Analysis of Satellite-Observed Tropical Cloud Clusters

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*E. Ruprecht was on leave from the Institute of Meteorology, Univ. of Bonn. FRG.
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Paper No. 219

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ABSTRACT

Composited Northern Hemispheric Data Tabulation rawinsonde data has been gathered relative to three satellite-observed tropical weather systems in the Western Pacific (Eq.-18°N) and in the West Indies ($\sim$ 15-30°N). These systems include the $\sim$ 4° wide cloud cluster, the cloud cluster environment ($\sim$ 2-6° latitude around the cluster center), and the clear region. Information is presented for the years 1967 and 1968. Over 10,000 individual rawinsonde reports have been processed to form composited information on 1341 cloud clusters, 1341 cloud cluster environments, and 449 clear regions. The data gathering philosophy and methodology follows that discussed in a previous report by Williams and Gray (1973).

Composited information is presented on individual weather system winds, divergence, vorticity, temperature, humidity, rainfall, diurnal variations, etc. The dynamic mechanisms, CISK and barotropic instability,are discussed. The mean cloud cluster vorticity budget is calculated. Significant differences exist between the Western Pacific and the West Indies weather systems.

Variations within weather systems are typically much larger than mean parameter differences between weather systems. This is believed to result from the substantial vertical mass recycling which is occurring in association with the cumulus convection. These large variations within weather systems prevent an accurate synoptic-scale resolution of the individual systems. They are likely to cause substantial difficulties for sub-grid scale parameterization and tropical forecasting.

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1. INTRODUCTION

Satellite meteorology was truly initiated in 1966 with the initial availability of NESS global daily digitized pictures. The more recent synchronous satellite launches have also greatly expanded our tropical data coverage and research potential. Before these advances in satellite technology can be fully exploited,a few years of picture compositing, processing, and digesting are required. Intensive statistical stratification of this new information is now possible.

Of particular importance has been the satellite picture observation and documentation of tropical weather systems. Attention has focused on the prominance of the meso-scale $\sim 4^{\circ}$ wide (Hayden, 1970) cloud cluster. These clusters are of growing interest because of their hypothesized role in the general circulation. The instigation of the GARP Atlantic Tropical Experiment (GATE) has been in response to this requirement for more physical understanding of tropical weather systems and in particular the mode of cumulus convection of the satellite-observed cloud cluster. It is important that we learn as much as we can about the dynamics of these clusters so that their influences can be better understood and parameterized in future global circulation models.

This very large increased satellite coverage by itself, however, will not significantly advance our basic understanding of tropical atmospheric dynamics unless the new cloud picture data is properly associated with the flow and thermodynamic patterns in which the cloud fields are embedded. This research report investigates these tropical satellite pictures and attempts to associate them with the characteristic flow conditions in which they are embedded. So far very little of this type of research has been attempted. The typical satellite study has concentrated on individual satellite pictures. Usually, only small amounts of upper air data is available to go with individual picture information. This is especially true over the tropical oceans. The authors feel that more involved long-term averaging of the satellite data in terms of the other meteorological parameters would significantly add to our knowledge of these systems. Most previous tropical weather system investigations have been accomplished without benefit of satellite pictures. The present research represents a new approach: the use of both conventional rawinsonde data and satellite data simultaneously in a large statistical survey of individual specified cloud systems.

The analysis of tropical weather systems has generally followed one of two methodological paths:

1) Analysis of tropical disturbances as a form of wave phenomena and investigation of wavelength, frequency, dynamic properties, etc., (Chang, 1970; Nitta, 1970; Reed, 1970; Reed and Recker, 1971; Yanai et al., 1968). A general summary of this research approach has been given by Wallace (1971).

2) Looking at the disturbances as a phenomenon not necessarily associated with a wave and investigating their in situ characteristics (Frank and Johnson, 1969; Riehl and Pearce, 1968; Simpson et al., 1967; Williams and Gray, 1973; Zipser, 1969).

This paper follows the latter point of view. It is an extension of the previous tropical analysis research of Williams and Gray (1973), Gray (1973), and Lopez (1973). All available data from routine rawinsonde observations, surface observations (rainfall), and satellite photographs were gathered, combined, and integrated. Emphasis was placed on the regional differences between Western Pacific and West Indies cloud clusters and on their structure and dynamics.

2. DATA AND METHOD OF ANALYSIS

2.1 Satellite Appearance of Tropical Cloud Clusters

The tropical cloud cluster appears in satellite photographs as a bright, solid white blob. This is due to the large cirrus canopy typically associated with the cluster. These cirrus canopies are produced by outflow from and remnants of cumulonimbi. Developing and conservative clusters maintain their cumulonimbi from a steady lower tropospheric convergence; clusters gradually die when their low level mass convergence is eliminated. The BOMEX project has well documented the 3 to 9 hour (or more) time lag between the satellite-viewed cirrus canopies of dying clusters and the active cumulonimbus clouds which produced them. Sometimes the cloud clusters are largely composed of middle-layer cloudiness (Sadler, 1962). Flying through the satellite-observed clusters, one sometimes observes very few cumulonimbi. In most clusters, large numbers of Cb's are believed to be present. Clusters sometimes lose a large part of their cloudiness due to temporary stabilizing buoyancy changes from cumulus downdrafts. Figure 1 shows typical satellite appearances of the tropical clusters we will be discussing. The last two diagrams show examples of clear regions.

2.2 Data Sources

Figures 2 and 3 show the rawinsonde data networks which are used in our analysis. From a geographical and climatological viewpoint, these regions have significant differences. The Western Pacific area is far from a continent. The rawinsonde stations are typically located on small islands and atolls. Cloud clusters are often associated with the ITCZ. In the West Indies 16 of the 34 radiosonde stations are located on the continent and 4 on large islands. West Indies clusters are not

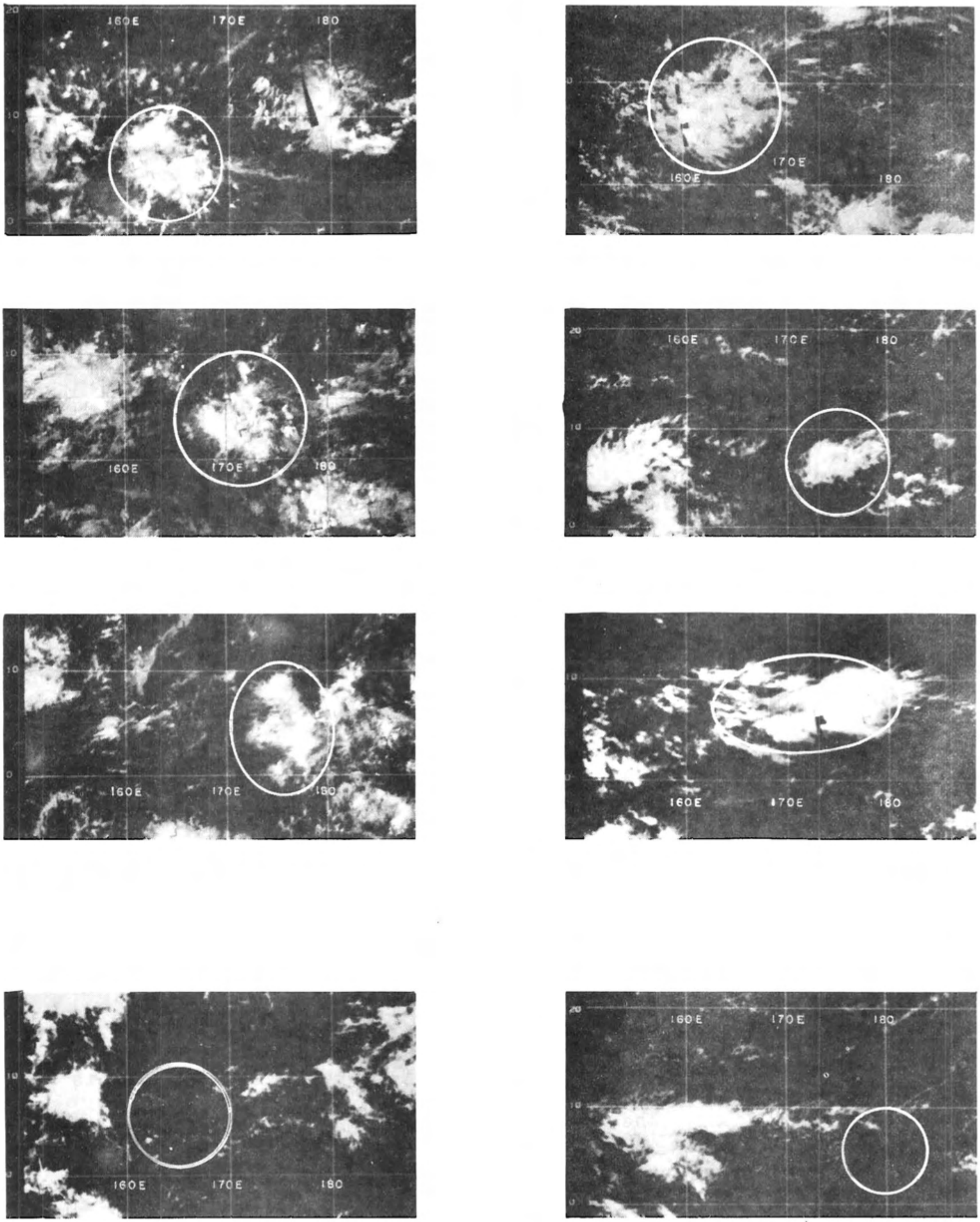


Fig. 1. Typical portrayal of satellite-observed cloud clusters and clear regions.

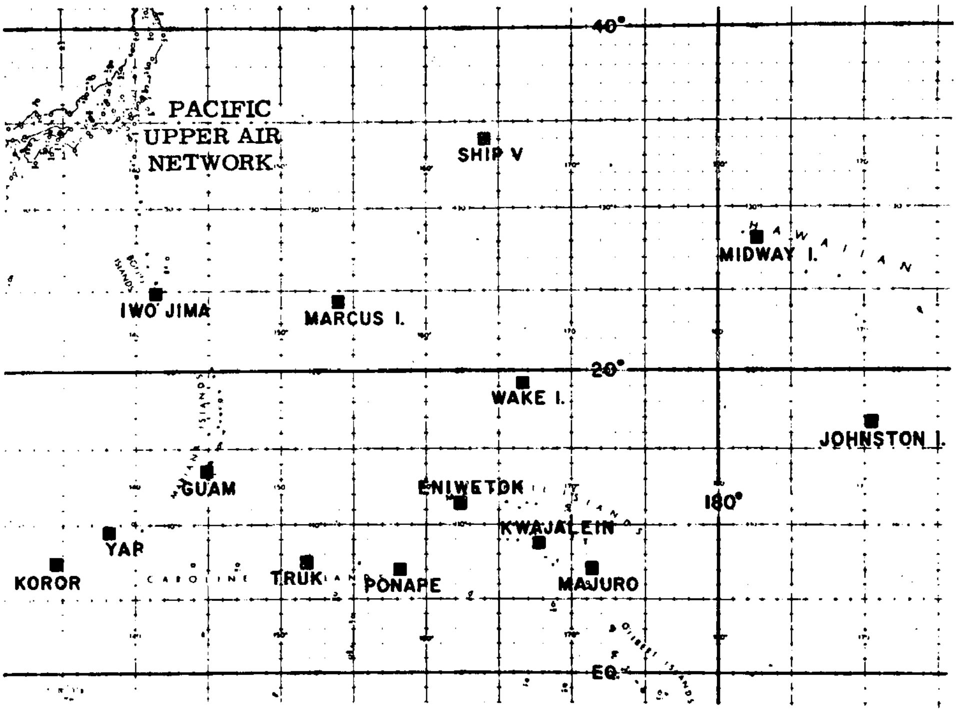


Fig. 2. Radiosonde network in the Western North Pacific Ocean.

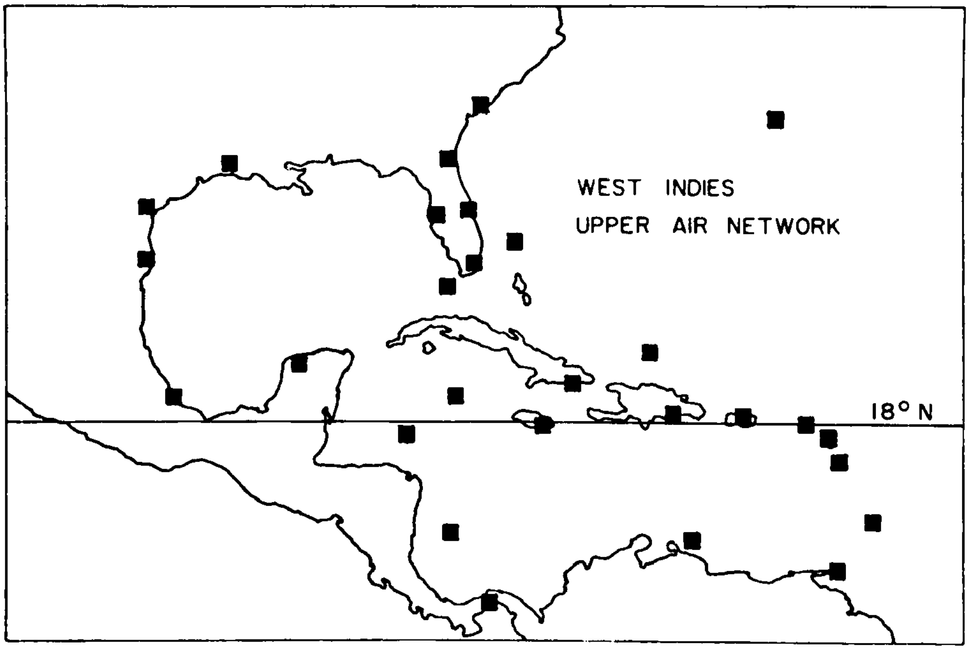


Fig. 3. Radiosonde network in the West Indies.

associated with the ITCZ. Appendix A gives more information on the rawinsonde stations used and the locations of the individual weather systems relative to these upper-air stations.

2.3 Compositing Philosophy

Due to deficiency in observation, the flow patterns associated with individual satellite-observed weather systems cannot be adequately described. The surrounding observations that are available at regular time intervals are often not representative. The authors feel that one can understand the basic physical processes involved with tropical systems only from a composite study of many systems with similar characteristics. The individual observations are seldom, if ever, of sufficient quantity or of sufficient representativeness to accurately describe the individual system.

A discussion of the used compositing technique has been previously given in a paper by Williams and Gray (1973). Figure 4 shows how the rawinsonde data was composited relative to the satellite-observed tropical clusters and clear regions. No effort has been made to classify different types of clusters as was done by Williams and Gray (1973). Table 1 gives information about the number of rawinsondes which are averaged for each weather system. The present investigation is limited in the Western Pacific to weather systems south of 18^{o}N and in the West Indies to systems north of 18^{o}N.[1] The West Indies cloud cluster occurred in the latitude range of $\sim$ 18 to 30^{o}. Appendix A shows the locations of all of the cloud clusters and clear regions.

[1]Williams and Gray (1973) included in their Pacific study all clusters and clear areas to 28^{o} latitude. Thus, differences between the results of this study and theirs will occur, especially for the clear regions.

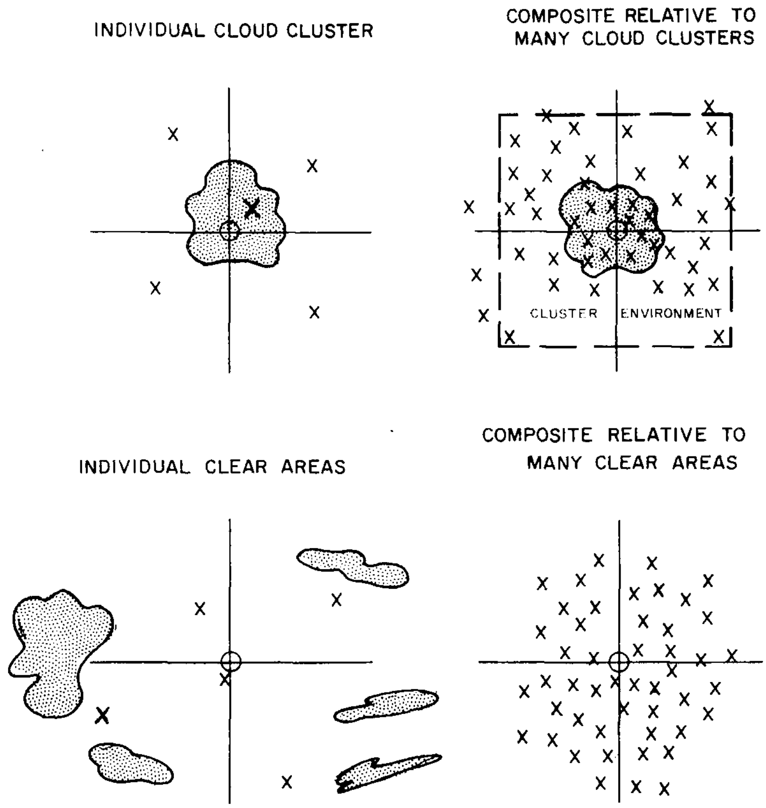


Fig. 4. Portrayal of how the rawinsondes are positioned and then composited relative to the cloud cluster and clear regions.

Table 1

Area	Western Pacific	West Indies
	equator-18°N	18°-30°N
	130°E-165°W	50°W-95°W
Time	Nov. 1966-Oct. 1968	Jan. 1967-Dec. 1968
No. of Weather Systems		
Cloud Clusters	1096	245
Cluster Enviornments	1096	245
Clear Regions	267	182
TOTAL NUMBER OF RAWINSONDES	5690	5035

2.4 Compositing Technique

Following the classification presented by Gray (1973), three different types of typical weather systems are defined and treated separately. These are:

1) The satellite-observed ∿ 4^{o} wide cloud cluster (Fig. 1) (as defined by Madison, Wisc., 21 Oct. - 8 Nov., 1968 special GARP study report on tropical disturbances) in the Western Pacific and in the West Indies.

2) Cloud Cluster Environment or variable cloud region defined as the area from $2\text{-}6^{o}$ radius around the cloud cluster center (Fig. 5).

3) Clear regions between cloud clusters where no cloudiness is seen on the satellite pictures (bottom diagrams of Fig. 1).

The positions of the centers of the cloud clusters and clear regions were determined from U. S. Weather Bureau ESSA satellite pictures for the two year period of November 1966-October 1968 for the Western Pacific and January 1967-December 1968 for the West Indies. All available rawinsonde data are composited with respect to these individual weather systems.

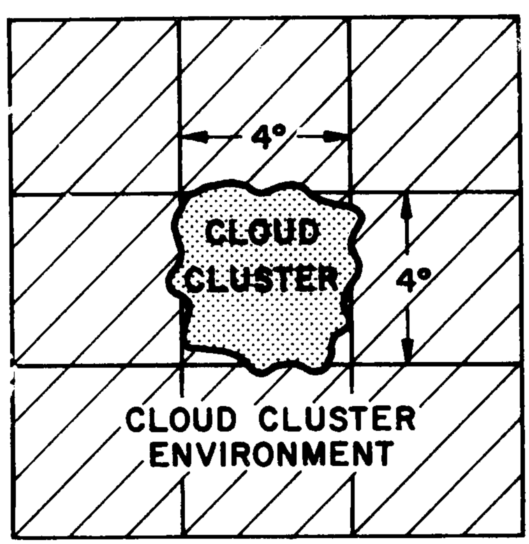
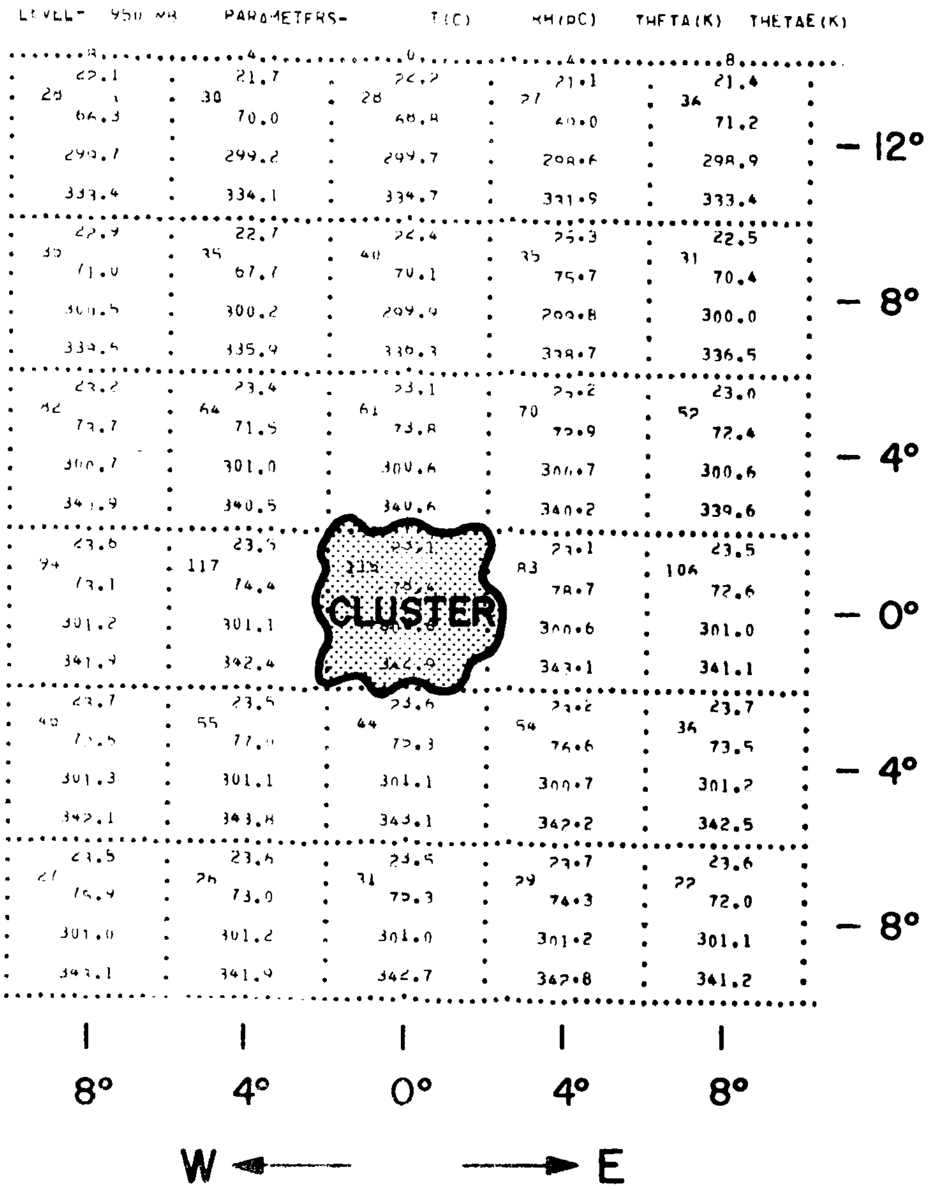


Fig. 5. Portrayal of typical size and relative location of the cloud cluster and the cloud cluster environment. Rawinsonde data has been averaged in each 4^{o} square.

