}$ )	-1.3	0.5	1.2
<u>By Intensity</u>			
Weak (1000-980 mb)	-1.4	-1.0	-0.3
Intense (950-980 mb)	-1.4	-0.4	-0.3
Very Intense ( $< 950$ mb)	-1.8	-2.0	-2.1
<u>By Intensity Change</u>			
Deepening North of $20^{\circ}N$	-0.9	-1.0	-1.5
Deepening South of $20^{\circ}N$	-1.7	-1.5	-1.5
Filling North of $20^{\circ}N$	-1.2	0.0	0.8
Filling South of $20^{\circ}N$	-2.2	-2.4	-2.6
<u>By Size and Intensity</u>			
Small Tropical Storm	-1.5	-1.0	-0.8
Medium Tropical Storm	-1.2	-0.5	-0.1
Large Tropical Storm	-2.4	-1.9	-1.4
Small Typhoon	-1.0	-0.6	-0.8
Medium Typhoon	-1.1	-0.2	0.4
Large Typhoon	-1.6	-0.7	-0.5
Mean	-1.5	-0.9	-0.5
Scatter	0.5	0.8	1.2

TABLE 16

Same as Table 15 except for west Atlantic tropical cyclones.

<u>STRATIFICATION</u>	<u>700 mb</u>	<u>600 mb</u>	<u>500 mb</u>
<u>By Latitude</u>			
Region I (South)	-0.6	-0.6	-1.0
Region II (North)	-1.2	-1.2	-1.4
<u>By Speed</u>			
Slow (1-3 m s <sup>-1</sup> )	-0.6	-0.6	-0.5
Fast (> 3 m s <sup>-1</sup> )	-2.0	-1.6	-1.5
<u>By Direction</u>			
Northward (316°-45°)	-1.7	-1.5	-1.4
Westward (225°-315°)	-0.8	-1.4	-1.9
<u>By Intensity</u>			
Hurricane	-1.0	-1.0	-1.3
Tropical Storm	-1.0	-1.0	-1.4
<u>By Size and Intensity</u>			
Small Tropical Storm	-1.3	-1.2	-1.2
Large Tropical Storm	-2.1	-1.7	-1.4
Small Hurricane	-1.5	-1.3	-1.2
Large Hurricane North	-2.1	-1.5	-0.8
Large Hurricane South	-1.0	-1.1	-1.7
Mean	-1.3	-1.2	-1.3
Scatter	0.5	0.4	0.4

TABLE 17

Same as Table 15 except for tropical cyclones in the Australian-south Pacific region.

<u>STRATIFICATION</u>	<u>700 mb</u>	<u>600 mb</u>	<u>500 mb</u>
<u>By Direction</u>			
Eastward ( $40^{\circ}$ - $150^{\circ}$ )	-3.1	-0.9	2.0
Westward ( $210^{\circ}$ - $320^{\circ}$ )	-0.1	-0.2	-1.5
<u>By Intensity and Region</u>			
Hurricane	-1.6	-0.9	-0.2
Coral Sea Hurricane	-2.6	-1.3	0.8
Coral Sea Tropical Storm	-2.1	-1.6	-0.6
West Australian Hurricane	-0.2	-2.0	-2.1
Mean	-1.6	-1.2	-0.3
Scatter	1.2	0.6	1.5

TABLE 18

Average  $5^{\circ}$ - $7^{\circ}$   $V_{PM}$  for all data sets in each ocean basin and the corresponding scatter at 700, 600 and 500 mb (in parentheses). Unit:  $m s^{-1}$ .

<u>Ocean Basin</u>	<u>700 mb</u>	<u>600 mb</u>	<u>500 mb</u>
Northwest Pacific	-1.5 (0.5)	-0.9 (0.8)	-0.5 (1.2)
West Atlantic	-1.3 (0.5)	-1.2 (0.4)	-1.3 (0.4)
Australian- south Pacific Region	-1.6 (1.2)	-1.2 (0.6)	-0.3 (1.5)

Summary. To compare results obtained from the different ocean basins, the mean values of  $\bar{V}_{PM}$  for all data sets in a given ocean basin and the corresponding scatter are presented in Table 18. One might conclude from this table that cyclones in both hemispheres move faster than the mid-tropospheric winds at 5-7° by an average of  $\sim 1 \text{ m s}^{-1}$ . Both 700 and 600 mb appear to be better levels than 500 mb.

