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AN OBJECTIVE ANALYSIS OF CLOUD CLUSTER DIMENSIONS AND SPACING IN THE TROPICAL NORTH PACIFIC

C. M. HAYDEN
National Environmental Satellite Center, ESSA, Washington, D.C.

ABSTRACT

The scale of cloud clusters occurring in the tropical North Pacific is objectively derived from vidicon data received from the ESSA satellites for July and October 1967 and January and April 1968. Attention is focused on the intertropical convergence zone, which is defined to be the 10° latitude strip with greatest average brightness. The predominant width of cloud clusters is found to range from 275 km in winter to 450 km in summer. The most frequent distances separating clusters are 6°–8° and 10°–12° (latitude) without seasonal variation. The results indicate that a grid size suitable for tropical analysis is about half that used by the National Meteorological Center for midlatitude analysis.

1. INTRODUCTION

Knowledge of the significant scales of weather systems is necessary to design observation networks or grid lattices for numerical forecast models. This is a major problem confronting the World Weather Watch Program and is of particular concern to the Global Atmospheric Research Program, which is charged with determining a global observation network compatible with the significant scales of atmospheric motion. Over large portions of the Northern Hemisphere, the atmosphere is sufficiently well sampled to permit investigation of the scale problem by numerical methods. Spatial resolution and subscale parameterization can be experimentally varied to seek solutions that conform to observations. In the Tropics, however, paucity of conventional data precludes this approach. The purpose of this study is to consider the tropical scale problem by analyzing satellite vidicon data, which provides the only comprehensive coverage of those regions.

The immediate question that arises is how an analysis of cloud photographs can yield information on the scales of atmospheric motion. It is apparent that a scale analysis of vidicon data gives direct information on the scales of only the cloud systems. Adaptation of the results to the scales of other meteorological variables such as pressure or wind fields is necessarily inferential. In middle latitudes, the correspondence between cloud and dynamic scales is well established. Examples are the familiar vortical patterns produced by frontal cyclones and the comma-shaped cloud systems associated with vorticity maxima. In the Tropics, correspondence has not been so firmly established; but it undoubtedly exists, particularly for cloud systems of the size considered below (with areal extent of at least 4000 sq km). A number of investigations have associated such cloud clusters with pressure or wind field disturbances important to numerical analysis and prediction. Consequently, although the results of this study provide objective measurements of cloud cluster dimensions and spacing, this information is also pertinent to the more important question of synoptic scales of motion in the Tropics.

Reported here is an examination of satellite pictures of the tropical North Pacific: 110° W. to 130° E., from the Equator to 30° N. Four months were considered: July and October 1967 and January and April 1968, using analyzed digitized brightness data produced by the Data Processing and Analysis Division of the National Environmental Satellite Center. For October 1967, the area 30° N. to 60° N. was also analyzed to provide a high-latitude sample for comparison. The data were subjected to two types of objective analysis. Most information was obtained with the first type, a screening of the brightness patterns to discriminate cloud clusters and their size and spacing. Fourier analysis, the second type, was less rewarding.

2. DATA REDUCTION, RELIABILITY, AND ANALYSIS

CLUSTER SCREENING PROCEDURE

The data reduction is a two-step procedure. First, the daily archived digitized vidicon data are reduced in resolution to a latitude-longitude lattice with a grid length of one-half degree. A single mean brightness value (B) is derived for each grid point. Second, the pattern of brightness values for each day is reduced to a distribution of cloud clusters of various sizes. Because the details of these procedures are important in evaluating the results, they will be considered here in detail.

Full resolution data are comprised of brightness values, scaled 0–14, at grid points covering two polar stereographic projections, one for each hemisphere (Bristor et al. 1966). These data have been reduced for archiving to mesoscale grids of 512×512 grid points for each hemisphere, representing a 64-fold decrease in the total number of grid points (Booth and Taylor 1969). The data are not archived