Data have been analyzed from rawinsondes taken at 00Z and 12Z. In accordance with the observed daily westward progression of the cloud clusters and the supporting information of Wallace (1970) and Chang (1970), it was assumed that the weather systems moved westward at a velocity of $\sim 6^{\circ}$ longitude per day. Station locations relative to the satellite picture time were adjusted accordingly.

The nearest rawinsonde observations to the satellite pictures (15 local time) were processed. For the Western Pacific stations the 00Z-soundings ($\sim$ 10 local time) were used, for the West Indies the 12Z-soundings ($\sim$ 07 local time) were used. The daytime relative humidities have been corrected for thermistor heating by a scheme discussed in Appendix B.

To have as large and as statistically significant a data sample as possible, all information was averaged with respect to the centers of the clusters and clear regions on a 4° latitude-longitude grid. This is similar to the grid averaging previously used by Williams and Gray (op. cit.). Thus, our 4°x4° grid cannot resolve smaller scale phenomena. Figure 5 portrays this grid resolution. Figure 6 is an example of the 4° resolution data listings relative to a composited cloud cluster.



	8° W	4° W	0°	4° E	8° E
12° N	25 obs; 22.1; 66.3; 299.7; 333.4	30 obs; 21.7; 70.0; 299.2; 334.1	28 obs; 22.2; 68.8; 299.7; 334.7	27 obs; 21.1; 60.0; 298.6; 331.9	36 obs; 21.4; 71.2; 298.9; 333.4
8° N	33 obs; 22.9; 71.0; 300.5; 334.5	35 obs; 22.7; 67.7; 300.2; 335.9	40 obs; 22.4; 70.1; 299.9; 336.3	35 obs; 25.3; 75.7; 299.8; 338.7	31 obs; 22.5; 70.4; 300.0; 336.5
4° N	82 obs; 23.2; 73.7; 300.7; 341.9	64 obs; 23.4; 71.5; 301.0; 340.5	61 obs; 23.1; 73.8; 300.6; 340.6	70 obs; 23.2; 72.9; 300.7; 340.2	52 obs; 23.0; 72.4; 300.6; 339.6
0°	94 obs; 23.6; 73.1; 301.2; 341.9	117 obs; 23.5; 74.4; 301.1; 342.4	115 obs; 23.1; 78.4; [illegible]; 342.9	83 obs; 23.1; 78.7; 300.6; 343.1	106 obs; 23.5; 72.6; 301.0; 341.1
4° S	40 obs; 23.7; 75.5; 301.3; 342.1	55 obs; 23.5; 77.0; 301.1; 343.8	44 obs; 23.6; 75.3; 301.1; 343.1	54 obs; 23.2; 76.6; 300.7; 342.2	36 obs; 23.7; 73.5; 301.2; 342.5
8° S	27 obs; 23.5; 75.9; 301.0; 343.1	26 obs; 23.6; 73.0; 301.2; 341.9	31 obs; 23.5; 75.3; 301.0; 342.7	29 obs; 23.7; 74.3; 301.2; 342.8	22 obs; 23.6; 72.0; 301.1; 341.2

Fig. 6. Sample computer printout of the 950 mb level composited data relative to a cloud cluster. In each box, the number of observations, average temperature, relative humidity, θ, and θ_e are shown. The numbers along the outside border indicate the degrees of latitude north and south, and of longitude east and west, of the mean cluster center. At the 4^o square just W of the cloud cluster there are 117 observations which yield the following average values: T = 23.5°C, RH = 74.4%, θ = 301.1°K, θ_e = 342.4°K.

3. WIND FIELDS ASSOCIATED WITH WESTERN PACIFIC AND WEST INDIES WEATHER SYSTEMS

3.1 Meridional Winds

Riehl (1945) was one of the first to associate concentrated areas of cloudiness and precipitation in the trade winds to wave type disturbances which propagate westward. He developed an easterly wave model with low level convergence and convective activity east of the trough line and subsidence west of it. This model was derived mainly for the West Indies area. A question arises whether the usual $\sim 4^{\circ}$ diameter satellite-observed cloud clusters are typically associated with such a wave model and also, how the cluster regions compare with the clear regions, etc. Figures 7-10 give zonal-height cross-sections of the composited meridional wind for the Western Pacific and West Indies cloud clusters and clear regions.

Western Pacific: East of the cloud cluster (Fig. 7) the expected S-winds are observed. However, the corresponding N-wind maximum is hardly in evidence. We might interpret the difference of the maximum of S-winds to the east of the cloud cluster ($\sim$ 1.9 m/sec) and of N-winds to the west of the cluster center as being in general agreement with Riehl's model. Many individual clusters would not fit this mean pattern however. No distinct east-west meridional wind pattern is found in the clear regions (Fig. 8).

West Indies: The distribution of the meridional winds (Fig. 9) shows only that the south winds to the east of the trough are stronger than the south winds to the west of the trough. Only a small west to east shear of meridional wind is observed. Again, this is an average pattern.

Fig. 7.

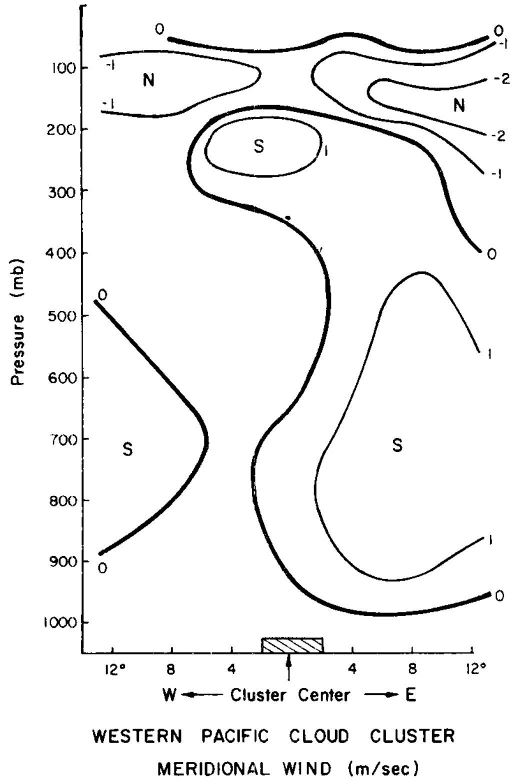


Fig. 8.

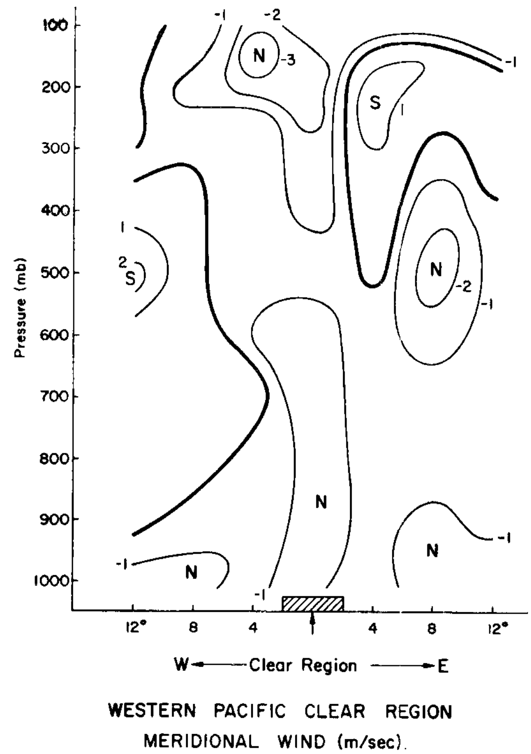


Fig. 9.

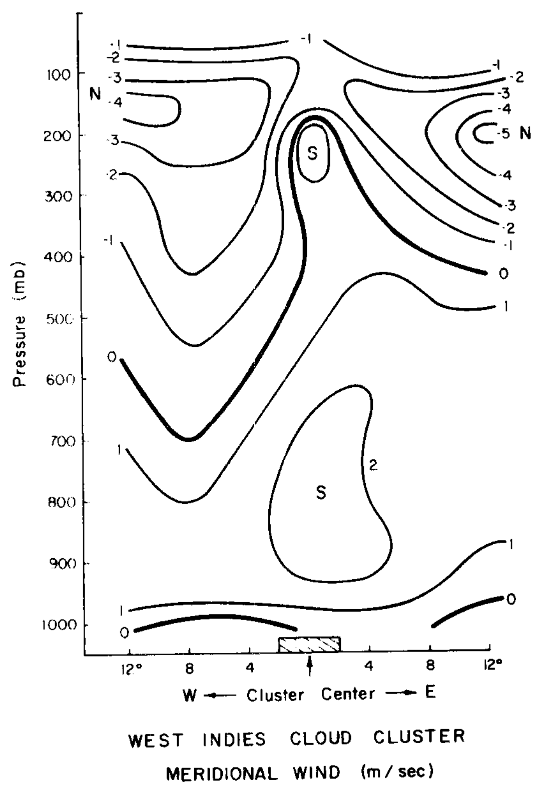
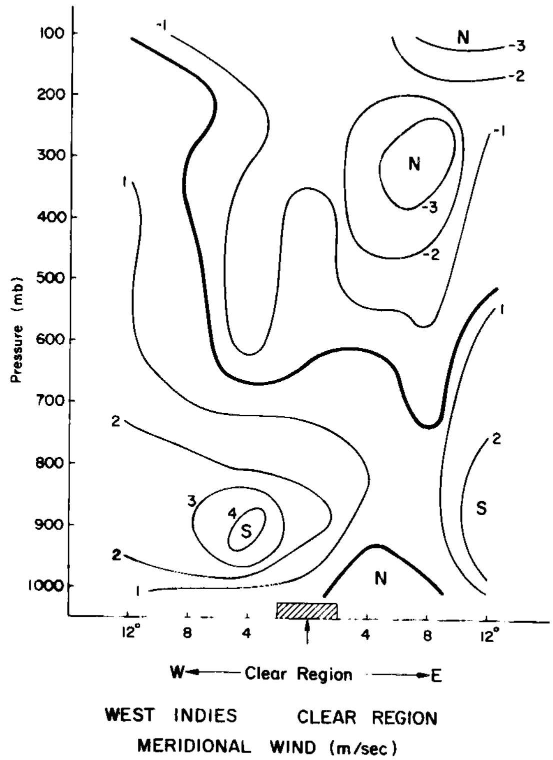


Fig. 10.



Figs. 7-10. West-east cross-sections of meridional wind for Western Pacific and West Indies cloud clusters and clear regions. The small hashed rectangular box at the figure bottom defines the 4^{o} cloud cluster or clear area width.

Many individual clusters may well have fit the Riehl easterly wave model. The West Indies clear regions (Fig. 10) indicate a west to east meridional wind shear in agreement with the ridge region of the Riehl wave model.

The distribution of the meridional wind around the clusters in both regions indicates a Hadley circulation with low level south winds and upper level north winds. The same is true for the West Indies clear region. However, a reverse Hadley cell is indicated for the Western Pacific clear areas.

The meridional wind distributions indicate that a number of cloud clusters are likely associated with wave disturbances. As discussed by Wallace (1971), spectrum analysis of tropical data indicates a wide range of waves and mutual interactions of tropical disturbances. Our 4^{o} compositing technique could not resolve the smaller scale wave components and our area of coverage precluded resolution of the hemispheric scale wave components.

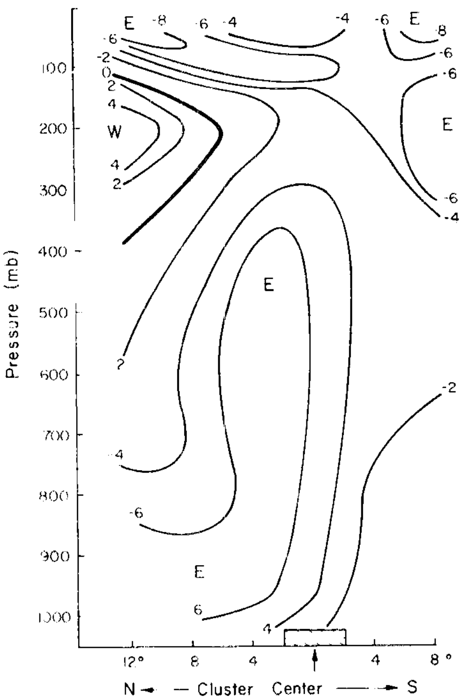
3.2 Zonal Winds

The largest differences between the Western Pacific and the West Indies areas occur with the zonal winds.

<u>Western Pacific</u>: The cloud cluster area is entirely within the tropical east-wind regime but the mid-latitude westerlies are present just north of the clear region centers (Figs. 11 and 12).

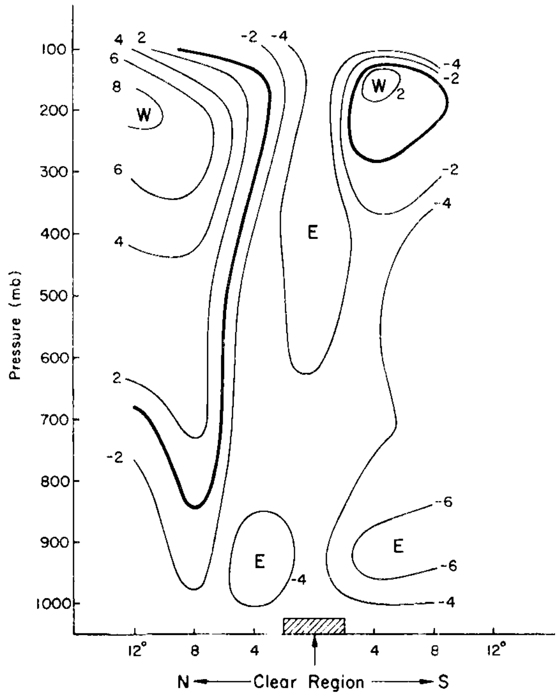
Although the average positions of the cloud cluster (9^{o}N) and the clear region (11^{o}N) are nearly the same, the trade wind maximum is north of the cloud cluster center (Fig. 11) and slightly south of the clear region center (Fig. 12). These contrasting positive and negative horizontal shearing patterns are believed to be a primary feature in producing the contrasting low level convergence and divergence patterns

Fig. 11.



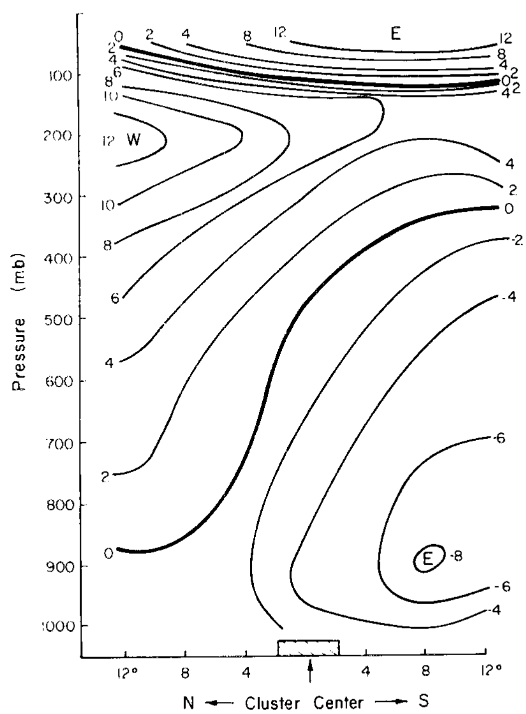
WESTERN PACIFIC CLOUD CLUSTER
ZONAL WIND (m / sec)

Fig. 12.



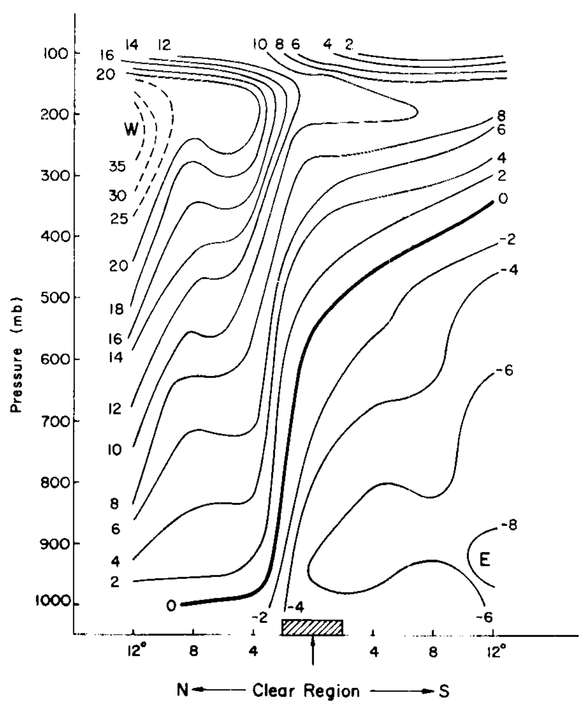
WESTERN PACIFIC CLEAR REGION
ZONAL WIND (m/sec)

Fig. 13.



WEST INDIES CLOUD CLUSTER
ZONAL WIND (m / sec)

Fig. 14.



WEST INDIES CLEAR REGION
ZONAL WIND (m/sec)

Figs. 11-14. North-south cross-sections of zonal wind for the Western Pacific and West Indies cloud clusters and clear regions. The small hashed rectangular box at the figure bottom defines the 4^{o} cloud cluster or clear area width.

associated with each system. The changing cloud patterns appear to result from a meridional shift of the trade wind maximum.

West Indies: This region is associated with two different tropospheric wind systems, the tropical easterlies and the mid-latitude westerlies. In contrast to the Western Pacific, the trade wind maximum is located well to the south of the cluster center. Both cluster and clear systems exist in a broad-scale anticyclonic north-south shear pattern.

Vertical Shear of Zonal Wind. A striking feature in the comparison of the zonal wind distributions is the change of zonal wind with height. The Pacific mean cluster shows zonal wind strengths are nearly constant up to 400 mb. North of the cluster center the vertical gradient of the zonal wind is positive; south of the cluster it is negative. This indicates that the cluster is located at the latitude of warmest surface to 400 mb temperature. This result is in contrast to Riehl's easterly wave model, which proposed a weak cold core for disturbances in the lower half of the troposphere. The vertical gradient of the zonal wind for the clear areas is always positive except for the center where it is nearly constant. This pattern indicates that the warmest areas are south of the clear region. In the West Indies the zonal vertical shear is much larger and always positive. Warmest tropospheric temperatures are found far to the south.

Figures 15 and 16 portray the vertical shear of the zonal wind for each weather system in both regions. Little difference is found between the weather systems of both regions. As the type and degree of organization of deep cumulus convection is highly dependent on the magnitude of tropospheric vertical shear, one would expect more organization of deep convection in the West Indies. Surface reports of cluster squall-

Fig. 15.

WESTERN PACIFIC

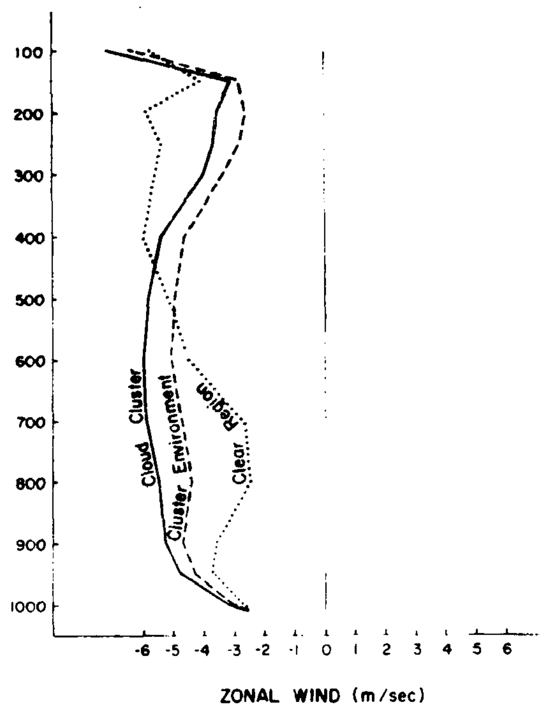
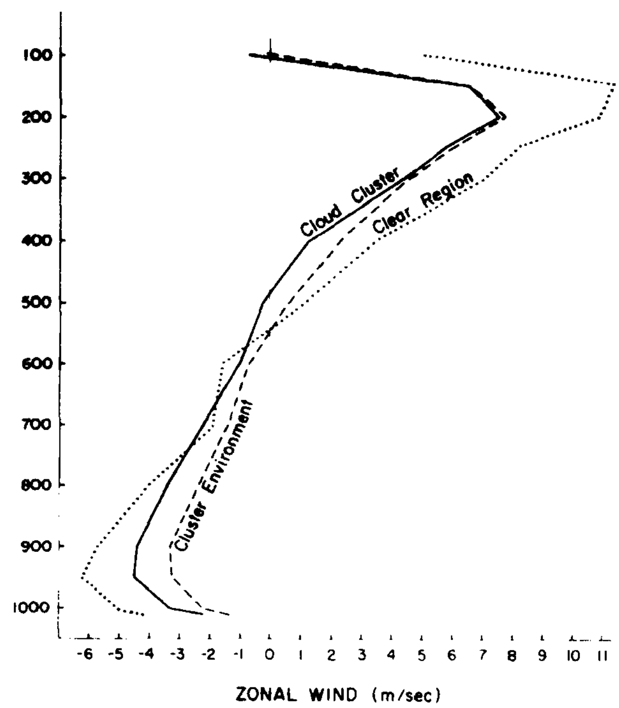


Fig. 16.