(iii) 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 mb 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 mb, surface to 300 mb, surface to 500 mb and 700 to 500 mb.

Northwest Pacific. Table 19 shows the four pressure-weighted layer averages and the 200 mb and 900 mb average  $\bar{V}_{PM}$  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. Therefore, it appears 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 mb and 900 mb average  $\bar{V}_{PM}$  are also very consistent. This suggests that it may be possible to use the 200 mb and 900 mb winds to describe tropical cyclone movement in the northwest Pacific with some degree of confidence.

West Atlantic. The layer-averaged 5-7°  $\bar{V}_{PM}$  values for west Atlantic tropical cyclones are shown in Table 20. The variation among



TABLE 19

Level- and layer-averaged  $5^{\circ}$ - $7^{\circ}$   $V_{PM}$  for different combination of levels for northwest Pacific tropical cyclones. See text for a description of how the averages were calculated. Unit:  $m s^{-1}$ .

Stratification	$\int_{\text{surface}}^{100\text{mb}}$	$\int_{\text{surface}}^{300\text{mb}}$	$\int_{\text{surface}}^{500\text{mb}}$	$\int_{700\text{mb}}^{500\text{mb}}$	200mb+900mb Average
<u>By Latitude</u>					
North of $20^{\circ}$ N	-0.6	-1.0	-1.7	-0.6	-0.6
South of $20^{\circ}$ N	-1.3	-1.6	-1.7	-1.5	-0.8
<u>By Speed</u>					
Slow ( $1-3 m s^{-1}$ )	-0.9	-0.9	-0.9	-0.6	-0.7
Moderate ( $4-7 m s^{-1}$ )	-1.1	-1.1	-1.3	-0.9	-1.1
Fast ( $> 7 m s^{-1}$ )	-0.1	-1.3	-3.0	-0.6	0.2
<u>By Direction</u>					
Westward ( $250^{\circ}$ - $310^{\circ}$ )	-2.2	-2.3	-2.4	-2.4	-1.7
Northward ( $310^{\circ}$ - $350^{\circ}$ )	-1.5	-1.0	-0.8	-0.9	-2.0
Eastward ( $350^{\circ}$ - $60^{\circ}$ )	0.2	-0.5	-1.8	0.2	0.2
<u>By Intensity</u>					
Weak (1000-980 mb)	-0.8	-1.1	-1.6	-0.9	-0.9
Intense (950-980 mb)	-0.7	-1.1	-1.6	-0.6	-0.7
Very Intense ( $< 950$ mb)	-1.4	-1.7	-1.9	-2.0	-0.5
<u>By Intensity Change</u>					
Deepening North of $20^{\circ}$ N	-1.0	-1.1	-1.1	-1.1	-0.5
Deepening South of $20^{\circ}$ N	-1.5	-1.7	-1.7	-1.5	-1.1
Filling North of $20^{\circ}$ N	0.2	-0.7	-1.9	-0.1	0.8
Filling South of $20^{\circ}$ N	-1.9	-2.3	-2.5	-2.4	-1.2
<u>By Size and Intensity</u>					
Small Tropical Storm	-1.3	-1.2	-1.5	-1.1	-1.5
Medium Tropical Storm	-0.2	-0.7	-1.4	-0.6	-0.1
Large Tropical Storm	-1.7	-1.9	-2.3	-1.9	-1.5
Small Typhoon	-1.2	-1.0	-1.0	-0.8	-1.4
Medium Typhoon	-0.1	-0.4	-1.0	-0.3	-0.2
Large Typhoon	-0.7	-1.0	-1.7	-1.0	-0.3
Mean	-0.9	-1.2	-1.7	-1.0	-0.7
Scatter	0.7	0.5	0.6	0.7	0.7

TABLE 20

Same as Table 19 except for west Atlantic tropical cyclones.