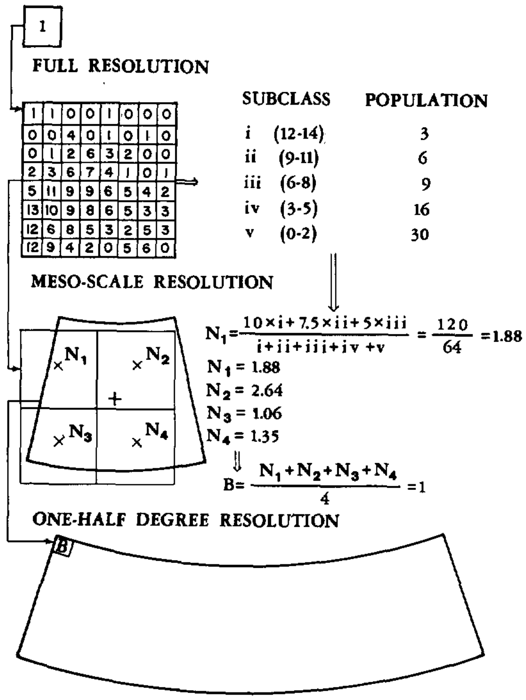


FIGURE 1.—Hypothetical example of data reduction from full resolution to geographical one-half degree grid lattice.

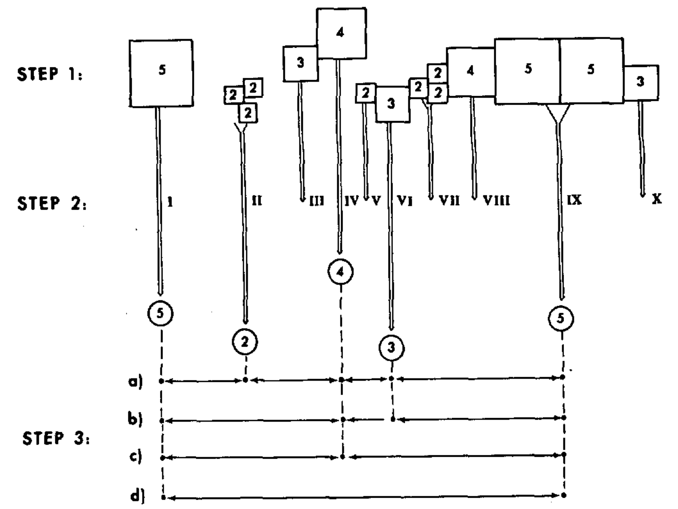


FIGURE 2.—Hypothetical example of cloud cluster selection process (steps 1 and 2) and measurement of cluster separation distances (step 3). Cluster designations are related to actual size in table 1.

as a single brightness value for each mesoscale grid point; rather, "populations" are recorded (i through v) for each mesoscale grid square. Each number is a count of the full resolution measurements that occur in five subclasses of the original brightness scale (fig. 1). Each subclass includes three consecutive brightness categories (of the full resolution scale); for example, i represents the population in the subclass 12–14 (the brightest) while v represents the population of the least bright, 0–2. In cases of no missing data, the sum of i through v is 64. Brightness values used in this study are obtained from the archived populations (i through v) by transforming populations into a single number (N) for each mesoscale grid point. Each population is weighted according to its brightness and normalized by

$$N=\frac{10\times i+7.5\times ii+5\times iii}{i+ii+iii+iv+v}. \quad (1)$$

This produces a value of N for each mesoscale grid scale on a 0–10 scale. Next, average brightness, B, is derived for each half-degree grid square (fig. 1). The included N's are averaged, and the result truncated to yield an integral value. In the example shown,

$$B=(N_1+N_2+N_3+N_4)/4. \quad (2)$$

Due to polar convergence, approximately five mesoscale data points on the polar stereographic projection occur in a half-degree grid square at the Equator, whereas only two occur at 30° N.

The second data reduction step screens the brightness values (B) to determine the location and size of cloud clusters. Each half-degree grid square with brightness, B, equal to one or greater is interpreted to be a cloud-covered square. The locally largest square arrays of contiguous cloud-covered grid squares are defined to be cloud clusters. Further, the arrays are required to have a center (half-degree) grid square. In consequence, the cloud clusters are made up of 3×3, 5×5, 7×7, etc. grid squares. The steps for discriminating cluster sizes and spacings, detailed below, are illustrated by the hypothetical example in figure 2.

Step 1) The largest, nonoverlapping square arrays (clusters) are identified. At this stage, cloud bands become contiguous arrays.