WEST INDIES



Figs. 15-16. Tropospheric distribution of zonal winds by type of weather system.

line activity indicate a greater prevalence in the West Indies. It appears that Western Pacific clusters have relatively few squall lines except in the winter and between Johnson and Kwajalein where vertical shear is larger.

3.3 Barotropic Instability of the Mean Zonal Flow

The north-south gradient of zonal wind in the Pacific gives rise to the possible existence of barotropic instability. Nitta and Yanai (1969) have indicated that at certain times and at certain levels conditions for barotropic instability are satisfied in the Western Pacific. Their stated necessary and sufficient condition is that the meridional gradient of absolute vorticity, i.e. $\frac{\partial}{\partial y}(f - \frac{\partial \bar{u}}{\partial y})$ or $(\beta - \frac{\partial^2 \bar{u}}{\partial y^2})$, changes sign.

Here y measures north-south distance, f is the Coriolis parameter, and $\bar{u}$ is the mean zonal wind. A necessary condition for instability is that the zonal flow has an inflection point (i.e. $\frac{\partial \bar{u}^2}{\partial y^2}$ changes sign).

Figure 17 shows the mean zonal wind profiles at selected levels for the Western Pacific and West Indies cloud clusters. The required inflection point is found at all levels except 200 mb for the Western Pacific cloud cluster. In the West Indies it is only found below 700 mb.

As seen in Fig. 18, the Western Pacific cluster absolute vorticity $(f - \frac{\partial \bar{u}}{\partial y})$ shows a maximum only at 400 mb. At all other levels and in the West Indies the absolute vorticity of the mean cluster does not change its sign.

These results indicate that the growth and development of the cloud cluster disturbances cannot be typically explained by the barotropic instability process on this 4° scale of shearing gradient. The decrease of the gradient of absolute vorticity around the Western Pacific cloud clusters, however, leads to the conclusion that the barotropic instability mechanism may, in some situations, be a significant energy source for disturbance growth. This can occur in individual situations when:

1) the gradient of north-south shearing fields is much larger than the mean shear shown and/or when

2) our 4° grid resolution was too broad to resolve the real shear which was occurring.

Nitta and Yanai (1969) have indicated that the mean zonal flow is characteristically barotropically unstable only in very small ($\sim 2^{\circ}$) latitude belts.

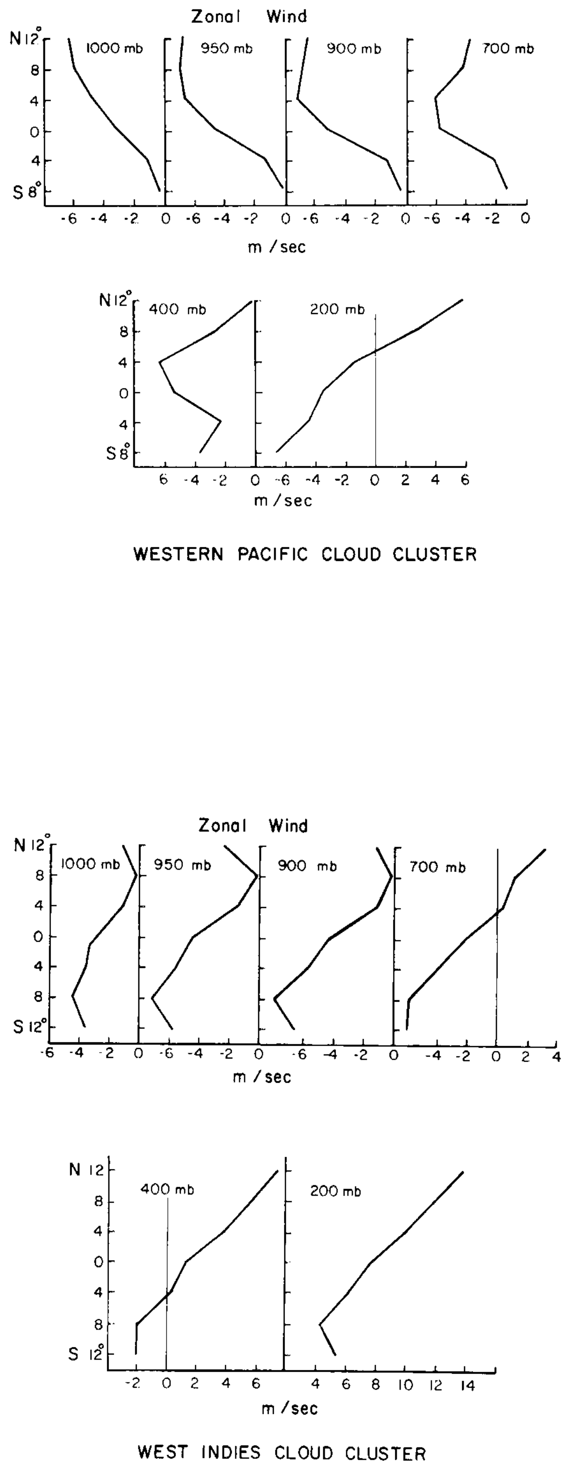
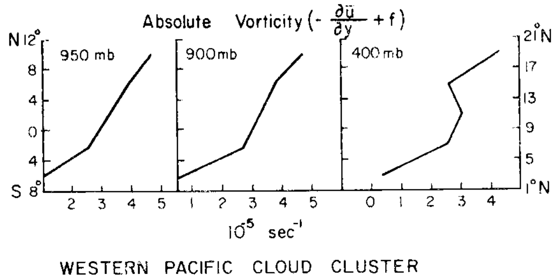


Fig. 17. Portrayal of north-south distribution of zonal wind relative to the Western Pacific and West Indies cloud clusters.



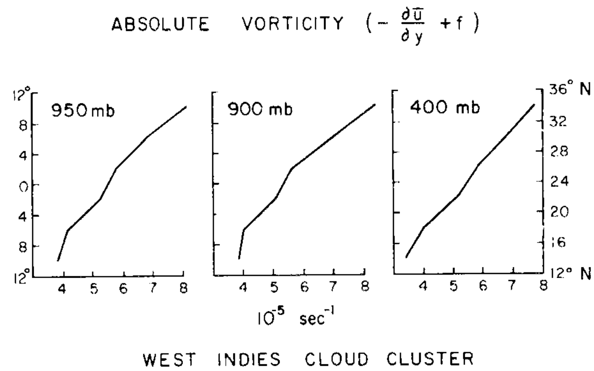


Fig. 18. Portrayal of north-south distribution of absolute vorticity relative to the Western Pacific and West Indies cloud clusters.

3.4 Divergence and Vertical Velocity

Williams and Gray (1973) have previously shown vertical divergence profiles for Western Pacific cloud clusters and clear regions. The cloud cluster profile showed a nearly constant inflow layer up to 400 mb and an intense outflow layer between 100-300 mb. Reed and Recker (1971) have also indicated a similar profile in the trough region of wave disturbances passing through the Marshall Islands. Yanai et al. (1973) have also derived this type of vertical divergence profile in the summer for a large hexagonal region in the Marshall Islands which by favorable circumstance straddled the ITCZ area of convection. A question arises whether this divergence profile is applicable to cloud clusters other than those of the Pacific. The comparison between the vertical divergence and vertical velocity profiles for the Western Pacific and the West Indies cloud cluster are given in Figs. 19 and 20.

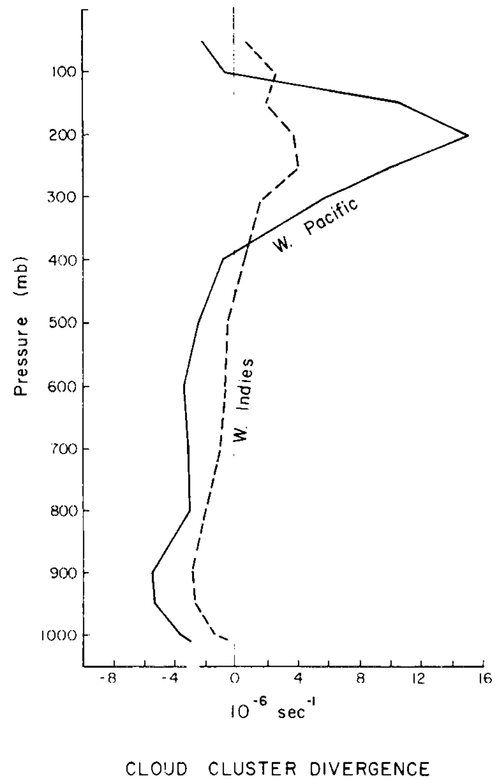


Fig. 19. Mean vertical divergence profiles for Western Pacific and West Indies cloud clusters.

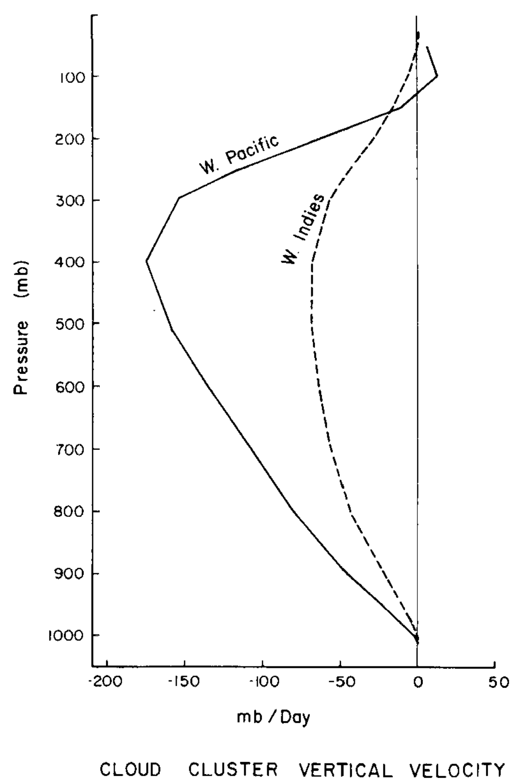


Fig. 20. Vertical profiles of the mean vertical velocity for Western Pacific and West Indies cloud clusters.

We conclude from these results that Western Pacific clusters are stronger and better developed than their counterparts over the West Indies. A two layer model of divergence can be generally applied to disturbances of both regions. The shape of the profiles are in general agreement. The intensity of the vertical circulation and middle-level convergence is significantly less in the West Indies. We interpret this weaker middle level convergence as indicating a smaller number of West Indies deep cumulus clouds and thus less middle-level entrainment into cumulus up- and downdrafts. The maximum vertical velocity at 400 mb is two-and-a-half times higher for the Western Pacific than for the West Indies. Similar conclusions have been advanced by Nitta and Esbensen (1973). The energy supply due to the release of latent heat thus appears to be more than twice as large in the Western Pacific clusters.

3.5 Boundary Layer Frictional Wind Veering

Table 2 lists observed 1st and 2nd km mean wind veering information for both regions without respect to weather systems. The West Indies data has been divided into two latitude belts (greater and less than 18^{o}). Data north of 18^{o} show larger veerings. This is probably due to the extra terrain influences of large islands. This information indicates that a distinct 10^{o} frictional veering is present in the lowest kilometer layer.

Figure 21 shows the vertical profile of observed wind veering for the Western Pacific atoll and island stations and for selective surface ships surrounding the atolls (see a report by Gray, 1972 for more discussion). This figure shows that there is essentially no difference between the statistical averages of the island-atoll and ship veerings.

Table 2

1st and 2nd km Wind Veering from Atoll and Island Stations

	sfc - 1 km	1 km - 2 km
Western Pacific (5-18° latitude) 7210 cases	10°	2°
West Indies (less 18° latitude) 9205 cases	10°	3°
West Indies (greater 18° latitude) 7980 cases	14°	3°
AVERAGE	11°	3°

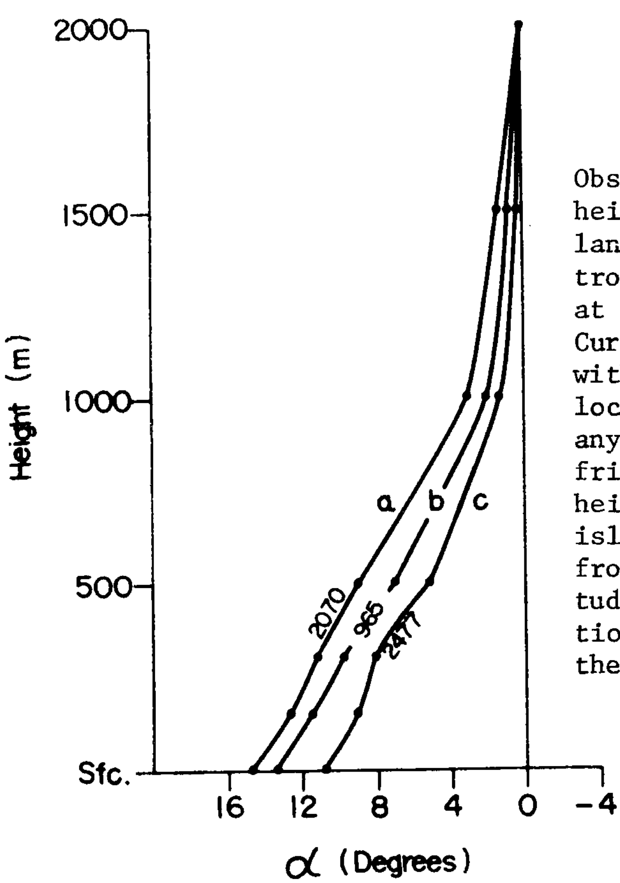


Fig. 21.

Observed wind angle veering with height in the lowest two km for island-atoll and ship reports of the tropical Pacific. Wind direction at two km is used as reference. Curve a represents veering of wind with height from ships which were located at least 1° latitude from any land. Curve b represents the frictional veering of wind with height as observed from the atoll-island data; curve c as observed from ships located within 1° latitude of land. Number of observations in each class is shown on the figures.

Table 3 shows the 1st and 2nd km wind veering for stations within 2° latitude of the center of the satellite-observed tropical cloud clusters and the average veering information relative to tropical clear

Table 3

Cloud Cluster vs. Clear Area 1st and 2nd km Wind Veering

Cloud Clusters:	(1 km - sfc)	(2 km - 1 km)
Western Pacific 536 cases	10^{o}	4^{o}
West Indies (less 18^{o} latitude) 266 cases	13^{o}	6^{o}
West Indies (greater 18^{o} latitude) 244 cases	27^{o}	9^{o}
CLUSTER AVERAGE	15^{o}	6^{o}
CLEAR AREAS AVERAGE	11^{o}	2^{o}

regions. Note that for the clusters the 1st km veering is more (15^{o} vs. 11^{o}), and it extends well into the second km level, (6^{o} veering for the clusters vs. 2^{o} veering for the clear areas). This is to be expected if the cumulus clouds act to carry turbulent sub-cloud layer momentum to higher levels. The clear area veering is very similar to the average of the ship and atoll-island stations. Thus, there does appear to be a significant amount of frictional wind veering associated with the cloud clusters. How closely is this frictional veering related to the observed low level relative vorticity fields?

3.6 Vorticity and the CISK Hypothesis

In order to test the validity of the physical mechanisms involved with the CISK hypothesis as advanced by Charney and Eliassen (1964) and since extended and altered by Bates (1973), Charney (1973), Israeli and Sarachik (1973), Lindzen (1974a, 1974b), and others, it is important to learn as much as possible about the vorticity patterns associated with these weather systems. Figures 11-14 show that the N-S zonal shear is basically different between the two regions. The location of the maximum trade winds is typically north of the clusters in the Pacific and south of the clusters in the West Indies. North-south wind shears are of opposite sign in each region. If the zonal shear dominates the vorticity, then we would expect vorticity of opposite sign in the two regions. This is verified in the vertical profiles of relative vorticity as seen in Fig. 22. In the Pacific cyclonic vorticity is present across the cloud clusters up to 300 mb. Above this level there is a change to anticyclonic vorticity. Clear regions show neutral low-level vorticity. Upper tropospheric clear region vorticity is positive. These Pacific vorticity fields are different than those of the West Indies. West Indies cluster

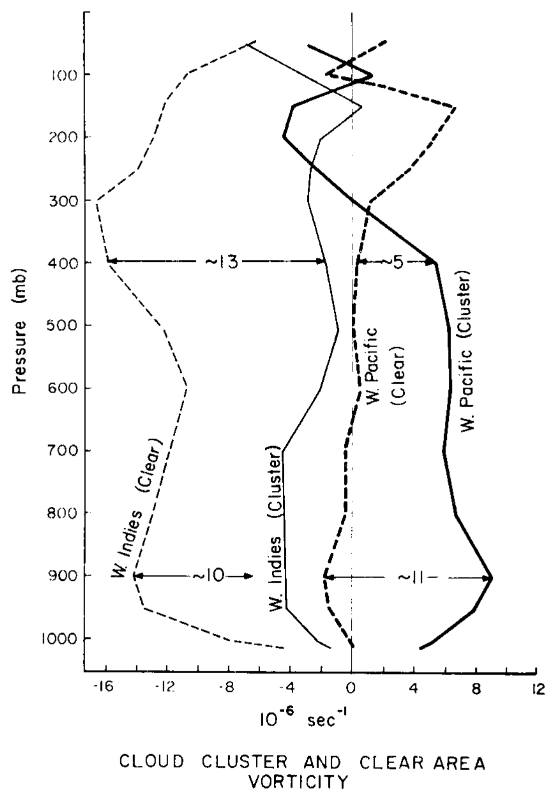


Fig. 22. Mean vertical vorticity profiles for cloud clusters and clear regions over the Western Pacific and the West Indies. Arrows give the difference between cloud cluster and clear region vorticity.

vorticity is slightly negative at all levels up to 200 mb. Only small height variations occur. The West Indies clear region vorticity is strongly anticyclonic at all levels.

In both regions the surface to 400 mb difference of vorticity between clear and cluster areas is nearly the same. The reversal of vorticity with height which takes place at 300 mb between the cluster and clear regions in the Pacific does not occur in the West Indies.

These similar region lower tropospheric vorticity differences between cluster and clear regions indicate that the large scale ($\sim$ 5-15^o) mean vorticity fields are less important in explaining the cluster and clear area divergence differences than the smaller scale variations of vorticity which are superimposed upon the mean field.

Low tropospheric convergence in the West Indies is present despite the negative cluster vorticity. Thus, at first glance, the CISK idea would seem to be invalid for West Indies cluster convection. If, however, one were to explain the observed West Indies convergence and divergence patterns in terms of deviation of vorticity from an average state, then the direct association of low level vorticity and convergence can be made. Table 4 portrays individual region mean values of divergence and vorticity and the cloud cluster and clear region deviation of these parameters from their broadscale regional averages. Here the positive association of low level vorticity and convergence can be made.

Thus, this information generally substantiates the CISK implied association of low level vorticity and divergence <u>if one interprets the vorticity and divergence in terms of their deviations from a regional mean state.</u> This is more in line with the new idea of 'wave' CISK as advanced by Lindzen (1974b).