Stratification	$\int_{\text{surface}}^{100 \text{ mb}}$	$\int_{\text{surface}}^{300 \text{ mb}}$	$\int_{\text{surface}}^{500 \text{ mb}}$	$\int_{700 \text{ mb}}^{500 \text{ mb}}$	200mb+900mb Average
<u>By Latitude</u>					
Region I (South)	-1.3	-0.9	-0.7	-0.7	-1.7
Region II (North)	-1.4	-1.3	-1.3	-1.3	-1.2
<u>By Speed</u>					
Slow ( $1-3 \text{ m s}^{-1}$ )	-0.5	-0.5	-0.6	-0.6	-0.3
Fast ( $> 3 \text{ m s}^{-1}$ )	-1.7	-1.8	-2.2	-1.7	-2.0
<u>By Direction</u>					
Northward ( $316^{\circ}-45^{\circ}$ )	-1.4	-1.6	-2.0	-1.5	-0.8
Westward ( $225^{\circ}-315^{\circ}$ )	-2.2	-1.4	-0.7	-1.3	-2.8
<u>By Intensity</u>					
Hurricane	1.3	-1.2	-1.1	-1.1	-1.4
Tropical Storm	-1.6	-1.3	-1.1	-1.1	-1.7
<u>By Size and Intensity</u>					
Small Tropical Storm	-1.4	-1.3	-1.4	-1.2	-1.2
Large Tropical Storm	-1.4	-1.8	-2.3	-1.7	-0.6
Small Hurricane	-1.3	-1.3	-1.5	-1.4	-1.0
Large Hurricane North	-0.6	-1.3	-2.2	-1.5	0.2
Large Hurricane South	-1.7	-1.5	-1.2	-1.3	-1.5
Mean	-1.4	-1.3	-1.4	-1.3	-1.2
Scatter	0.4	0.4	0.6	0.3	0.8

different averages is also small for most data sets. The scatter among data sets is about the same for all four layer-averages.

The 200 mb 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.

Australian-south Pacific region. Table 21 shows the level- and layer-averaged  $\bar{V}_{PM}$  5-7° for tropical cyclones in this region. As mentioned before, the vertical speed shear in this region is relatively large (see Fig. 15). Therefore, a large variation among different layer-averages exist for a given data set, as seen in Table 21. Both the surface to 500 mb and the 700 mb 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 describes the directional movement of a cyclone in this region. 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 mb and 900 mb average  $\bar{V}_{PM}$  has a wide scatter among data sets in this region. The possibility of using 200 mb 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.

TABLE 21

Same as Table 19 except for tropical cyclones in the Australian-south Pacific region.

Stratification	$\int_{\text{surface}}^{100\text{mb}}$	$\int_{\text{surface}}^{300\text{mb}}$	$\int_{\text{surface}}^{500\text{mb}}$	$\int_{700\text{mb}}^{500\text{mb}}$	200mb+900mb Average
<u>By Direction</u>					
Eastward ( $40^{\circ}$ - $150^{\circ}$ )	0.2	-0.8	-2.5	-0.5	1.0
Westward ( $210^{\circ}$ - $320^{\circ}$ )	-2.2	-1.9	-1.5	-0.6	-3.3
<u>By Intensity and Region</u>					
Hurricane	-0.7	-1.3	-2.1	-0.8	-0.4
Coral Sea Hurricane	-0.8	-1.5	-2.4	-0.9	-0.7
Coral Sea Tropical Storm	-2.4	-2.1	-2.4	-1.4	-2.4
West Australian Hurricane	-0.1	-1.0	-1.7	-1.5	1.0
Mean	-1.0	-1.4	-2.1	-1.0	-0.8
Scatter	1.1	0.5	0.4	0.4	1.8

TABLE 22

Same as Table 18 except for level- or layer-averaged  $V_{PM}$ .

Ocean Basin	$\int_{\text{surface}}^{100\text{mb}}$	$\int_{\text{surface}}^{300\text{mb}}$	$\int_{\text{surface}}^{500\text{mb}}$	$\int_{700\text{mb}}^{500\text{mb}}$	200mb+900mb Average
Northwest Pacific	-0.9 (0.7)	-1.2 (0.5)	-1.7 (0.6)	-1.0 (0.7)	-0.7 (0.7)
West Atlantic	-1.4 (0.4)	-1.3 (0.4)	-1.4 (0.6)	-1.3 (0.3)	-1.2 (0.8)
Australian- south Pacific Region	-1.0 (1.1)	-1.4 (0.5)	-2.1 (0.4)	-1.0 (0.4)	-0.8 (1.8)