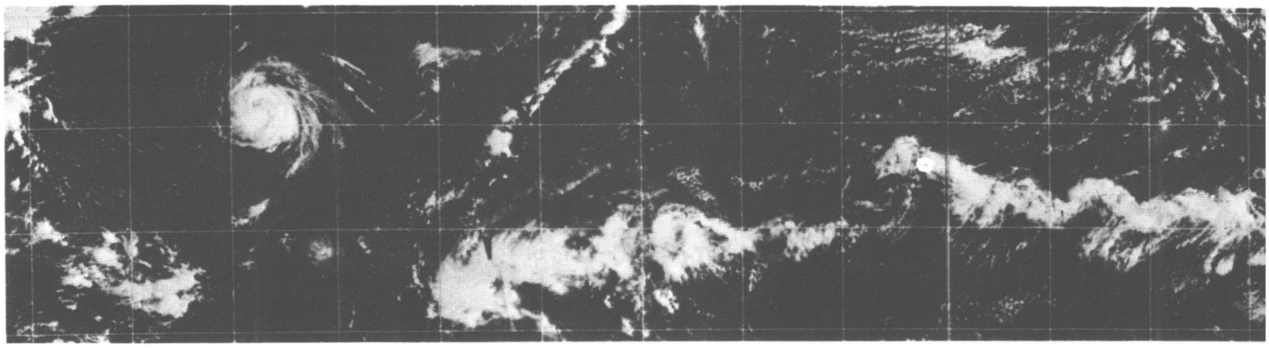
Step 2) Isolated arrays are retained unmodified (namely, arrow I of fig. 2). Contiguous arrays are treated further to distinguish prominent nodes (presumed to be disturbances) in the bands. This is done by applying two rules:

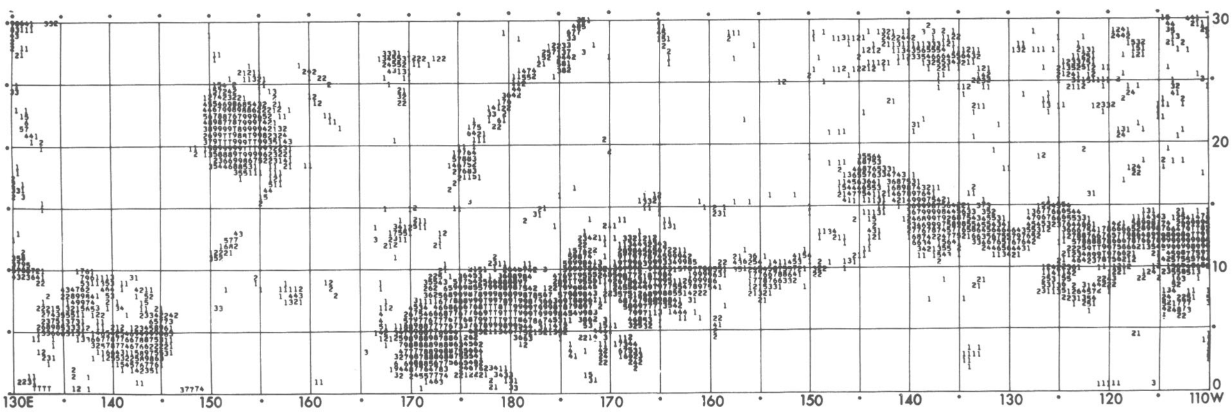
a) Any array connected, either directly or by contiguous arrays of an equal size, to a larger array is eliminated (namely, arrows III, V, VII, VIII, and X).

b) Contiguous arrays of equal size (not already treated in step a) are replaced by a single array at their mean geographical position (namely, arrows II and IX). The arrays retained and their locations are indicated by the circles immediately beneath step 2 of figure 2.