Table 4

Comparison of Convergence and Vorticity at 900 mb in the Western Pacific and West Indies -- All Values in Units of $10^{-6} sec^{-1}$

	WESTERN PACIFIC			WEST INDIES		
	Regional Mean	Cluster	Clear Regions	Regional Mean	Cluster	Clear Regions
Mean Convergence	0	6	-3	0	3	-2
Mean Vorticity	3	9	-2	-10	-4	-14
Deviation of convergence from regional mean	-	+6	-3	-	+3	-2
Deviation of vorticity from regional mean	-	+6	-5	-	+6	-4

3.7 Relative Contribution of the Zonal and Meridional Components to Divergence and Vorticity

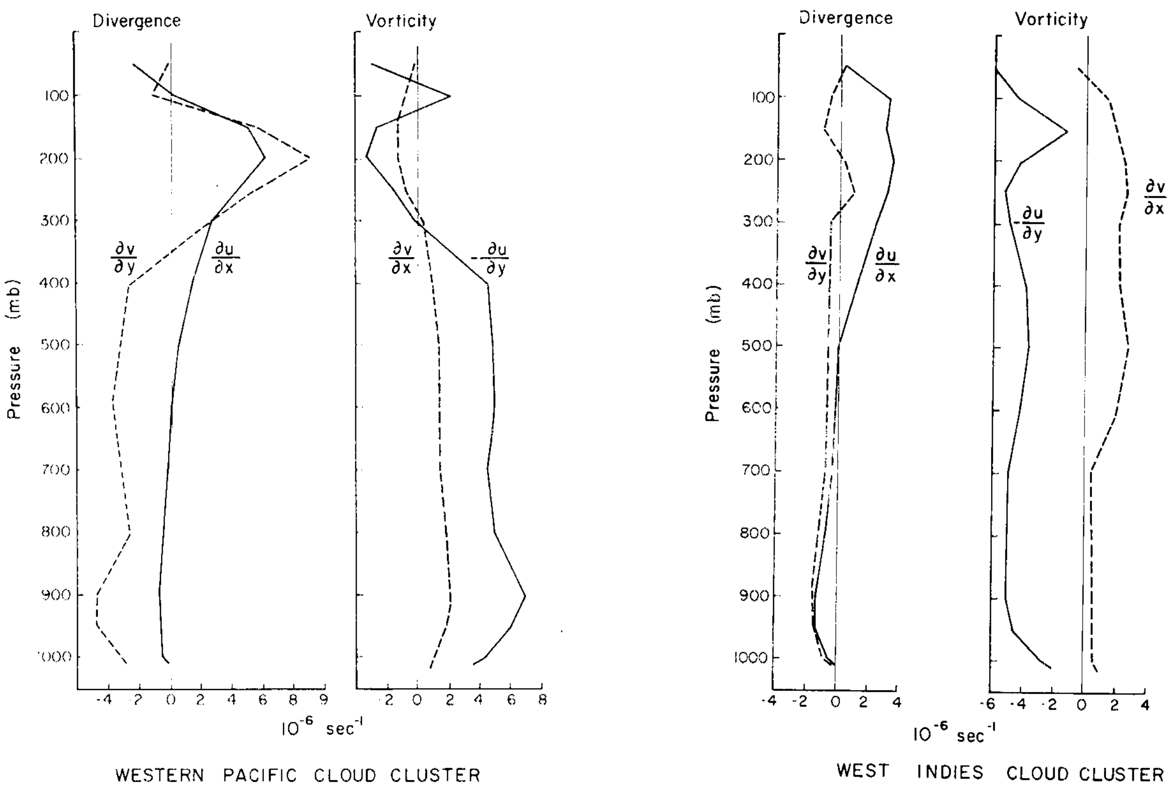
The discussion of the wind cross sections (Figs. 7-14) showed that the horizontal shear of the broadscale zonal and meridional winds was significantly different in the two regions. Williams and Gray (1973) stated that the ratio of zonal to meridional horizontal shear in the Western Pacific is about 3 to 1 at nearly all levels. Reed and Recker (1971), however, have stated that the relative contributions of both components in moving trade wind waves are about equal. This larger contribution of the meridional shearing component in the Reed and Recker study is understandable because of the difference in the compositing schemes. They based their compositing scheme on already determined strong meridional wind changes that are typical of well defined westward moving systems. The typical satellite-observed cloud cluster often appears not to be associated with trade wind waves.

It is natural to ask which of the shearing wind components is most responsible for the vertical vorticity and divergence profiles. The variations in these components are portrayed in Figs. 23 and 24. In the Pacific, convergence from the surface to 400 mb is produced mostly by the north-south shear of the meridional winds. Outflow divergence is found in both components. Vorticity is mostly the result of the N-S shear of the zonal wind. In contrast, the divergence in the West Indies is made up almost equally of the $\frac{\partial u}{\partial x}$ and $\frac{\partial v}{\partial y}$ terms. The $\frac{\partial u}{\partial y}$ term of West Indies vorticity is of opposite sign to that of the Western Pacific. The large negative contribution of the u-component cannot be balanced by the E-W shear of the v-component.

The contribution of the wind components to divergence and vorticity is schematically summarized in Fig. 25. The meridional and zonal wind components are shown with respect to their influence on divergence and vorticity for the 900 and 200 mb levels. These are the levels of maximum inflow and outflow. The striking feature in this figure is the change of the meridional wind north and south of the Western Pacific cloud cluster between 900 and 200 mb. At the lower level the v-components are directed into the cluster, at the upper level both components are directed away from the cluster center. In contrast, the meridional winds blow through the West Indies cloud cluster from south to north at both levels. The zonal winds do not significantly change their speed as they blow through the cluster. This figure also indicates the importance of the N-S zonal wind shear. Despite the change of the zonal wind direction with height in the West Indies the zonal wind provides a large anticyclonic shear at both levels, whereas, over the Western Pacific the E-winds north of the cloud cluster center decrease with height while the E-winds south of the center remain constant.

Fig. 23.

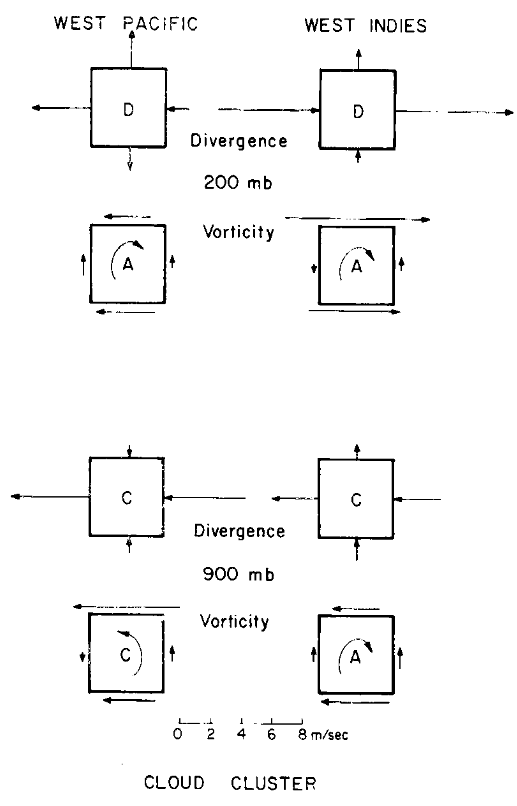
Fig. 24.



Figs. 23-24. Individual term contributions to divergence and vorticity of the Western Pacific and West Indies cloud clusters.

Fig. 25.

Schematic diagram of the contribution by the zonal and meridional winds to divergence and vorticity at 900 mb and 200 mb levels for Western Pacific and West Indies cloud clusters.



4. WESTERN PACIFIC AND WEST INDIES TEMPERATURE, MOISTURE AND PRECIPITATION FIELDS

4.1 Temperature and Pressure-Height

Virtual temperature differences between the cloud cluster and its environment are negligible. At no level are they as much as $1^{o}C$. Temperature differences between the clear regions and the cloud clusters are also very small. No regular or significant patterns were found.

Tables 5 and 6 give information on Western Pacific and West Indies temperature, virtual temperature and pressure-height and their differences between the cloud cluster, cloud cluster environment and clear regions. In all regions the temperatures and pressure-heights show no significant differences. These results do not change whether one uses the virtual or actual temperatures.

Temperature and pressure-height differences are too small for a meaningful resolution of these parameters. Although some cloud clusters may be measurably cooler at middle and lower levels, arguments over the average cold or warm core nature of these systems appear not to be very meaningful. Some are slightly cool and some are slightly warm. No general statement can be made. As discussed in section 6 the variability of nearly all parameters within the individual weather system type is much greater than the differences between the systems.

4.2 Humidity

Of all parameters, relative humidity best defines the cluster. Figures 26-29 show how the cluster center relative humidity at middle levels is much higher than in the environment. Below 900 mb the fluctuations are very small. These large middle level humidity variations have also been reported by Reed and Recker (1971) and Riehl and Pearce (1968).

Table 5

Actual (t) and virtual (t_v) temperature and pressure-height (z) for Western Pacific cloud clusters. Differences of virtual temperatures (Δt_v) and pressure-heights (Δz) of the cloud cluster from its immediate environment and from the clear regions are also shown. All data are taken at 00Z (∿ 10 LT).

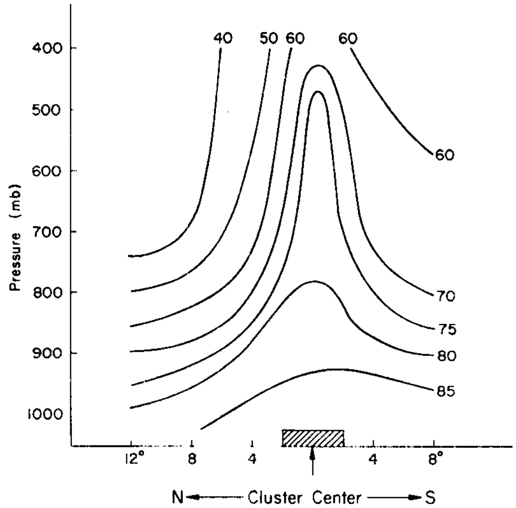
	Temperatures (°C)				Pressure-heights (m)		
Pressure (mb)	Cluster t	Cluster t_v	Envir. Minus Cluster Δt_v	Clear Minus Cluster Δt_v	Cluster z	Envir. Minus Cluster Δz	Clear Minus Cluster Δz
sfc	27.0	30.4	0.6	1.7			
1000	26.4	29.6	0.3	1.2	90	-1	8
950	23.1	25.8	0.0	-0.2	540	0	11
900	20.3	22.6	0.0	-0.4	1010	-1	9
800	15.2	17.0	-0.1	-0.3	2070	-1	8
700	9.3	10.5	0.0	0.3	3150	-1	9
600	2.3	3.1	0.0	0.5	4410	0	11
500	-5.3	-4.8	0.1	0.0	5860	1	13
400	-15.2	-15.0	-0.1	0.5	7590	0	11
300	-29.9	-29.9	-0.2	-1.2	9700	-1	4
250	-40.1	-40.1	-0.3	-1.0	10970	-2	-1
200	-52.9	-52.9	-0.2	-0.3	12450	-4	-6
150	-68.1	-68.1	0.2	0.8	14240	-3	-3
100	-79.2	-79.2	0.2	-0.2	16590	-1	5

Table 6

Actual (t) and virtual (t_v) temperature and pressure-height (z) for the West Indies cloud clusters. Differences of virtual temperatures (Δt_v) and pressure-heights (Δz) of the cloud cluster from its immediate environment and from the clear regions are also shown. All data are taken at 12Z (∿ 07 LT).

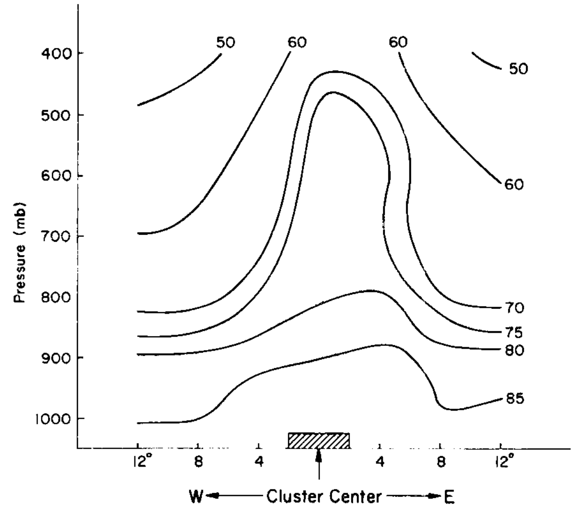
	Temperatures (°C)				Pressure-heights (m)		
Pressure	Cluster		Envir. Minus Cluster	Clear Minus Cluster	Cluster	Envir. Minus Cluster	Clear Minus Cluster
(mb)	t	t_v	Δt_v	Δt_v	z	Δz	Δz
sfc	24.6	27.6	0.2	0.1			
1000	24.4	27.3	0.2	0.5	140	1	-2
950	21.7	24.3	0.2	-1.0	580	4	0
900	18.9	21.0	0.1	-1.2	1060	1	-5
800	13.5	14.9	-0.1	-1.4	2060	2	-9
700	7.3	8.3	-0.1	0.5	3170	2	-11
600	0.2	0.8	0.0	1.2	4430	3	-6
500	-8.0	-7.7	0.0	0.6	5870	3	-1
400	-19.0	-18.9	0.0	0.2	7570	3	2
300	-34.3	-34.3	0.1	-0.3	9650	5	3
250	-44.3	-44.3	0.2	0.0	10890	5	2
200	-55.8	-55.8	0.4	0.4	12350	8	4
150	-66.3	-66.3	0.2	0.1	14140	7	3
100	-71.6	-71.6	0.2	-3.6	16550	7	-13

Fig. 26.



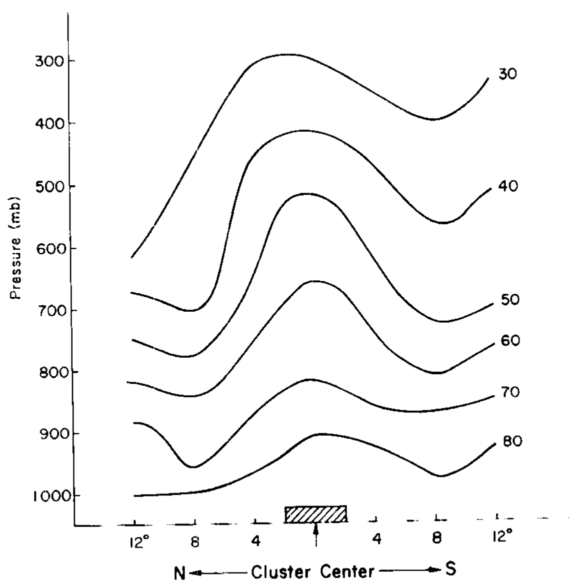
WESTERN PACIFIC CLOUD CLUSTER
RELATIVE HUMIDITY (%)

Fig. 27.



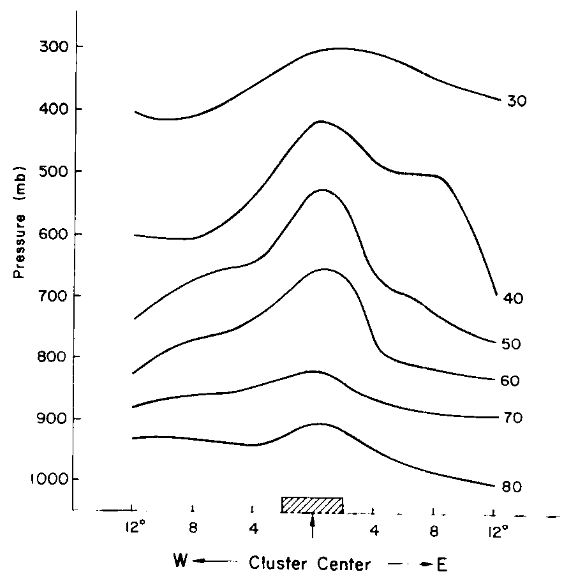
WESTERN PACIFIC CLOUD CLUSTER
RELATIVE HUMIDITY (%)

Fig. 28.



WEST INDIES CLOUD CLUSTER
RELATIVE HUMIDITY (%)

Fig. 29.



WEST INDIES CLOUD CLUSTER
RELATIVE HUMIDITY (%)

Figs. 26-29. North-south and west-east vertical cross-sections of relative humidity with respect to Western Pacific (above) and West Indies (below) cloud clusters.

Daytime humidity values which are shown have been corrected for solar thermistor heating. The method for this correction is discussed in Appendix B.

4.3 Vertical Distribution of θ_e

Figures 30 and 31 portray equivalent potential temperatures. Their variations, because of the lack of temperature variation, are due primarily to water vapor content differences. In both regions the θ_e profiles 8^{o}E, W and S of the cloud cluster center agreed at all levels. Thus, only one average profile is given. The same is true for the θ_e profiles of the Western Pacific clear region and for the area 8^{o}N of the cluster center. Although Western Pacific clusters have higher humidity than West Indies ones, differences in the vertical θ_e gradient between each region are quite small.

It is obvious that the increased humidity of the cluster leads to a decrease of moist potential buoyancy. This was expected. This common fill-in of the middle level θ_e with increased cumulus convection is well known over land areas. It appears to be a common occurrence with all tropical weather systems.

4.4 Character of Rainfall Underneath Western Pacific Summer Clusters

In order to study the characteristic precipitation associated with the cloud cluster, summertime Western Pacific hourly rainfall intensities underneath clusters were analyzed. The rainfall data was from 10 of the 12 Western Pacific rawinsonde stations listed in Appendix A. The period of study was June through September for 1967 and 1968. Most of these stations are atolls or small islands. The island influence on the rainfall, especially when cluster systems are overhead, is believed

Fig. 30.

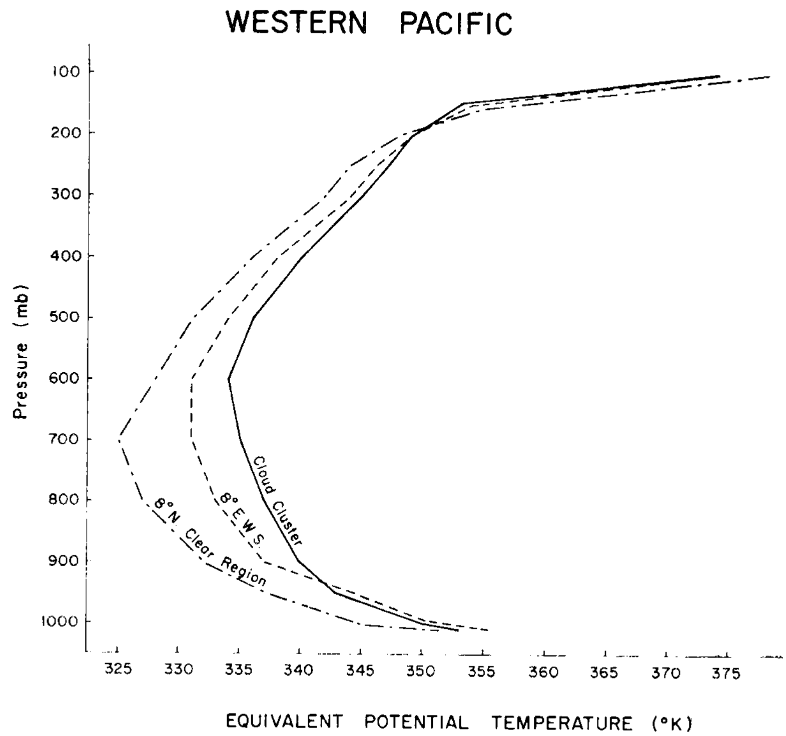
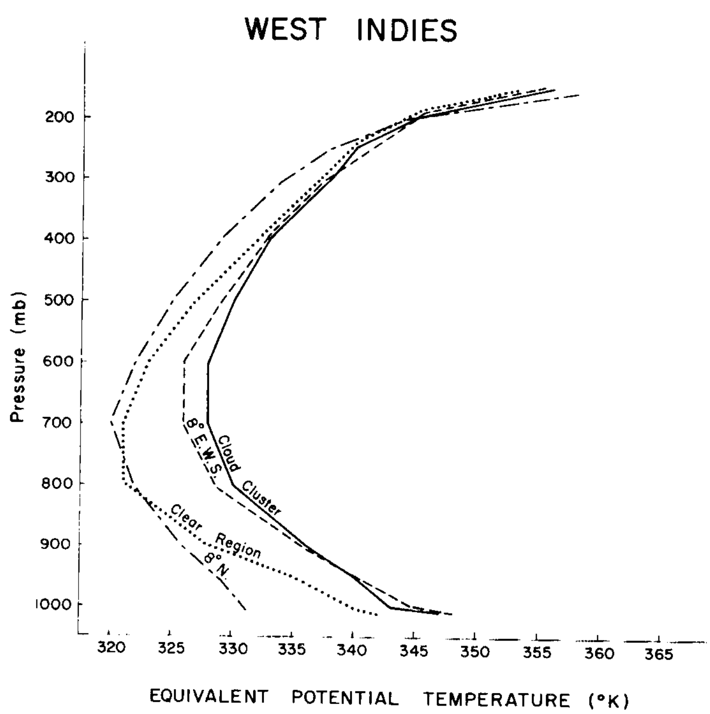


Fig. 31.



Figs. 30-31. Vertical profiles of θ_e for various weather systems and places relative to the weather systems of the Western Pacific and West Indies. E.W.S.N. stands for east, west, south and north of the cloud cluster center.

to be small. As expected, the character of the rainfall underneath the clusters was highly variable. The daily rainfall for the cloud cluster days shows that:

1) ∿ 7% of the station observations had no rainfall at all during the whole period which the cluster was over them,

2) 20% of the stations showed rainfall of less than 2.5 mm during the period which the cluster was over them,

3) the most frequent station cluster rainfall amounts were 10 to 40 mm, and

4) in a number of cases individual clusters give station rainfall as high as 100 mm.

These large differences emphasize the local concentration of rainfall within the clusters and the differences between clusters. Some satellite-observed clusters have very little rainfall within them.[2]

The typical size and speed of the cloud cluster (∿ 6-8 m/sec) limit its duration above an observing station to about 16-20 hours. In order to estimate the average rainfall output of a cluster we analyzed the hourly rainfall values in five hour segments centered on the 00Z (∿ 10 LT) and 12Z (∿ 22 LT) rawinsonde times. Hourly rainfall amounts were gathered from 2 hours before to 3 hours after rawinsonde release times within the cluster.

Space Distribution. With the hourly precipitation amounts and by assuming that the cluster rain areas move uniformly over the stations at 6^{o} longitude per day (i.e. 15 knots) one is able to derive area distributions of the rainfall intensity. Figure 32 shows the percentage of the horizontal cluster area which is occupied by various rainfall intensities. The concentrated nature of the cluster rainfall is quite evident.

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[2]The second author has flown over cloud clusters in the Truk and Ponape area in June 1970 and observed a number of them with extensive middle cloud layers but no active Cb convection. The satellite pictures used in this study would show the middle cloudiness but not the lack of Cb activity.