Summary. Layer-averaged  $\bar{V}_{PM}$  for all data sets in each of the three ocean basins is shown in Table 22. It can be seen that in the three ocean basins, cyclones always move faster than the mean 5-7° level- or layer-averaged winds. The most consistent layer-average appears to be the surface to 300 mb average. The mid-tropospheric average is also about the same between the three oceans. Therefore, it seems that what layer-average is the best depends very much on the vertical wind shear profile in the environment. The 200 mb and 900 mb average  $\bar{V}_{PM}$  appears not to be nearly as useful as the mean layer information.

b. Individual Octants

As discussed in section 3, radial band average winds are not typically available in individual storm situations. Therefore, one needs to find a sector of the radial band which gives similar consistency among all data sets. The scatter of  $V_{PM}$  for all eight octants at 5-7° were calculated at 700, 600 and 500 mb. The average  $V_{PM}$  between 200 mb and 900 mb is also calculated just to see if some of the octants may give better results than the belt average. The results for both the mid-tropospheric levels and the 200 mb and 900 mb average show in general a larger variation than the radial band average values. However, if the average between the two octants 1 (front) and 5 (rear) is taken, a consistency comparable to that of the radial band average is obtained.

Northwest Pacific. Table 23 shows that standard deviations for the different levels are almost the same, with the mean 200 mb and 900 mb  $V_{PM}$  being the smallest. Therefore, it appears that at least in the northwest Pacific, the 200 mb and 900 mb wind in the front and rear

TABLE 23

Values of  $V_{PM}$  in the northwest Pacific averaged between octant 1 (front) and octant 5 (rear) in the 5-7° radial band at various pressure levels.

STRATIFICATION	700mb	600mb	500mb	200mb+900mb Ave.
<u>By Latitude</u>				
North of 20°N	-0.6	0.2	-0.4	-0.5
South of 20°N	-0.8	-0.7	-0.3	-0.1
<u>By Speed</u>				
Slow (1-3 m s <sup>-1</sup> )	-1.4	-0.6	-2.1	-0.6
Moderate (4-7 m s <sup>-1</sup> )	-0.2	0.2	0.1	-0.3
Fast (> 7 m s <sup>-1</sup> )	-0.8	0.3	0.3	-0.2
<u>By Direction</u>				
Westward (250°-310°)	-1.5	-1.2	-0.4	-1.0
Northward (310°-350°)	0.2	0.3	-0.7	-0.6
Eastward (350°-60°)	0.1	1.4	1.3	0.5
<u>By Intensity</u>				
Weak (1000-980 mb)	-0.5	0.4	1.1	-0.1
Intense (950-980 mb)	0.1	0.7	0.1	0.2
Very Intense (< 950 mb)	-0.8	-0.7	-1.1	-0.6
<u>By Intensity Change</u>				
Deepening North of 20°N	-1.6	-1.2	-3.1	-1.5
Deepening South of 20°N	-0.9	-0.8	-1.4	-0.3
Filling North of 20°N	0.6	0.8	0.6	1.4
Filling South of 20°N	-0.6	-0.8	-1.0	-0.9
<u>By Size and Intensity</u>				
Small Tropical Storm	-0.3	0.2	0.4	-0.8
Medium Tropical Storm	-0.7	0.1	1.0	-0.1
Large Tropical Storm	-2.4	-1.6	-0.8	-0.9
Small Typhoon	0.8	1.5	1.0	-0.7
Medium Typhoon	-1.2	-0.7	-0.6	0.2
Large Typhoon	-1.4	-0.5	-0.9	0.4
Mean	-0.7	-0.1	-0.3	-0.3
Scatter	0.8	0.8	1.1	0.6

TABLE 24

Same as Table 23 except for west Atlantic tropical cyclones.