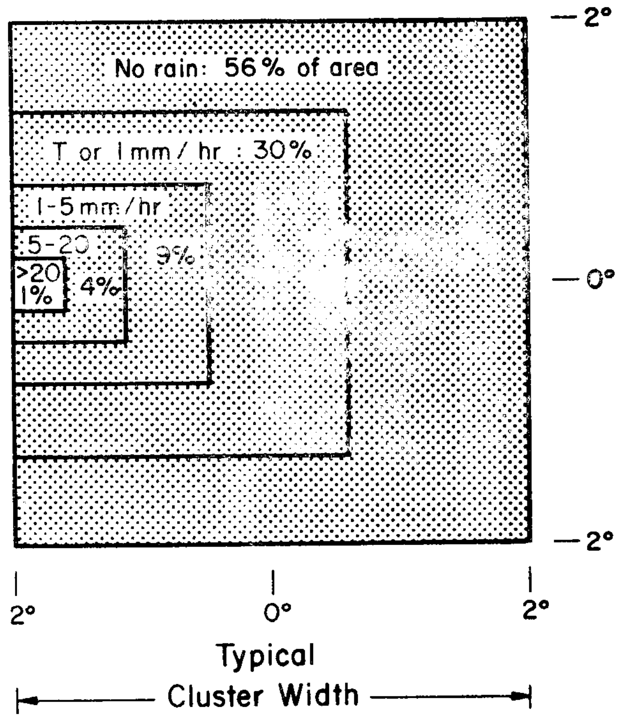


Fig. 32. Area distribution of rainfall intensity within the typical Western Pacific cloud cluster.

56% of the cluster area reports no precipitation. 30% reports only a trace or light rain (< 1 mm/hr). 9% report rainfall between 1-5 mm/hr. Only 5% of the cluster area has rainfall intensities greater than 5 mm/hr. About 1% of the cluster area has rain with intensity greater than 20 mm/hr. This agrees with radar observations in other tropical regions as discussed by Lopez (1973), Martin and Suomi (1972), and Ruprecht et al. (1973).

This space distribution of precipitation leads to an average 4^{o} diameter cluster rainfall of ∿ 2.5 cm/day. As previously discussed by Williams and Gray (1973) about 80% of this precipitation can be accounted for by horizontal advection into the cluster from its sides and the remaining 20% by local evaporation from the sea.

Rain Frequency vs. Intensity. Figure 33 portrays three classes of cloud cluster cumulative rainfall percentage vs. hourly rainfall intensity for the Western Pacific clusters. Curve (a) shows the accumulation of

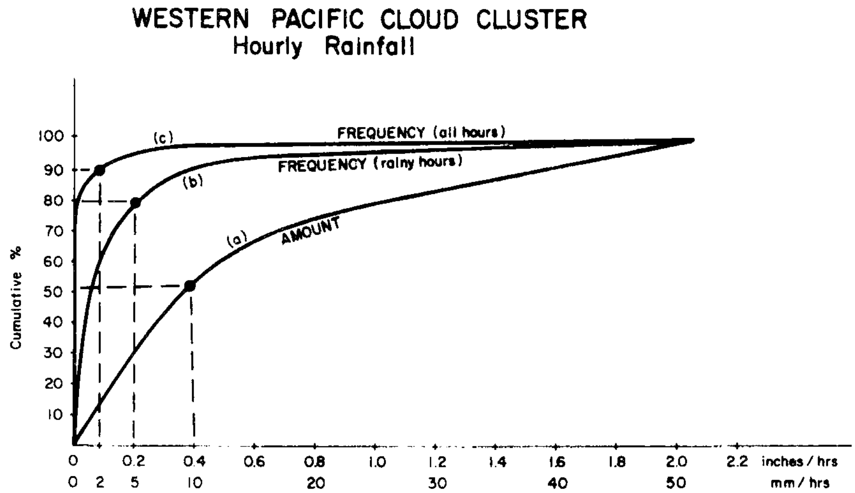


Fig. 33. Western Pacific cloud cluster cumulative rainfall vs. hourly rainfall intensity. Curve (a) is for total rainfall amount. Curves (b) and (c) portray the cumulative frequency of rainfall vs. rainfall intensity for rainy hours (curve b) and for all hours (curve c).

cluster precipitation vs. rainfall intensity. The dot on this curve means that about 50 percent of the cluster precipitation is accounted for by hourly rainfall intensities greater than 10 mm/hr (0.4 inches/hr). The other half of the precipitation comes from hourly rainfall intensities of less than 10 mm per hour. Curve (b) shows the cumulative cluster frequency of rainfall vs. rainfall intensity. The dot on curve (b) means that 80% of the time that rainfall was measured in the cluster, the intensity of the hourly rainfall was less than 5 mm/hr. On 20% of the times that rainfall was reported, the hourly intensity was greater than 5 mm/hr. Curve (c) shows the cumulative precipitation frequency for both rain and non-rain time periods underneath the cluster. The dot on this curve means that only 10% of the time a station is under a cluster its hourly precipitation intensity is greater than 2 mm/hr. During 90% of the time surface reports under a cluster give no rain, or if there was rain the intensity was less than 2 mm/hr. These cluster precipitation results agree well with the typical rainfall statistics for the tropics that have previously been discussed by Atkinson (1971) and Riehl (1954). About half of the cluster rainfall occurs in heavy showers during only 10% of the time rain is reported. Approximately half of the cluster rainfall occurs in heavy rain episodes during only 2% of the under cluster observational times.

4.5 Diurnal Variation of Western Pacific Summer Rainfall and Convergence

The hourly rainfall around 00Z and 12Z was also analyzed for diurnal differences. The period treated was June through September 1967 and 1968. We were quite surprised to find that the mean hourly rainfall during the five hour period around 00Z (07-12 LT) is more than twice as much as the rainfall around the five hour period of 12Z (19-24 LT). We also examined the five hour rainfall around 00Z and 12Z for the cloud cluster environment and then for all available Western Pacific stations whether associated with clusters or not. Table 7 gives the percentage of rainfall which fell in each five hour period straddling the 00Z and 12Z time periods.

Table 7

Weather system comparison of percent of rainfall which occurs in 5 hour period straddling 00Z vs. the 5 hour period straddling 12Z. All data are for the Western Pacific during months of June through September.

	Cloud Cluster	Cloud Cluster Environment	All Stations
5 hours straddling 00Z (∿ 10 LT)	∿ 70%	∿ 60%	∿ 57%
5 hours straddling 12Z (∿ 22 LT)	∿ 30%	∿ 40%	∿ 43%

A striking (70 vs. 30%) diurnal rainfall variation is observed for the cloud clusters. Morning (07-12 LT) rainfall amounts are two and a half times greater than early evening amounts (19-24 LT). Other rainfall not directly associated with our cloud clusters also shows these higher morning amounts but the percentage differences are less. These results were quite unexpected. They are primarily due to the presence of more intense morning showers. Table 8 portrays diurnal rain intensity differences between morning and evening in percent. The large diurnal difference in evening vs. morning heavy shower activity is clearly evident.

Table 8

Comparison of Western Pacific frequency of various rainfall intensities in the morning vs. early evening.

Rain Intensities		5 hrs straddling 00Z (∿ 07-12LT)	5 hrs straddling 12Z (∿ 19-24LT)
Cluster Precipitation			
Precipitation	> 1.0 cm/hr	∿ 75%	∿ 25%
	0.25-1.0 cm/hr	∿ 60%	∿ 40%
	T to 0.1 cm/hr	∿ 55%	∿ 45%

		5 hrs straddling 00Z (∿ 07-12LT)	5 hrs straddling 12Z (∿ 19-24LT)
All Stations - Clusters and Non-Clusters			
	T and ≤ 0.1 cm/hr	50%	50%
	0.1 - 0.5 cm/hr	55%	45%
	0.5 - 1.0 cm/hr	57%	43%
	1.0 - 2.0 cm/hr	60%	40%
	>2.0 cm/hr	70%	30%

These higher Western Pacific morning cluster rainfall values are well substantiated by the cluster divergence profiles shown in Fig. 34. The magnitude of 00Z (10 LT) surface to 400 mb convergence and upper tropospheric divergence is about twice as large as it is at 12Z. These diurnal differences should not be associated with diurnal atoll and island daytime heating. It would be absurd to associate such large 200 mb 00Z vs. 12Z divergence differences with local atoll-island influences. This diurnal divergence is largely locally balanced by opposite divergence in the surrounding clear regions.

If cloud cluster middle tropospheric convergence is primarily due to mass input into deep cumulus up-and downdrafts, then the much weaker 12Z middle tropospheric convergence can be interpreted as due to fewer deep cumulus at this time period. These large cluster diurnal variations of

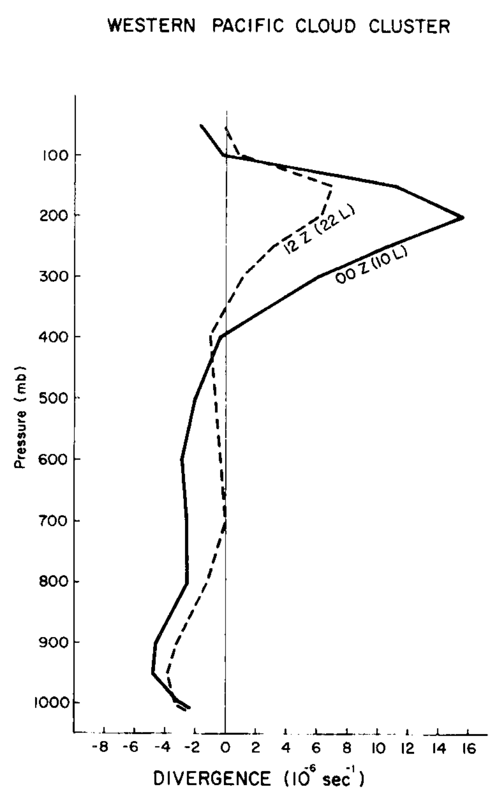


Fig. 34. Diurnal variation of Western Pacific cloud cluster divergence.

both rainfall and divergence thus appear to be mutually consistent and lend confidence to the separate results.

We think these associated diurnal convergence and precipitation differences are related in some way to thermal stability differences induced by diurnal net radiation variations. We are not prepared at this time to confidently advance a specific physical hypothesis.

5. SUMMARY

The main characteristics of the cloud clusters and some of their important regional differences are listed below:

	Western Pacific	West Indies	Remarks
Size	$4^o x 4^o$	$4^o x 4^o$	Same.
Movement	∿6^o long./day towards W	∿6^o long./day towards W	Same despite different ambient wind fields.
4^o Scale Divergence	Convergence below 400 mb divergence above	Convergence below 450 mb divergence above	Shape of the profiles similar, magnitude 2-3 times higher in Pacific, less middle level convergence in West Indies.
4^o Scale Vorticity	Cyclonic below 300 mb anti-cyclonic above	Anticyclonic at all levels	Large differences because of opposite sign of north-south zonal shear.
4^o Scale vorticity differences between clear and cluster regions	Much larger cluster vorticity ∿$10x10^{-6} sec^{-1}$	Much larger cluster vorticity ∿$10x10^{-6} sec^{-1}$	Pattern similar for both regions.
4^o Scale virtual temperature	Insignificant variations	Insignificant variations	Not a significant analysis parameter
4^o Scale humidity	Primary humidity difference between cluster and clear region at middle levels ∿30-40%	Primary humidity difference between cluster and clear region at middle levels ∿30-40%	Higher relative humidity in Pacific clusters. Differences between cluster and clear regions about the same.
4^o Scale vertical shear of zonal wind	Nearly constant with height	Large and positive sign of zonal wind changes	Squall lines more probable over the West Indies, more unorganized cluster Cb's in W. Pacific.

	Western Pacific	West Indies	Remarks
Wave Disturbances	S-winds E of center, weak N-winds W, rough agreement with wave model	Less agreement with wave model, vorticity of the v-component positive	Some clusters are associated with wave disturbances, some are not.
Barotropic instability	Inflection point in the u-profile at all levels below 400 mb. Change of sign in the meridional gradient of absolute vorticity only at 400 mb. Decrease of the gradient around cloud cluster center at all levels	Inflection point in the u-profile at all levels below 700 mb No change of sign in meridional gradient of the absolute vorticity. Decrease of gradient of absolute vorticity at low levels around cloud cluster center	Not primary energy source for cloud clusters, but possible contributing mechanism for smaller scale growth in some cases
CISK	Low level cluster convergence and vorticity well associated, clear region divergence not well associated with anticyclonic vorticity	Low level divergence and clear region anticyclonic vorticity well associated, cluster vorticity and divergence not in agreement	CISK concept of vorticity and convergence association is valid only if vorticity is interpreted as a deviation from the regional mean value
Rainfall	Measured cluster rainfall agrees with 4^{o} scale vapor convergence, cluster rainfall is highly concentrated	Not available	Rainfall amounts and concentration are likely to show large variations between individual clusters
Diurnal variations of rainfall and convergence	Significant 00Z vs. 12Z variations in both rainfall and convergence, heavier morning rainfall due to presence of more heavy showers	Smaller diurnal divergence differences between 00Z(19LT) and 12Z (07LT), these are not the best times for detection	An unexpected, but highly significant component appears to be present.

5.1 Regional Similarities

From the viewpoint of the digitized satellite pictures, the majority of cloud clusters look much the same. Still, a variety of different types of disturbances are likely to be embedded within similar $\sim 4^{o}$ clusters. This generally agrees with the conclusions of the NOAA Hurricane Center in Miami as discussed in their yearly surveys of Atlantic tropical disturbances, (see Simpson et al., 1968, 1969; and Frank, 1970).

It was unexpected that the cluster movement towards the west would be similar in both regions despite significant differences in the ambient wind fields. As discussed by Wallace (1971) cluster propagation may not be well related to the velocity of the embedded flow field.

The two layer divergence model of these disturbances as observed by Williams and Gray (1973) is supported by both divergence profiles. Although the basic flow fields in both regions are different, the individual region cluster minus clear region differences of vorticity and divergence are nearly the same. Weather system deviations of vorticity from a mean state environmental flow field are very similar. Cluster convergence below 400 mb is primarily due to the v-component gradients, the vorticity is due mainly to the zonal wind shears.

5.2 Regional Differences

The major differences between the two regions appear to be due to location. Clusters averaged $\sim 9^{o}$N in the Western Pacific and $\sim 24^{o}$N in the West Indies. The Western Pacific area is located equatorward of the trade wind maximum, the West Indies area is located on the poleward side of the trades. Therefore, the mean zonal flow provides cyclonic shear over the Western Pacific and anticyclonic shear over the West

Indies. Cluster and clear region wind deviations in the Western Pacific were superimposed on a basic cyclonic shearing pattern while West Indies systems were superimposed on an anticyclonic shearing field. This seems to indicate that the cluster systems can travel and maintain themselves in an unfavorable or anticyclonic (from CISK point of view) flow field.

The West Indies region is not a favorable area for cluster genesis. Frank (1970) and Simpson et al. (1968, 1969) have shown that West Atlantic weather systems typically tend to be in a "coasting" or "running down" mode as they cross the West Indies. They found that 90% of the disturbances observed in the West Indies during 1967 and 1968 were generated far to the east, 50% coming out of Africa. The much higher values of the cluster divergence profile for the Western Pacific and the typical lack of cluster genesis in the West Indies support this assessment.

6. VARIABILITY OF INDIVIDUAL SOUNDINGS

6.1 Humidity Characteristics

The mean summertime humidity profiles for the three weather systems are shown in Fig. 35 and Table 9. Due to the errors of the daytime radiational heating of the hygristor only nighttime mean moisture values are given. Values are presented as differences from the summertime (June-September) mean West Indies soundings as published by C. L. Jordan (1958). Positive values mean the relative humidities of the individual weather systems are greater than the Jordan mean.

The average nighttime relative humidity for the Western Pacific cloud cluster is very high. At 400 mb it averages no less than 72%. Above 600 mb these mean cluster humidities are 30% larger than those quoted by Jordan (1958) for the mean summertime West Indies. For the Western Pacific cloud cluster the Jordan values are too low. For the West Indies, however, his values agree well with our cluster results but are too high for the clear regions.

The cloud cluster boundary layer shows a nearly constant relative humidity of 87% which indicates large boundary layer mixing (see also Figs. 36 and 37). Between 750 and 550 mb the mean relative humidity increases. Many measurements indicate saturation.

6.2 Temperature Characteristics

In addition to the relative humidities the average weather system temperature differences from the mean summertime tropical West Indies sounding of Jordan (1958) were also calculated. Temperature values are listed in Table 10. Below 600 mb these differences are very small,

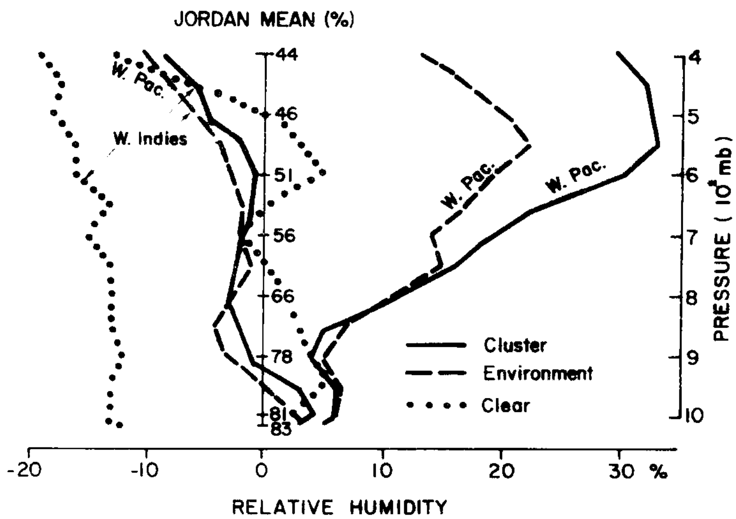


Fig. 35. Differences in relative humidity (June-September) of tropical weather systems from the Jordan (1958) mean West Indies summer sounding.

Table 9

Nighttime Relative Humidities (June-September) as Differences from the Mean Tropical Summer Atmosphere of Jordan (1958).

		WESTERN PACIFIC (12Z)			WEST INDIES (00Z)		
(mb)	Jordan RH (%)	Cloud Cluster	Cluster Environ.	Clear Areas	Cloud Cluster	Cluster Environ.	Clear Areas
Sfc	83	5	5	2	3	3	-12
1000	81	6	6	2	4	3	-13
950	81	6	6	5	3	0	-13
900	78	4	5	4	-1	-3	-12
850	73	5	7	3	-2	-4	-13
800	66	11	11	2	-3	-3	-13
750	59	16	15	0	-2	-1	-13
700	56	19	14	-2	-2	-2	-15
650	53	23	17	0	-1	-2	-13
600	51	29	19	5	-1	-3	-16
550	48	33	22	3	-2	-4	-16
500	46	31	20	1	-5	-6	-18
450	44	30	17	-7	-6	-8	-17
400	44	28	13	-13	-9	-10	-19

Table 10

Nighttime Temperature Differences (June-September) from the Mean Summer Tropical Atmosphere as Portrayed by Jordan (1958) in °C.

(mb)	Jordan T (°C)	WEST PACIFIC (12Z) Cloud Cluster	Cluster Environ.	Clear Areas	WEST INDIES (00Z) Cloud Cluster	Cluster Environ.	Clear Areas
Sfc	26.5	-0.4	-0.3	0.0	-1.1	-1.8	2.6
1000	26.1	-0.2	-0.1	0.4	-1.1	-1.5	2.1
950	23.1	0.1	0.3	0.6	-0.9	-0.9	1.6
900	20.2	0.5	0.5	0.5	-0.7	-0.6	1.3
850	17.4	0.8	0.7	0.7	-0.8	-0.6	1.2
800	14.7	0.7	0.7	0.7	-0.8	-0.7	0.9
750	11.8	0.7	0.7	1.1	-0.7	-0.7	0.7
700	8.6	0.8	0.8	1.3	-0.7	-0.7	0.5
650	5.0	0.7	0.9	1.2	-0.7	-0.7	0.6
600	1.3	0.7	0.9	1.0	-0.8	-0.7	0.5
550	-2.7	1.0	1.0	1.1	-0.7	-0.6	0.6
500	-7.1	1.4	1.3	1.3	-0.5	-0.6	0.6
450	-12.0	1.6	1.5	1.5	-0.7	-0.9	0.4
400	-17.8	2.0	1.8	1.8	-0.8	-1.0	0.1
350	-24.9	2.3	2.1	2.0	-1.1	-1.1	0.2
300	-33.4	2.5	2.3	2.1	-0.5	-0.8	0.4
250	-43.4	2.1	2.3	2.0	-1.8	-0.8	0.6
200	-55.4	1.1	1.3	1.9	-0.4	-0.3	1.2
175	-61.2	-0.4	-0.2	0.8	-0.4	-0.2	1.2
150	-67.6	-1.5	-1.5	-0.2	1.0	1.1	1.9
125	-71.9	-4.1	-4.4	-3.2	2.0	2.0	1.7
100	-72.7	-4.8	-5.3	-6.1	1.8	2.3	0.8
80	-69.4	-3.5	-3.5	-3.5	1.3	1.7	0.7

nearly always less than $1^{o}C$. Large differences are observed only above 150 mb indicating the height differences of the tropopause. As a systematic feature, it can be seen that the Western Pacific weather systems are always slightly warmer and the West Indies cloud cluster and environment slightly cooler than the Jordan mean. Above 175-150 mb these temperature features reverse.

Some of these differences from the Jordan mean sounding can be accounted for by Jordan's use of 03Z and 15Z soundings (∿ 22 LT and 10 LT) while we employed 00Z (19 LT) and 12Z (07 LT) data.

Diurnal Range of Values. In the last few years it has become obvious that the U. S. Weather Bureau and the military AN/AMT-R sondes (which were used in this study) give unrealistic humidity differences between day and night. Much of this diurnal variation of relative humidities is likely due to night-day differences in rawinsonde package hygristor heating. Special tests by Morrissey and Brousaides (1970) and Ostapoff et al. (1970) indicate that these diurnal differences are due to direct solar heating of the rawinsonde carbon strip. This leads to significant decrease of the measured daytime humidity values. Table 11 shows the night (12Z or ∿ 22 LT) vs. day (00Z or ∿ 10 LT) differences of relative humidities and temperatures for the summertime Western Pacific cloud cluster and clear areas. Except for the surface layer, the mean temperature differences are negligible.

Only small diurnal (4 to 8%) differences in the humidity are present in the cloud clusters below 600 mb. This small diurnal difference is apparently due to a diminishing of the direct solar radiation on the humidity sensors below the cluster middle cloud decks. Above 600 mb in the clusters and in the clear regions significant (10 to 25%)

Table 11

Night Minus Day Differences of the Relative Humidities (%) and Temperatures (°C) for Western Pacific Weather Systems for June-September.

WESTERN PACIFIC

	Clusters		Clear Areas	
Pressure	ΔRH	ΔT	ΔRH	ΔT
sfc	4	-1.3	13	-3.1
1000	7	-0.7	14	-1.9
950	7	-0.1	17	-0.1
900	6	0.0	18	-0.1
850	4	0.3	19	-0.2
800	5	0.0	18	-0.4
750	6	0.1	14	-0.2
700	8	0.1	14	-0.1
650	8	-0.1	15	-0.4
600	13	-0.1	18	-0.4
550	19	-0.2	15	-0.5
500	21	-0.2	16	-0.5
450	25	-0.4	9	-0.5
400	25	-0.4	7	-0.3

diurnal humidity differences are found. The smaller diurnal humidity variations above 500 mb are believed to result from the inaccurate humidity measurements when the values are low. A method of correcting for these diurnal differences is discussed in Appendix B.

6.3 Inner Weather System Parameter Variability

It is generally accepted that meteorological parameters can undergo large variations in the tropics. These variations are, however, usually assumed to apply to differences between the ITCZ and the trade wind zones or between tropical disturbances and their surrounding environments. We have just discussed the mean humidity and temperature values within the cloud clusters and clear regions. The question now arises : How large are these and other parameter variations within each weather system compared with the mean difference of parameters between systems?

Relative Humidity Variability. To show the inner weather system variability of relative humidity, Table 12 and Figs. 36-37 were prepared. The table shows the mean summertime humidity deviations within each of the classified weather systems. By assuming a normal distribution of the relative humidity deviations the mean deviation ($\sim$ 0.8 of the standard deviation) encompasses $\sim$ 56% of the observations. Except in the boundary layer where the relative humidities are very high, the deviations closely approximate a normal distribution. The unexpected result as seen in Table 12 is that the mean deviations for all weather systems are about the same - approximately 15-20%.

Table 12

Inner Weather System Mean Deviations of Nighttime Relative Humidities (Data from June-September soundings only)

	WESTERN PACIFIC (12Z)			WEST INDIES (00Z)		
	Cloud Cluster	Cluster Environ.	Clear Areas	Cloud Cluster	Cluster Environ.	Clear Areas
Sfc	5	5	6	9	7	10
1000	4	4	5	8	7	9
950	6	6	5	7	9	11
900	9	8	10	9	10	12
850	11	10	12	12	12	14
800	10	10	16	16	15	15
750	10	11	16	17	17	15
700	13	13	16	20	18	14
650	11	14	17	19	20	16
600	11	17	19	21	21	16
550	15	20	21	22	22	16
500	16	21	21	22	21	14
450	16	22	16	20	19	13
400	12	22	15	15	17	13

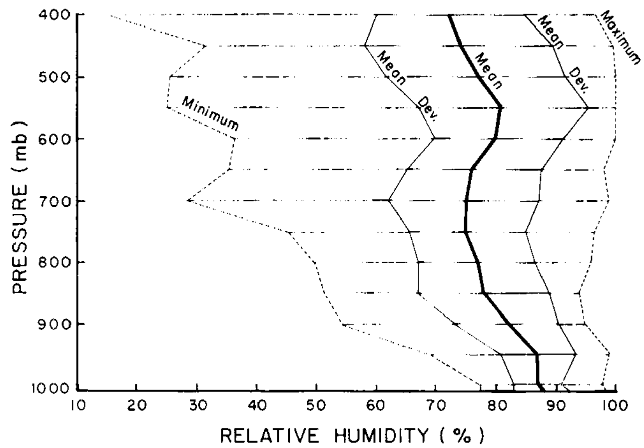


Fig. 36. Mean relative humidity and its variation for the summer cloud clusters over the Western Pacific south of 18°N.

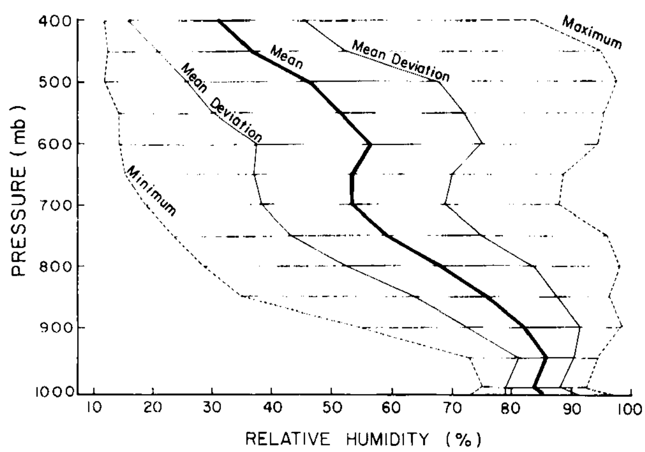


Fig. 37. Mean relative humidity and its variation for the summer clear areas over the Western Pacific south of 18°N.

In Figs. 36-37 the mean relative humidities, the mean deviations and the minimum and maximum relative humidities for Western Pacific cloud clusters and clear regions are shown, respectively.

Mean cluster humidity deviations increase with height. Typical values are about $\pm$ 5-10% in the boundary layer and $\pm$ 15-20% at the middle levels. About 20 percent of all observations at each level show humidity greater than $\sim$ 90%. Between 850 and 500 mb about a fifth of all observations show a humidity less than 65%. The lines farthest to the right and left of these figures portray the average of the three highest and three lowest relative humidities. A large number of very dry soundings are present within the cluster.

Figure 37 shows that the same large variations in relative humidity can also be found in the clear regions. There is little difference in boundary layer relative humidity between the cluster and the clear region. Higher up larger differences are found. At 700 mb and 400 mb the cluster minus clear region differences are about 20 and 40%, respectively. The humidity variability in the cluster and clear areas is about the same. The higher humidity values found in the clear region may be due to the existence of clouds at sounding time which were not detected in the satellite picture a few hours before or later, or to the presence of clouds too small to be seen by the satellite pictures. Advection of moist air from cluster or cluster environment regions may also help to explain a number of these higher clear area humidities.

These large relative humidity variations are believed to result from:

1) The natural differences within the tropical cloud clusters. Some clusters are very moist, others are in a dying or quiescent stage where only layered clouds are present.

2) Strong downdraft drying which can occur in and around areas of strong cumulus convection. Zipser (1969) has previously shown examples of this type of cluster downdraft drying.

<u>Parameter Differences Between Weather Systems vs. Interior Parameter Variability</u>. Figure 38 compares mean parameter differences between the separate weather systems with interior weather system parameter deviations. Summertime (June-September) temperature, relative humidity, and zonal wind comparisons are shown. The heavy solid lines compare the cloud cluster and the clear areas, the heavy dashed lines compare the cloud cluster (0-2° radius) and its surrounding 2 to 6° radius

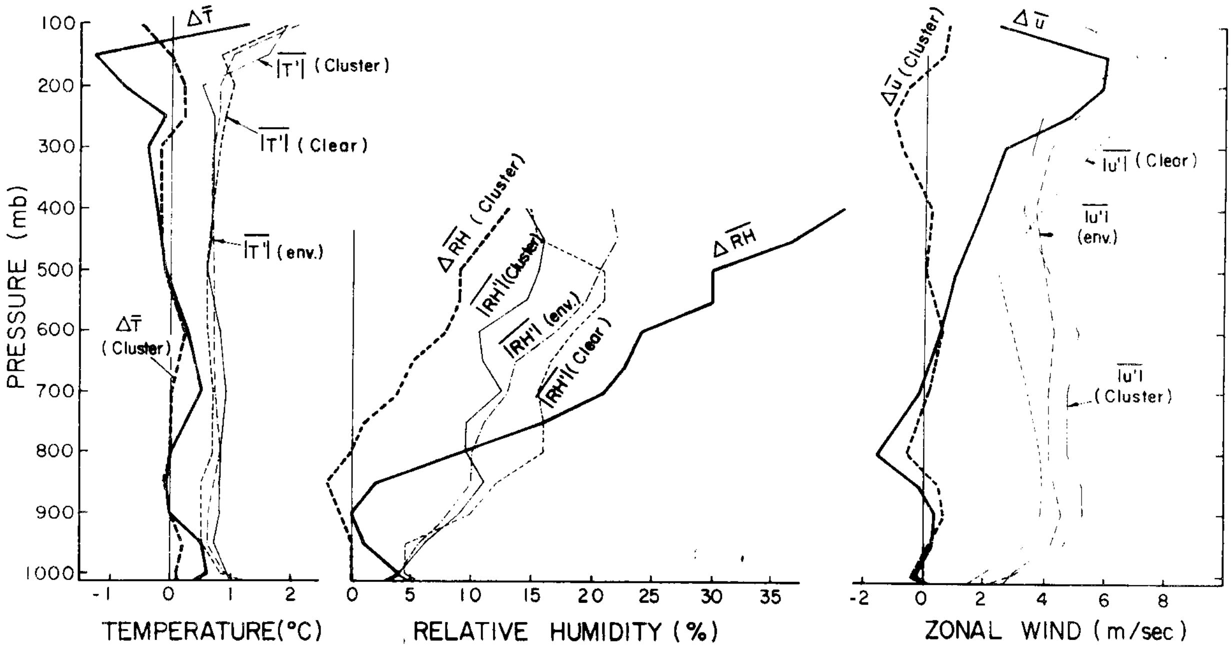


Fig. 38. Differences between the Western Pacific weather system averages and the mean deviations within each weather system type. Temperature (T), relative humidity (RH) and zonal wind (u) are treated. Δ^- denotes mean parameter differences between the cloud cluster and the clear region. Δ^- (cluster) denotes the mean parameter difference between the cloud cluster (0-2° radius) and the cloud cluster environment. ' primes refer to mean deviation of individual parameters from the inner-weather system average, (env.) stands for the cloud cluster environment.

environment. The thin solid, thin dashed lines, and the dashed-dotted lines show the mean deviations within the cloud cluster, clear area and cluster environment regions, respectively.

It was unexpected that the temperature variations within each weather system ($\sim \pm$ 1°C) would be 3 to 10 times larger than the mean temperature differences between systems ($\sim \pm$ 0.2°C) and be constant with height - see the left side of Fig. 38.

Except in the upper troposphere the inner weather system variations of zonal wind ($\sim \pm$ 5 m/sec) are also much larger than the mean zonal wind differences between systems ($\sim \pm$ 1-2 m/sec) - see the right side of this figure.

The inner system relative humidity deviations are also larger than the mean differences between systems except in the case of the middle level cluster minus clear region values. The middle part of this figure shows that the inner weather system relative humidity variations are typically 2-5 times larger than the mean relative humidity differences between the cluster and the cluster environment.

Processes Responsible for Parameter Deviations. These large parameter deviations are believed to be primarily a result of the large vertical mass recycling which is occurring within the tropical troposphere. The frequent development of downdrafts associated with cumulus convection is felt to be the primary genesis mechanism of the vertical recycling. To date, direct observational evidence of the downdraft has been rare. The data from this study gives clear evidence of downdrafts. It appears that our cloud cluster soundings can be separated into four classes:

Type 1 - Soundings which are dry and warm at all levels below 400 mb.

Type 2 - Soundings which are moist and cool at all levels below 400 mb.

Type 3 - Soundings which are cool at all levels below 400 mb but moist below 600 mb and dry above.

Type 4 - Soundings which are warm below 400 mb but dry below 600 mb and moist above. (Downdraft subsidence associated with cumulus).

Some soundings cannot be separated into these four types. Nevertheless, the point is made that within individual classes of weather systems, a wide variety of temperature and humidity values can be found. Thus, at individual places and times the tropical troposphere is in a highly variable state. Individual site observations often may not be representative of the mean or synoptic state of the atmosphere. Individual rawinsondes cannot well distinguish between a tropical cloud cluster, its environment, or a tropical clear region.

7. CLUSTER VORTICITY BUDGET

Recent diagnostic studies of tropical disturbances (e.g. Gray, 1973; Lopez, 1973; Yanai et al., 1973; Zipser, 1972) indicate a large vertical mass recycling within the cloud cluster. At lower levels the magnitude of this eddy up-and-down mass recycling is an order of magnitude or more larger than the mean upward mass flow. A general consensus on the magnitude of this large vertical recycling is now occurring. The above studies have calculated this vertical recycling circulation from required mass, total energy, and moisture budgets. Little has been accomplished with regard to the cloud cluster vorticity and momentum budgets. This chapter discusses the cloud cluster vorticity budget.

Williams and Gray (1973) have previously calculated the large-scale terms of the vorticity equation and found large lower and upper tropospheric imbalances of opposite sign. They concluded that Cb scale eddy vorticity transports carry an appreciable amount of vorticity from the lower to upper troposphere. A similar conclusion was reached by Pearce (Riehl and Pearce, 1968) for easterly waves in the West Indies area. In the summer monsoon region around the Himalaya Mountains, Holton and Colton (1972) have also indicated that sub-grid scale vertical transport of vorticity must be occurring. They concluded that cumulonimbus convection must play an important role for vorticity balance at 200 mb. The decrease of vorticity due to 200 mb divergence over this region must be largely balanced by a selective Cb importation of vorticity from lower levels. Yanai (1961) and Yanai and Nitta (1967) have performed case studies for a Western Pacific tropical storm and an easterly wave in the West Indies. They indicate that there is a significant synoptic scale residual in the vorticity equation. This residual must be ascribed either to the twisting term or to sub-synoptic scale eddy exchanges. Reed and Colton (1971) also indicated a sub-grid scale vorticity imbalance in their study of tropical disturbances. In an attempt to determine what these eddy processes might be, a further more detailed analysis of the cloud cluster vorticity equation will now be made.

The vorticity equation for an x, y, p-system will be integrated over the 4^{o} diameter cloud cluster of area A. This includes all the cloud cluster individual cumulus elements and their immediate environment. The vorticity equation for the cloud cluster can be written as:

$$\frac{\partial \overline{\zeta}}{\partial t} = - \frac{1}{A} \oint_{s} \zeta_a \; \mathbb{V}_n \; dl - \overline{\omega \frac{\partial \zeta}{\partial p}} - (\overline{\frac{\partial \omega}{\partial x} \frac{\partial v}{\partial p} - \frac{\partial \omega}{\partial y} \frac{\partial u}{\partial p}}) - \overline{\text{rot } F} \tag{1}$$

where

ζ, ζ_a	=	relative and absolute vorticity
$\mathbb{V}_n$	=	horizontal wind component normal to the cluster, positive outward
dl	=	length along cluster boundary s
F	=	friction
—bar	=	means an average over A

With the expansion of the second and third terms on the right and the usual eddy assumption where ' is a deviation from an area mean we obtain:

$$\frac{\partial \overline{\zeta}}{\partial t} = - \frac{1}{A} \oint_{s} \zeta_a \; \mathbb{V}_n \; dl - \overline{\omega} \frac{\partial \overline{\zeta}}{\partial p} - \overline{\omega' \frac{\partial \zeta'}{\partial p}} - (\overline{\frac{\partial \omega'}{\partial x} \frac{\partial v'}{\partial p} - \frac{\partial \omega'}{\partial y} \frac{\partial u'}{\partial p}}) - \overline{\text{rot } F} \tag{2}$$

The mean components of the twisting term are zero because $\overline{\omega}$ is the area mean. The twisting term is due only to eddies.

Equation (2) was used for the evaluation of the cloud cluster vorticity balance in both regions. Two assumptions were made:

1) The horizontal eddy transport at the cloud cluster boundary is negligible and the first term on the right of equation (2) can be calculated by consideration of only mean values.

2) Gust-scale mechanical friction is only effective in the boundary layer. Dissipation of momentum by small-scale turbulence effect is negligible above 900 mb. With the Gauss theorem the friction term can then be written as:

$$\int_A \text{rot } F \, df = \oint_S F_x \, dx + F_y \, dy$$

The surface friction was estimated using the formula:

$$F = \frac{C_D}{H} \left| \mathbb{V}_o \right| \mathbb{V}_o \qquad (3)$$

$C_D = 1.3 \times 10^{-3}$; $H = 750$ m; and $\mathbb{V}_o$ = surface (10 m height) wind.

Figures 39 and 40 show the results of these calculations. R stands for residual. It is composed of the eddy vertical advection, eddy twisting term and all data and physical hypothesis inadequacies:

$$R = - \overline{\omega' \frac{\partial \zeta'}{\partial p}} - \left(\overline{\frac{\partial \omega'}{\partial x} \frac{\partial v'}{\partial p} - \frac{\partial \omega'}{\partial y} \frac{\partial u'}{\partial p}} \right) + \text{all data and physical hypothesis inadequacies} \qquad (4)$$

The horizontal divergence of the vorticity transport is the predominant term in the budget in both regions. Clusters gain large amounts of vorticity in the lower half of the troposphere by convergence. They lose large amounts of vorticity through upper tropospheric divergence.

Lower and upper level transports nearly balance. Terms 1, 3, and F are seen to make only small contributions to the vorticity budget. Thus, the residual term is primarily a result of the horizontal transport.

Neglecting data and previously assumed hypothesis inadequacies the eddy processes included in R must transport vorticity out of the lower troposphere and transport it into the upper troposphere. If this does not occur, then the eddy processes must act in some fundamental way to dissipate vorticity at low levels and generate it at high levels. The authors know of no physical basis for the latter conclusion. They, therefore, accept the idea of a large magnitude of eddy transport of vorticity from lower to upper troposphere. It seems reasonable that Cb convection could accomplish this.

Vorticity Transports by Cumulonimbi. In order to show more details of the likely cloud cluster vertical eddy transports we shall discuss what we think to be a reasonable estimate of the vorticity distribution and mass flux within the cloud cluster associated with cumulonimbus convection. The 4^{o} diameter cloud cluster area will be divided into three regions:

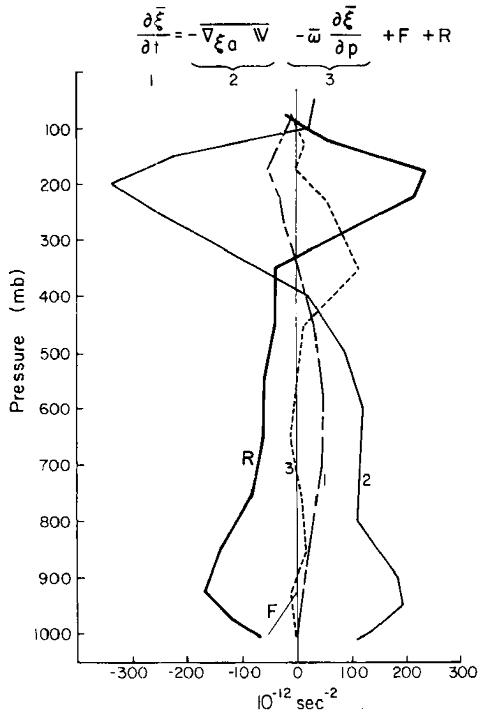
a) region of strong updrafts - horizontal fractional area σ_u,

b) region of strong downdrafts - horizontal fractional area σ_d, and

c) region within the cloud cluster between the strong up- and downdrafts, where it is assumed that the average of the residual vertical motion is zero - horizontal fractional area $\sigma_e = 1 - (\sigma_u + \sigma_d)$.

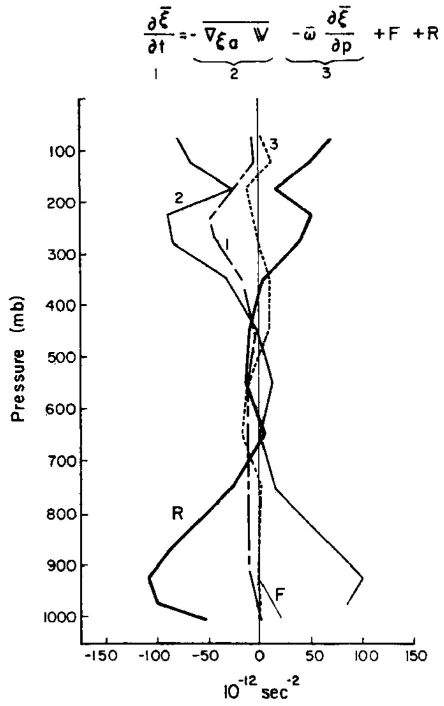
Our up-and downdrafts will be composed only of the vertical motions associated with deep cumulonimbus convection. The mean upward motion within the cloud cluster is assumed to result from a greater mass

Fig. 39.



WESTERN PACIFIC CLOUD CLUSTER
VORTICITY BUDGET

Fig. 40.



WEST INDIES CLOUD CLUSTER
VORTICITY BUDGET

Figs. 39-40. Vorticity budgets for the Western Pacific and West Indies cloud clusters. (F = friction term, R = residual = eddy plus twisting terms).

transport by the strong updrafts compared to the strong downdrafts.

Figures 41-44 show the results of our hypothesized model. The essential aspects of these figures are not the exact values of the profiles shown but the magnitudes of the differences between the up- and downdrafts and the mean values.