STRATIFICATION	700mb	600mb	500mb	200mb+900mb Ave.
<u>By Latitude</u>				
Region I (South)	0.2	-0.7	-1.0	-1.8
Region II (North)	-0.8	-1.1	-1.4	-0.1
<u>By Speed</u>				
Slow ( $1-3 \text{ m s}^{-1}$ )	-0.5	-0.8	-1.0	-0.4
Fast ( $> 3 \text{ m s}^{-1}$ )	-1.3	-1.4	-1.3	-0.4
<u>By Direction</u>				
Northward ( $316^{\circ}-45^{\circ}$ )	-1.5	-1.7	-1.6	0.8
Westward ( $225^{\circ}-315^{\circ}$ )	0.4	-0.5	-1.4	-2.3
<u>By Intensity</u>				
Hurricane	-0.2	-0.5	-0.8	-0.2
Tropical Storm	-0.6	-1.5	-2.1	-1.9
<u>By Size and Intensity</u>				
Small Tropical Storm	-1.1	-1.2	-1.3	-0.4
Large Tropical Storm	-2.1	-1.7	-1.4	0.6
Small Hurricane	-0.8	-1.0	-1.2	0.2
Large Hurricane North	-2.6	-1.4	-0.7	0.5
Large Hurricane South	-0.4	-1.0	-1.0	0.0
Mean	-0.9	-1.1	-1.3	-0.4
Scatter	0.9	0.4	0.4	1.0

octants would be as useful in describing cyclone speed as similar mid-tropospheric data.

West Atlantic. The octants 1 and 5 averaged  $V_{PM}$  are shown in Table 24. The smallest scatter appears at 600 mb and 500 mb. The 200 mb and 900 mb average appears less useful than in the northwest Pacific.

Australian-south Pacific region. Octants 1 and 5 averaged  $V_{PM}$  for Australian-south Pacific systems are given in Table 25. Much more variability exists at all the levels. Using winds at one or two octants to describe cyclone speed will probably not be satisfactory. The scatter among data sets for the 200 mb and 900 mb average  $V_{PM}$  appears too large to be of much use.

Summary. Because of the difference in the environmental flow between cyclones in different ocean basins, the possibility of using winds at one or two octants to describe cyclone speed really depends on the vertical homogeneity of the flow. Individual octant information, in general, is not as useful as radial band average data in describing cyclone speed.



TABLE 25

Same as Table 23 except for tropical cyclones in the Australian-south Pacific region.

<u>STRATIFICATION</u>	<u>700mb</u>	<u>600mb</u>	<u>500mb</u>	<u>200mb+900mb Ave.</u>
<u>By Direction</u>				
Eastward (40°-150°)	-4.9	-1.3	1.6	1.6
Westward (210°-320°)	-0.6	-1.5	-2.2	-1.6
<u>By Intensity and Region</u>				
Hurricane	-2.2	-1.3	-0.7	0.2
Coral Sea Hurricane	-5.0	-4.9	-1.9	2.1
Coral Sea Tropical Storm	-3.6	-2.6	-0.1	-0.3
West Australian Hurricane	-0.7	-0.9	-1.5	-0.8
Mean	-2.8	-2.1	-0.8	0.2
Scatter	2.0	1.5	1.4	1.4

## 5. SUMMARY AND DISCUSSION

The main conclusions of this study are:

- a) the large-scale circulation is a key factor in determining the movement of tropical cyclones;
- b) wind data at the mid-troposphere (700, 600 and 500 mb) correlates best with both the direction and speed of cyclone movement;
- c) on the average, tropical cyclones in the Northern Hemisphere moves  $\sim 10^{\circ}$ - $20^{\circ}$  to the left of the surrounding mid-tropospheric winds at  $\sim 6^{\circ}$  radius from the cyclone center; an approximate opposite directional deviation occurs for cyclones in the Southern Hemisphere;
- d) on the average, tropical cyclones move faster by  $\sim 1 \text{ m s}^{-1}$  than the surrounding mid-tropospheric winds at  $\sim 6^{\circ}$  radius from the cyclone center;
- e) cyclones having different zonal directions of cyclone motion have different relationships with their  $5\text{-}7^{\circ}$  surrounding flow;
- f) 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; and
- g) 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 so 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,  $0.9 \text{ m s}^{-1}$  more northward and  $3.4 \text{ m s}^{-1}$  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 if one makes a forecast from a scheme based on steering flow, he would tend to

predict the cyclone to move to the right of the actual track and slower than observed. 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 on steering flow alone 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), Sanders et al. (1975), Anthes and Hoke (1975), Harrison (1981), etc. 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 Holland (1982) and Chan (1982) also arrive at the same conclusion. They explained both the directional deviation and the difference in cyclone speed and environmental wind speed in terms of the variation of the Coriolis parameter across the cyclone.

All these observational and theoretical results suggest 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.

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