The vertical mass flux (Fig. 41) is derived from our calculated mean Western Pacific cloud cluster divergence. It is assumed that the middle level convergence feeds into the downdrafts. The updrafts result from the mass accumulation of the downdrafts into the surface

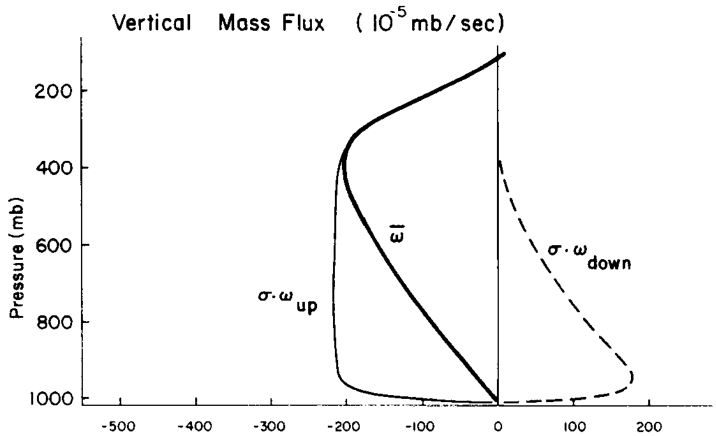


Fig. 41. Mean cloud cluster vertical motion (in 10^{-5} mb/sec)by the mean circulation ($\bar{\omega}$), the upward component by the deep cumulus convection ($\sigma \cdot \omega_{up}$) and the downdraft motion ($\sigma \cdot \omega_{down}$) of the deep cumulus.

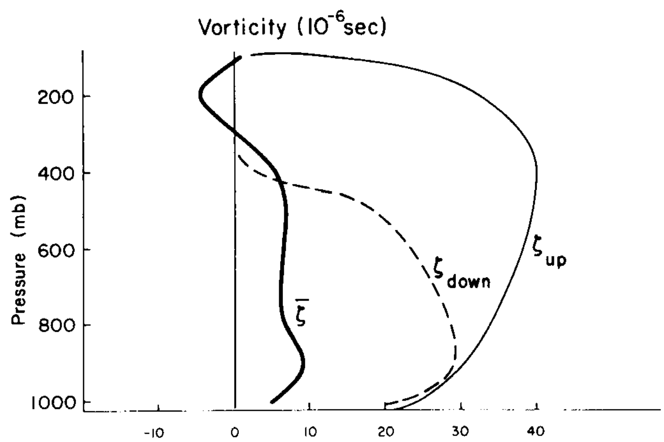


Fig. 42. Cloud cluster mean vorticity ($\bar{\zeta}$) and hypothesized vorticity within deep cumulus updrafts (ζ_{up}) and downdrafts (ζ_{down}).

to 900 mb layer and the mean cloud cluster upward transport. The upward mass flux in the middle levels (500-900 mb) is nearly constant, and the downward mass flux increases from zero at 400 mb to its maximum at the top of the boundary layer ∿ 900 mb.

Our very large mass flux in the strong up-and downdrafts is in reasonable agreement with the estimated values of Gray (1973). He indicated a larger magnitude of recycling in the lower troposphere

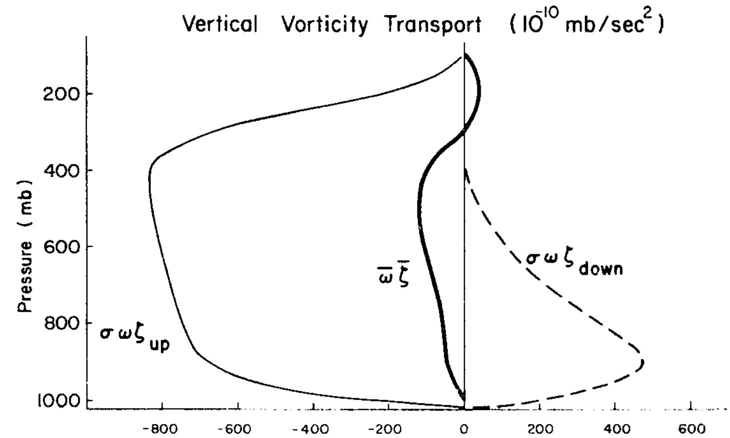


Fig. 43. Comparison of mean cloud cluster vertical vorticity transport by the mean circulation ($\overline{\omega}\ \overline{\zeta}$) and by updraft and downdraft components of the deep cumulus convection.

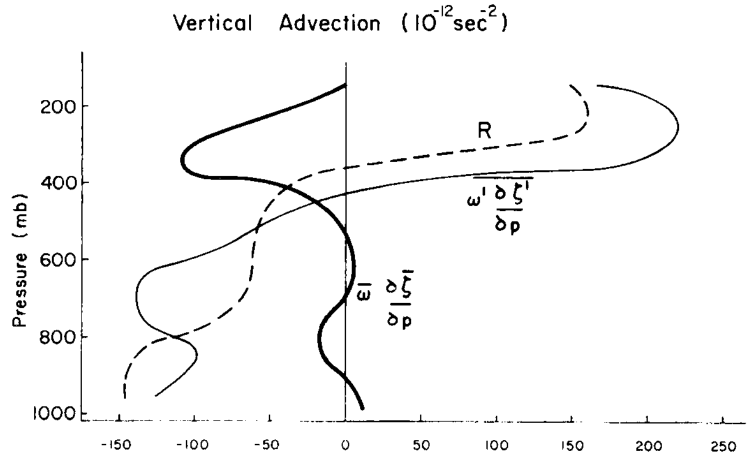


Fig. 44. Comparison of the mean and eddy vertical vorticity advection terms with the vorticity residual calculated in Fig. 39.

than we are showing. We are neglecting the influence of the extra recycling by small cumulus up-and-down motion because we believe they do not contribute in a direct way to the net cluster mass and vorticity budget. By contrast, the deep cumulus are the major contributors.

Assuming a cluster horizontal fractional area σ_u = 1% for the intense updrafts at 900 mb we calculated a mean vertical velocity of about 2 m/sec at this level for the Cb updrafts. E. Zipser has indicated (personal communication, 1973) that in squall line systems over the West

Indies the downdraft region exceeds the updraft area by a factor of 2 or more. We will assume the horizontal fractional area of the cloud cluster downdrafts (σ_d) to be $\sim$ 2%. With this we calculated a mean downdraft velocity of about 0.8 m/sec at 900 mb.

These values are slightly larger than those found by Yanai et al. (1973). He and his group made calculations in a large hexagonal region in the Marshall Islands enclosing both cloud and clear regions on both disturbed and undisturbed days. By contrast, our calculation is made only for the disturbed cloud cluster area.

A scale analysis of convergence beneath and within up-and downdrafts indicates that local draft values can be two or more orders of magnitude larger than the cloud cluster average convergence. A scale analysis of vorticity shows that it can increase by a factor of 3 to 10 beneath and within Cb up-and downdrafts. The vertical cluster vorticity profiles shown in Fig. 42 were derived accordingly. We feel these are reasonable estimates of the vorticity within deep cumulus up-and-downdrafts.

The vorticity in the updrafts increases slightly up to 400 mb. It is dissipated by spin-down processes of the upper level outflow. Downdraft vorticity reaches its maximum at the top of the boundary layer where it spreads out and reduces its spin.

The profiles in Figs. 41 and 42 were used to calculate the vertical vorticity transport in the up-and downdrafts and the eddy vertical vorticity advection. This was done so that we could compare this hypothesized model of vorticity advection with the observed cluster residual vorticity budgets of Figs. 39 and 40. These mean vs. eddy transports are compared in Fig. 43. The vertical vorticity transport within the cumulonimbus updrafts is an order of magnitude greater than the vorticity carried by the mean upward circulation. This figure also shows the large magnitude of the vorticity downdraft transport to the boundary layer to balance the large export by the updrafts. These strong downdrafts are a necessary ingredient of the vorticity budget. It becomes more and more clear how important the cumulus-scale vertical transport processes are to the dynamics of the cloud cluster.

Figure 44 gives a direct comparison between our hypothesized model and our calculated mean vorticity budget. The eddy advection term $\overline{\omega' \frac{\partial \zeta'}{\partial p}}$ was calculated with the values from Figs. 41-42. The dashed curve shows that the Western Pacific determined residual of vorticity is in good agreement with the eddy advection term. We thus feel that this explanation of the mean vorticity residual as being primarily due to selective transport by the deep cumulus is, indeed, a reasonable one.[3] We believe the twisting term, therefore, is of only minor importance.

These results indicate the vorticity equation can be treated as a transport equation where the sink of vorticity is the divergence term. A large amount of vorticity is horizontally transported into the lowest layers of the cloud cluster, and is selectively transported upwards by the Cb updrafts. This eddy vertical transport is necessary for the maintenance of the vorticity loss due to upper tropospheric divergence.

For a number of years the second author has believed in the fundamentally important role played by deep cumulus convection in selective vertical transport of momentum and vorticity (Gray, 1966, 1967).

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[3]After finishing this manuscript the authors have just become aware of a study by R. J. Reed and R. J. Johnson: The Vorticity Budget of Synoptic-Scale Wave Disturbances in the Equatorial Western Pacific. (Submitted to J. Atmos. Sci.). Their results on the role of selective transport of vorticity by deep cumulus agree well with this model.

8. DISCUSSION

This report will, hopefully, aid in setting an observational framework for future cloud cluster studies. We hope that it has shown that routine tropical data, when augmented by the satellite, can be profitably used for significant knowledge gains. One does not necessarily have to rely on special research programs such as LIE, BOMEX, and GATE to improve our knowledge of the structure of tropical weather systems.

It is expected that the coming GATE project will be able to define the individual cloud cluster and offer the needed observational description of the separate time period cumulus and meso-scale interaction processes. This study could not deal with the individual cluster system. However, probably no more than 12-15 cloud clusters will pass through the B-scale GATE array during the entire GATE period. This study may aid in determining the "typicability" of the GATE clusters and offer certain "bench mark" information to which the GATE data can be compared. This background cluster information may be of some use to the GATE project in its operational and data processing decisions.

Our observations lead us to conclude that:

1. There are significant parameter differences between the Western Pacific and West Indies clusters.

2. Soundings within individual weather system types exhibit greater variability (except for middle level relative humidity) than the mean parameter differences between systems.

3. The CISK concept of convergence-vorticity association is applicable to the West Indies clusters only if the vorticity is interpreted as a deviation from a mean state vorticity field which is always negative.

4. There are large diurnal variations in Western Pacific cloud cluster convergence and rainfall. This is primarily a result of local cluster-clear region compensation. The magnitude of this diurnal variation was quite unexpected. It is likely to be present in other oceanic regions.

5. The importance of the cumulus-scale influences on the cluster vorticity budget is fundamental. This supports previous speculations on the probable importance of cumulus scale influences on the broader scale motions and the necessity to correctly parameterize these influences in the cumulus convective atmosphere so that they can be properly dealt with from synoptic-scale observations.

6. As expected, the cluster rainfall is very highly concentrated in only a very small percent of the cluster area.

7. Cloud clusters cannot always be associated with traveling easterly waves. Some clusters are well identified with systematic variations of the meridional wind components as would occur with traveling waves in the trades. Many other cloud clusters are not associated with systematic changes in the meridional winds. (There are a number of semantical questions which have to be sorted out before this can be generally resolved. How should we define these waves?)

Compositing Technique. An auxiliary purpose of this paper has been to show that meaningful physical insights into the structure and dynamics of meso-scale tropical systems can be gained even though the data network used to obtain this information is of a course scale.

The compositing technique of this paper is different than that employed by the UCLA group under Professor M. Yanai (Yanai et al., 1973) and the U. of Washington group under Professor R. Reed (Reed and Recker, 1971). The Yanai group has composited selective Marshall Island areas of $\sim 10^{o}$ width. Data is simultaneously averaged over both cloud and clear regions. Cloud and clear regions are not isolated and treated separately as in this study. The Reed group has composited their data with respect to meridional wind changes as indicated by the presence of easterly waves. They average these waves by combining trough positions, etc. Their averaging is independent of cloudiness. As we have found, the typical cloud cluster is not necessarily associated with systematic changes in the meridional wind. Thus, differences must be expected in comparing these results with those obtained by the Yanai and Reed groups.

Organization of Cb Convection. The tropospheric vertical wind shear patterns in the two regions are significantly different. Lack of strong cloud cluster vertical wind shear in the Western Pacific indicates (and the observations generally support this) that Cb convection is typically not well organized in squall lines. Here the vertical shear of the zonal wind can be either positive or negative. The zonal vertical shear of the West Indies, on the other hand, is nearly always positive and is typically larger. This implies that Cb convection in the West Indies should more often be organized in squall lines. Observations indicate that this may be the case.

Figure 45 compares the summertime cluster horizontal and vertical wind shears in the Western Pacific and West Indies with the available climatological information on these wind shears in the GATE B-scale array. It appears that the horizontal shear in the GATE network will be more typical of that of the West Indies, while the vertical shear will be more similar to that of the Western Pacific. To the extent this GATE information is representative, this may indicate that the West African squall activity may not frequently progress into the GATE array and that Cb organization may not be as frequent in GATE as it is in the West Indies.

Study's Major Shortcomings. This study could obviously not deal with the individual weather system. This is believed to be its major shortcoming. There are likely to be significant differences between individual cloud cluster systems. Some of our clusters likely did not exhibit active cumulus convection at the time of observation. Some may have been made up of only middle-level cloudiness. The authors hope to next perform some delineation of clusters by rainfall intensity.

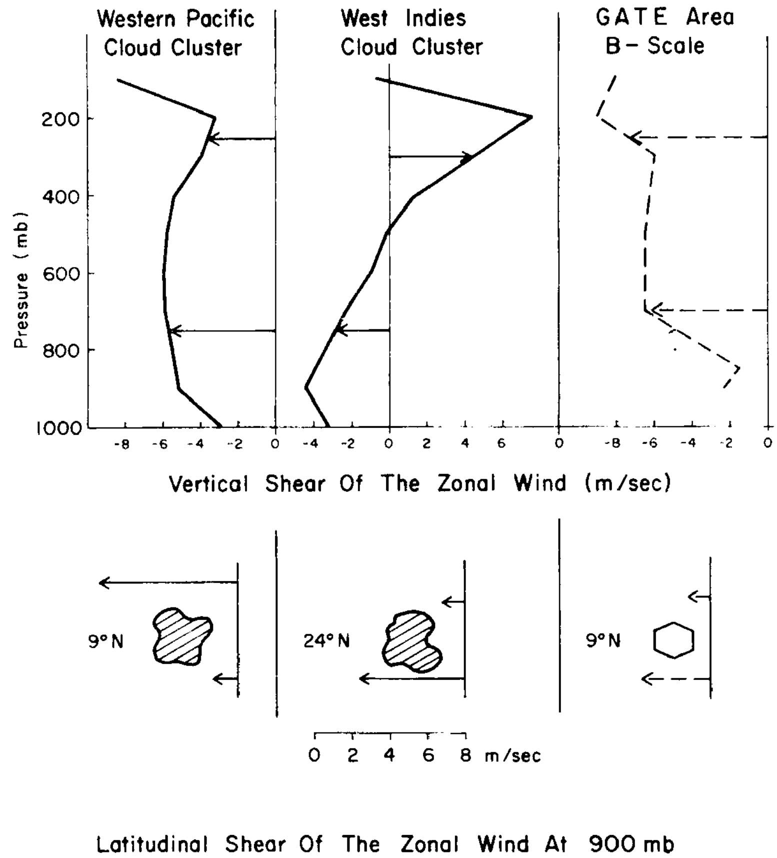

Fig. 45. Vertical and horizontal shear of the zonal wind for the Western Pacific and West Indies cloud clusters and for the GATE B-scale area. The winds for the GATE area are climatological data from Crutcher (1959) and Atkinson and Sadler (1970).

The lacking information on the variability of Cb activity within different cluster systems should be forthcoming from the GATE project and from new satellite systems. The authors next hope to stratify clusters by intensity of Cb activity.

Our budgets apply to mean 4^{o}-scale cluster conditions. Most active clusters will exhibit vertical circulations more intense than the ones reported here.

Implication for Tropical Analysis. This study has lead the authors to believe that the typical tropical rawinsonde measurements are often unrepresentative of the synoptic-scale environment in which they are embedded. Individual rawinsondes cannot distinguish between a tropical cloud cluster, its environment, or a tropical clear region. Inner-weather-system variability is too large. It appears that a realistic synoptic analysis in the tropics requires a much higher rawinsonde density than has been envisaged for future tropical analyses which only plan augmentation of the standard middle latitude rawinsonde networks. To properly measure the large-scale flow patterns in which cumulus convection is embedded such that a representative synoptic analysis can be obtained it may be necessary to develop measuring systems with sensors which can integrate meteorological parameters over distances and time of ∿ 100 km, ∿ 3 hrs. Perhaps future developments in satellite, radar, and radio sensing systems will allow such area-time parameter integrations. The rawinsonde instrument employed on a 300-500 km grid at 12 or 6 hour time intervals is clearly incapable of such an analysis.

Implication for Tropical Forecasting. It is generally agreed (see U. S. National Academy of Sciences Report, edited by J. C. Charney, 1966) that in the next quarter century improved global numerical forecasting skill will be determined by the degree to which man is able to:

1) accurately measure the synoptic scales of motion,
2) parameterize the processes occurring on the subsynoptic scales in terms of the synoptic scale and
3) control the calculation processes such that they do not introduce unrealistic computational phenomena to the forecast scheme.

An insufficiency in any of these requirements will lead to unrealistic parameter analysis and rapid decrease of forecasting skill. An appreciation for the difficulties of the latter two requirements is rather generally accepted. The authors question, however, the degree of appreciation for the difficulties which are likely to be encountered in meeting the first requirement in the tropical regions. An increase in the tropical rawinsonde or single site measurements to density levels of the U. S. and European standards will not, due to reasons just discussed, allow the first requirement to be met. Individual site measurements are likely to be grossly insufficient for proper synoptic flow representation. In the middle latitudes, the synoptic scale changes are much larger, the degree of cumulus activity is less, and the synoptic observation network is often able to determine a representative broad-scale flow field.

Future Research. There is much more useful data compositing which can be accomplished in the Western Pacific and West Indies data networks. This study has accomplished only a very small bit of what can be done. In particular, the new satellite techniques now permit the direct sampling of the individual Cb elements. Clusters can now be stratified by their degree of deep cumulus activity. The authors believe that a significant expansion of our knowledge on tropical weather systems can be gained from the vast amounts of already existing observations. It is hoped that the coming GATE project will not siphon off all of our tropical meteorology research resources. There are still many important tropical meteorology questions which only the long term existing data networks can answer. We will hopefully pool our knowledge from both data sources and obtain a reasonable research balance between old and new data sources.

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APPENDIX A

DATA SOURCES AND LOCATIONS OF CLOUD CLUSTERS AND CLEAR REGIONS

Table A1

Rawinsonde Stations in the Western Pacific and West Indies

a) Western Pacific

Name	Lat. N	Long. E	Location
Koror	7.3	134.5	I
Yap	9.5	138.0	I
Guam	13.6	144.8	I
Truk	7.5	151.9	I
Ponape	7.0	158.2	I
Eniwetok	11.4	162.4	I
Wake Island	19.3	166.7	I
Kwajalein	8.7	167.7	I
Majuro	7.0	171.4	I
Johnson Island	16.7	169.5W	I
Iwo Jima	24.9	142.0	I
Marcus Island	24.5	154.0	I

b) West Indies

Name	Lat. N	Long. W	Location
Barbados	13.0	59.5	I
Chaguaramas	10.7	61.6	I
Raizet	16.3	61.6	I
Antigua	17.1	62.8	I
St. Marteen	18.0	63.1	I
Kindley Bermuda	32.4	64.7	I
San Juan	18.4	66.0	cI
Santa Domingo	18.5	69.9	cI
Plesman	12.2	69.0	I
Turks Island	21.5	71.1	I
Guantanamo	19.9	75.2	cI
Kingston	17.9	76.8	cI
Gold Rock	26.6	78.3	I
Albrook	9.0	79.6	c
Miami	25.8	80.3	c

b) West Indies (cont'd)

Name	Lat. N	Long. W	Location
Charleston	32.9	80.0	c
Cape Kennedy	28.2	80.6	c
Grand Cayman	19.3	81.4	I
Jacksonville	30.4	81.7	c
San Andres	12.6	81.7	I
Key West	24.6	81.8	I
Tampa	28.0	82.5	c
Athens	34.0	83.3	L
Swan Island	17.4	83.9	I
Montgomery	32.3	86.4	L
Boothville	29.3	89.4	c
Merida	20.9	89.7	L
Jackson	32.3	90.1	L
Lake Charles	30.1	93.2	L
Shreveport	32.5	93.8	L
Vera Cruz	19.2	96.1	c
Victoria	28.9	96.9	L
Fort Worth	32.9	96.9	L
Brownsville	25.9	97.4	L

Location: I = Island stations
cI = Coastal stations on big islands
c = Coastal stations
L = Land stations

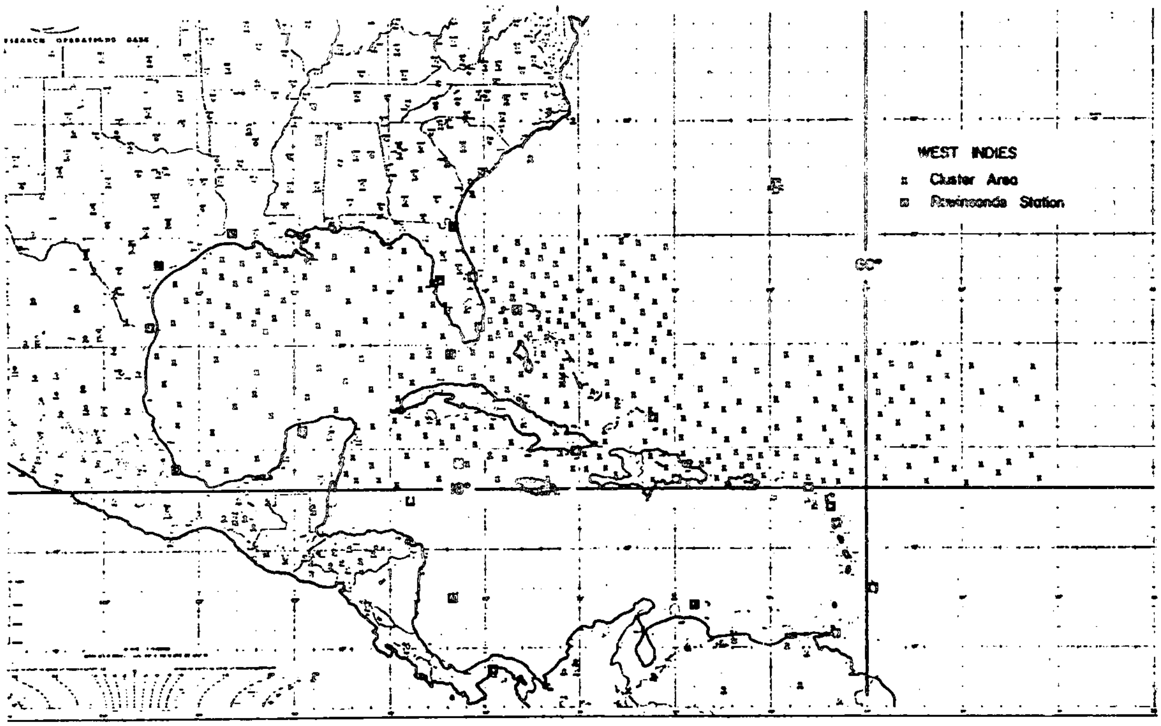

Fig. A1. Location of cluster regions in the West Indies.

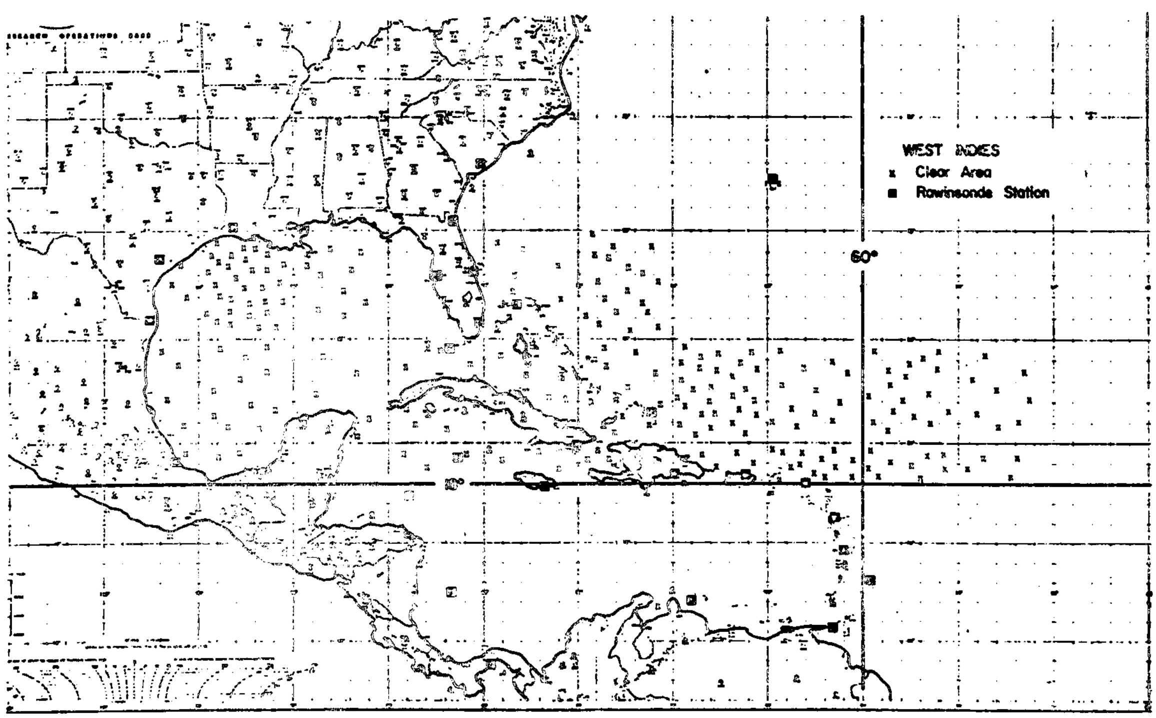

Fig. A2. Location of clear regions in the West Indies.

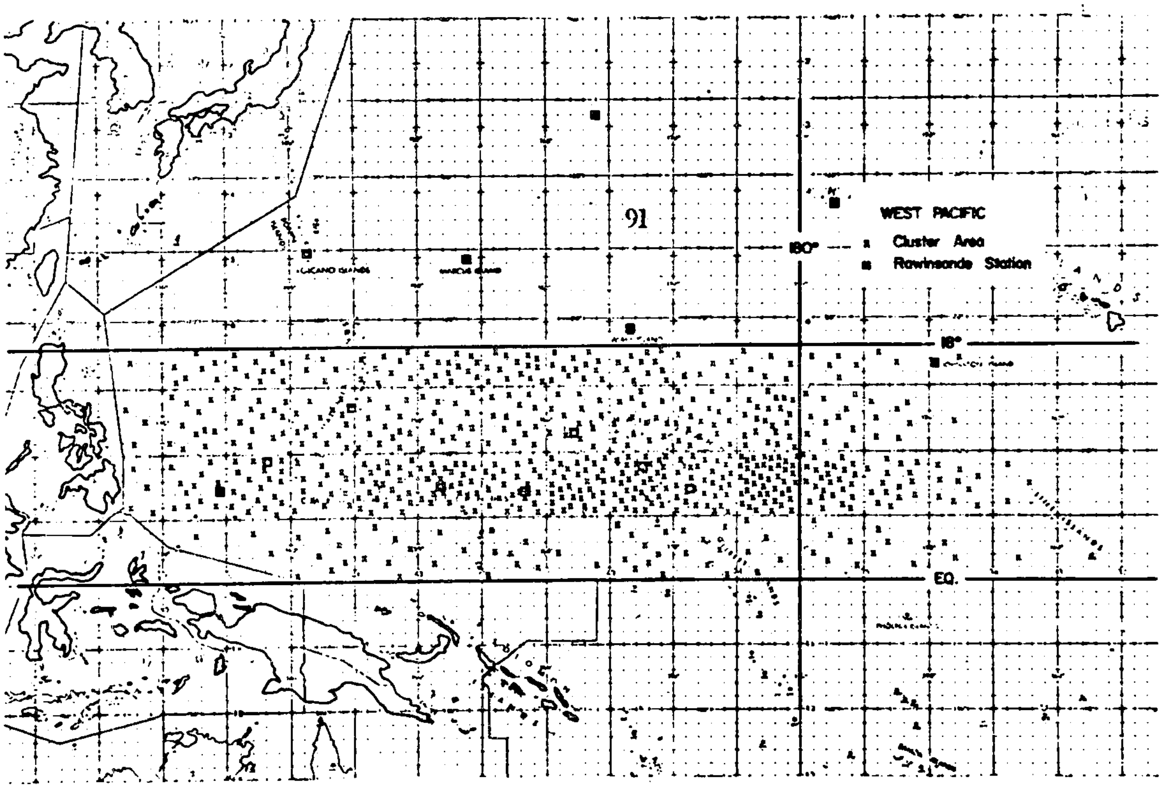

Fig. A3. Location of cluster regions in the Western Pacific.

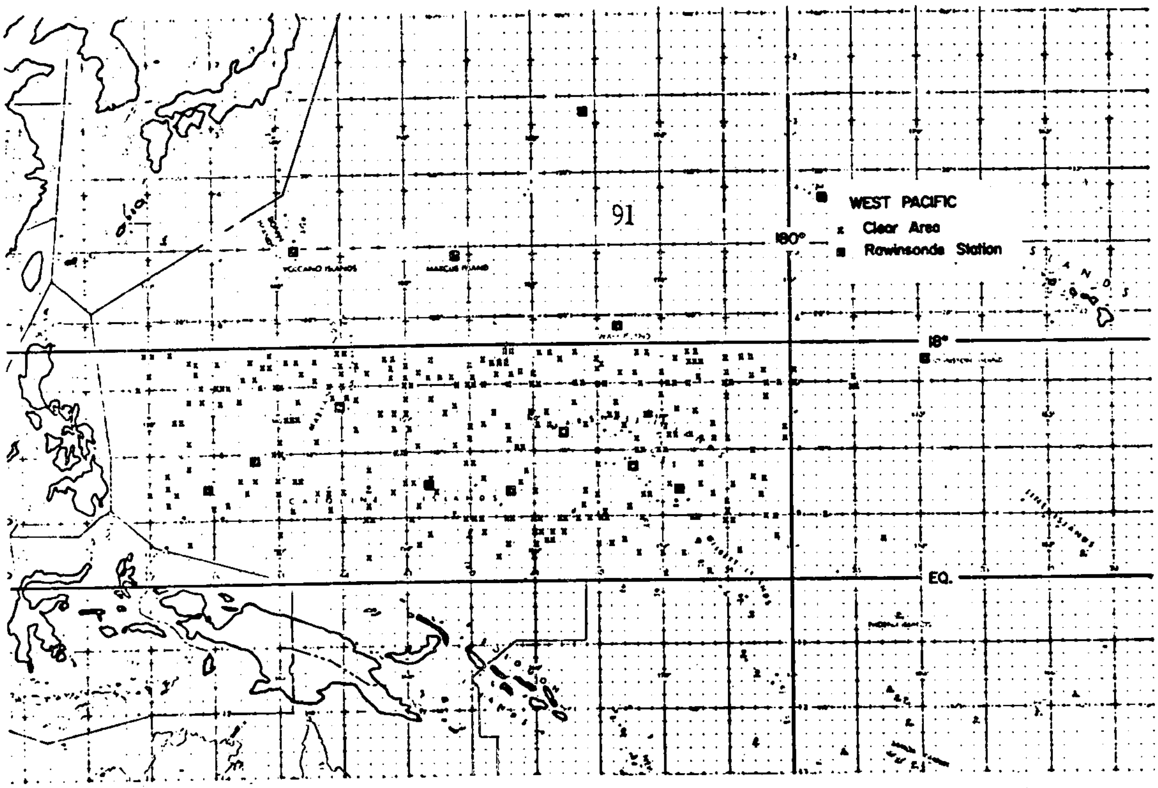

Fig. A4. Location of clear regions in the Western Pacific.

APPENDIX B

DIURNAL TEMPERATURE CORRECTIONS FOR RAWINSONDE HUMIDITY SENSORS

1. Introduction

During the evaluation of a number of recent tropical field experiments (e.g. ATEX, BOMEX, VIMHEX) meteorologists became aware of the spurious day versus night variations of relative humidity. Each of these groups developed their own correction scheme (Ostapoff et al., 1970; Sanders et al., 1973; Betts, 1972).

Ostapoff et al. (1970) carried out flight experiments and laboratory tests to examine the daytime error of the humidity sensor. They give a mean correction of the daytime humidity for the undisturbed trade wind region with a maximum correction of about 15% for a daytime reading of 65% and no correction for 100% and 20% daytime humidity. The corrections are independent of height.

The BOMEX daytime humidity correction (Sanders et al., 1973) was done using the daytime temperature difference between the rawinsonde humidity sensor and the ambient air. This temperature difference was calculated based on the day versus night humidity difference. The result for the average of five undisturbed and two disturbed days during BOMEX is shown in Fig. 1.

Betts (1972) calculated the correction for the VIMHEX daytime humidity data from the difference at the surface between the rawinsonde and the well ventilated aspirated psychrometer for each sounding. The temperature difference between the hygristor and thermistor was derived from this humidity difference and used to correct the relative humidities at all levels.

A more general approach to this problem has been taken by Morrissey and Brousaides (1970) who tested the U. S. Weather Bureau ML-476 sonde and the military AN/AMT-12 sonde in several experiments. In general, they verified the results of the previous experiments. Their corrections increase with height for undisturbed days.

The purpose of this study is to show, from a statistical analysis, how the corrections which must be applied to the U. S. Weather Bureau sonde vary with different weather systems and with height. The corrections will be related to varying downward solar irradiance and sky cover.

2. Procedure

A statistical approach is employed. Day versus night humidity and temperature information has been gathered on a large sample of weather systems in the Western Pacific. It is assumed that direct solar radiation on the carbon strip of the sonde hygristor is an important determinant in the measured day versus night humidity differences. The problem resolved to that of specifying how much the daytime humidity values should be corrected for the individual weather system. No corrections will be made for the time lag or the error due to the internal heating of the hygristor by the electric equipment of the sonde.

The relative humidity (RH) is believed to be underestimated because the saturation vapor pressure, e_s, corresponding to the temperature of the hygristor is too large. The temperature dependency of RH and e_s are given by the formula:

$$\frac{1}{RH}\frac{dRH}{dT} = \frac{1}{e_s}\frac{de_s}{dT} \quad . \tag{1}$$

With the use of the Clausius-Clapeyron equation and integrating over the observed range of the humidity and temperature we obtain:

$$\ln \frac{RH_2}{RH_1} = \frac{L}{R_v} \left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad . \tag{2}$$

where

- RH_1 = measured relative humidity of the daytime sonde
- RH_2 = measured relative humidity given by the nighttime sonde
- L = heat of condensation, which was assumed constant over the temperature range of consideration
- R_v = gas constant for water vapor
- T_1 = the daytime temperature of the hygristor which is influenced by extra solar absorption
- T_2 = the daytime environmental temperature near the thermistor
- $\Delta T = T_1 - T_2$ = the excess temperature of the hygristor relative to the ambient air temperature.

After some rearrangements Eq. (2) can be put in the form:

$$\Delta T = \frac{\frac{R_v}{L} \; T_2^2 \; \ln \frac{RH_2}{RH_1}}{1 - \frac{R_v}{L} \; T_2 \; \ln \frac{RH_2}{RH_1}} \quad . \tag{3}$$

The environment-hygristor temperature difference, ΔT, is believed to be the source of the humidity error. It is assumed to be a function of height and cloudiness above measurement point. From the various measured relative humidities this temperature excess was calculated for Eq. (3).

3. Results

Eq. (3) was evaluated for average conditions in four different weather systems over the Western Pacific. Weather system data was taken from Gray et al. (1974). Nighttime soundings were taken at 12Z (about midnight local time) daytime soundings at 00Z (about noon local time). See Gray et al. (1974) for the definition of the weather systems and more information about the data. Table 1 shows the relative humidity differences between night and day for the different weather systems and for BOMEX as given by Sanders et al. (1973).

Day minus night mean humidities vary about 10%. These differences typically increase with height and with lack of cloudiness. Relative humidities less than 35%, especially at higher levels for the clear areas, reduce the accuracy of the humidity measurements which is indicated by the scatter of our results.

Fig. 1 portrays the daytime temperature differences (hygristor - ambient air) for the four Western Pacific weather systems:

1) typhoon (0-2^{o} latitude around the center),

2) cloud cluster (0-2^{o} latitude around the center),

3) cloud cluster environment (2-6^{o} latitude around the cloud cluster center),

4) clear region.

Calculated values differ in magnitude and in profile slope. This is believed to be inversely related to cloudiness. There is a systematic decrease of cloudiness from the typhoon to the clear region. Calculated hygristor temperature corrections correspondingly increase.

The vertical relative humidity profiles for the Western Pacific cloud cluster and its environment (Table 1) show a sharp increase (8 to

Table 1. Night minus day differences of relative humidity (%) for various tropical weather systems.

Pressure (mb)	Cloud Cluster	Cluster Environment	Clear Region	Typhoon	BOMEX
Sfc	4	8	13	4	17
1000	7	10	14		
950	7	11	17	5	18
900	6	11	18	5	20
850	4	11	19	8	21
800	5	11	18	10	10
750	6	12	14	13	9
700	8	11	14	12	8
650	8	12	15	7	10
600	13	13	18	7	16
550	19	17	15	8	18
500	21	18	16	11	21
450	25	19	9	8	
400	25	21	7	12	

19%) between 650 and 550 mb indicating an increase in cloudiness in this layer. The typhoon case does not show this temperature correction increase with height. The smaller typhoon night minus day relative humidity differences indicate that the rawinsonde is probably being protected from the direct solar radiation by higher clouds.

The profiles for the cluster and cluster environment show reasonable agreement. They are, however, quite unlike the shape of the undisturbed system. The "BOMEX" profile by Sanders et al. (1973) - an average of five undisturbed and two disturbed days - fits just between our cluster environment and clear region cases.

Assuming that the excess of the hygristor temperature is the result of the radiational effect on the humidity sensor, the temperature differences should be proportional to the direct solar radiation absorbed by the hygristor at each level. The crosses in Fig. 1 give the downward solar irradiance calculated by Cox et al. (1973) for cloud free days during BOMEX. The agreement of their irradiance profile with our results for the clear region supports this assumption.

4. Effect of cloudiness

These diurnal temperature variations are inversely related to the interception of solar radiation by cloudiness. The profiles for the two disturbed systems (i.e. cluster and cluster environment) can be generalized as follows: near constant temperature differences up to $\sim$ 700 mb and then a linear (with pressure) increase above. The height up to which ΔT is nearly constant appears to depend on the height of maximum cloudiness. Little increase is observed with height in the typhoon which has extensive high cloudiness. An inverse relationship between sky cover and our calculated heating profiles is present.

Quinn (1971) found that for the Western Pacific island stations the transmission of the troposphere and therefore the incoming solar radiation at the surface decreases linearly with increasing total opaque sky cover. We assume the total opaque sky cover for the four weather systems is as follows:

Total Opaque Sky Cover (in tenths)

Typhoon	Cloud Cluster	Environment	Clear Region
10	9	5	0

Fig. 2 shows the dependency of the hygristor temperature excess on the total opaque sky cover at the surface and at 900 mb. The linear relationship between the sky cover and the temperature excess is clearly seen. Application of the correction lines of Figs. 1 and 2 are thus shown to give reasonably accurate daytime relative humidity values.

5. Summary of results

The main error in the daytime relative humidities appears to arise from the heating of the sonde hygristor by direct solar radiation. This is confirmed by the agreement between the profiles of the downward solar irradiance and the temperature excess of the hygristor for the clear region (so defined with satellite pictures). The total opaque sky cover proved to be a useful parameter to determine the temperature differences. This is in agreement with the results of Quinn (1971).

In the disturbed cases the temperature corrections below 600 mb can be assumed to be approximately constant and to linearly increase with decreasing total opaque cloudiness. These results are based on a very large statistical analysis. Results will be less applicable in individual cases.

Based on the results of the NOAA Sea-Air Interaction Laboratory test (Ostapoff *et al*., 1970) the U. S. Weather Bureau sonde was modified. Riehl and Betts (1972) showed that the new sonde gave no systematic differences between day and nighttime humidities. The modified rawinsonde is available since 1972, thus, most rawinsonde stations should have used it by now and the daytime humidity corrections are unnecessary in the future.

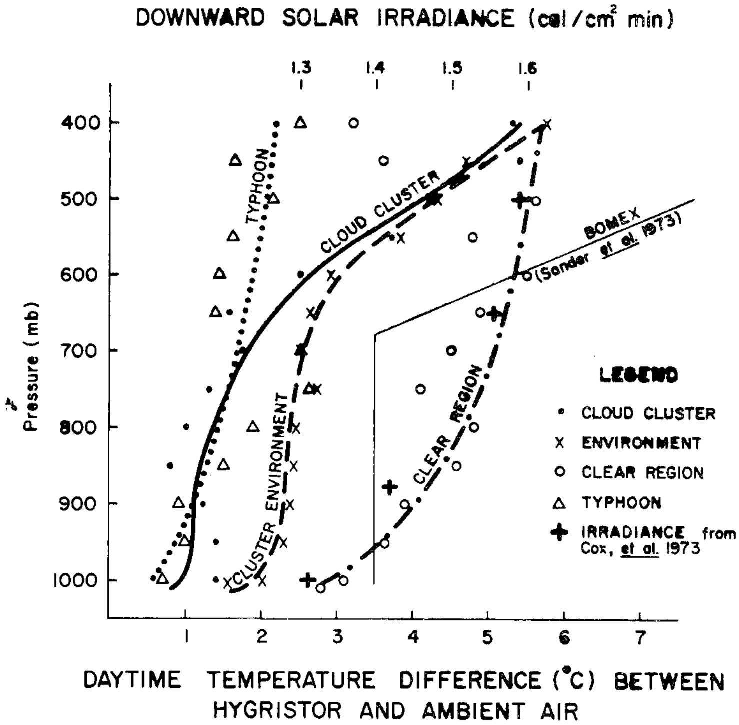

Fig. B1. Vertical profiles of the calculated temperature differences between hygristor and ambient air for different weather systems.

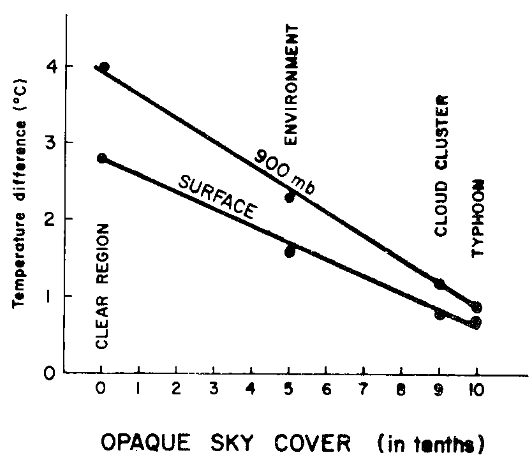

Fig. B2. Calculated temperature differences between hygristor and ambient air as function of the opaque sky cover.

APPENDIX-BIBLIOGRAPHY

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