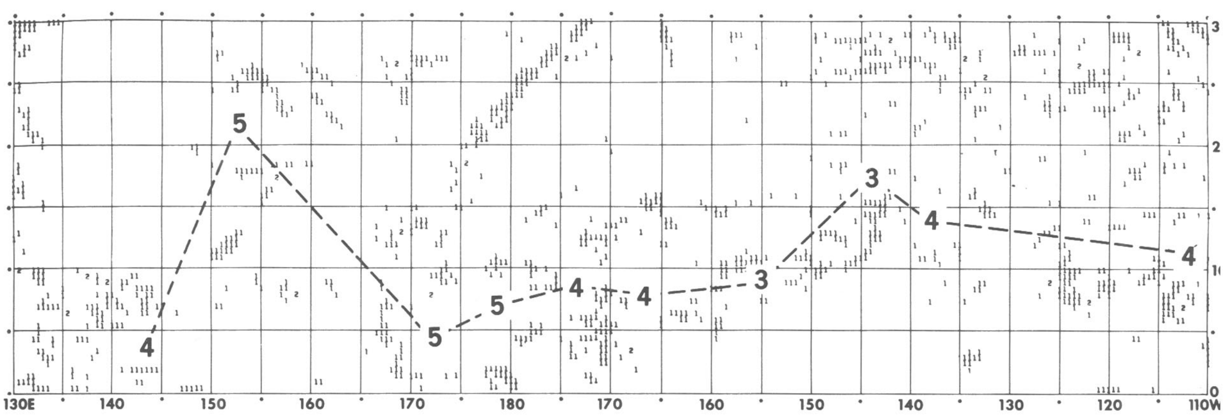
Step 3) From each retained cluster the shortest distance is determined to a neighbor of the same or larger size as shown by step 3a of figure 2. In this figure, four sets of separation distances are illustrated (steps 3a through 3d), which are computed as smaller clusters are sequentially disregarded. The purpose of this sequential computation is discussed in connection with figure 5.

Only east-west distances are shown schematically at the bottom of figure 2; but in the analysis of real data, total





DIGITIZED BRIGHTNESS 2 OCTOBER 1967



CLOUD CLUSTER DISTRIBUTION 2 OCTOBER 1967

Figure 3.—Top, full resolution brightness mosaic; middle, one-half degree resolution brightness values (B); and bottom, cloud cluster selection with sizes and separation distances.

distance was computed. Figure 3 illustrates a real case. The separation distances measured along the broken lines (fig. 3, bottom) correspond to step 3b of figure 2; that is, separation distances are measured for clusters with size designations of at least 3. Clusters with array designation 2 are also shown, but not in boldface type. Cluster size designation used on figure 3 is defined in table 1.

For reasons mentioned later, sizes and spacings were computed for two grid areas. One type was the 10° latitude band (selected to the nearest half degree) that exhibited the greatest averaged brightness, and the

TABLE 1.—*Relationship between array dimension and size designation (figs. 2 and 3) and corresponding approximate cloud cluster width*

Array size	Array designation	Approximate cluster width
(grid points)	*(no.)*	*(deg latitude)*
1	1	Not considered
3×3	2	1°
5×5	3	2°
7×7	4	3°
9×9	5	4°
11×11	6	5°

screening treated only those cloud clusters within the band. The second type of area was the entire 30° region, as illustrated in figure 3.

DATA RELIABILITY

The significance and physical reality of the results derived here depend on the reliability of the data, both in their initial form and the form they assumed through the successive steps of analysis. In order of increasing importance, three aspects are:

- The quality of the data in mesoscale form.
- Integrity of the data after reduction to the half-degree grid squares.
- The ability of the cluster selection technique to discriminate significant cloud systems.

The major considerations concerning quality of the mesoscale data are variations of (brightness) response as a sensor ages and the difference in response from sensor to sensor. These variations were examined by Taylor and Winston (1968) for the period February 1967 through February 1968, which includes three of the months used here. They demonstrate that sensor response had considerable variation, and they devised a technique to normalize the mesoscale data. In this study, however, it was concluded that no such adjustment was necessary. It appeared that other approximations discussed below greatly outweigh the effect of variable sensor response on cloud cluster analysis. Moreover, this variation has no effect on the Fourier analysis results because, although it produced variations in the mean brightness from day to day, it did not affect longitudinal brightness changes.

The quality of mesoscale data is also somewhat degraded by nonuniformity of the archived product. Occasionally, quality decreased due to equipment malfunction. Such instances are easily recognized and have been excluded from this study. Nonuniformity is also created where adjacent orbits do not overlap. Fortunately these holes usually are smaller than the one-half degree lattice; but where a grid square did not contain mesoscale data, the grid point was assigned the average value of the four surrounding grid points. Such occurrences were too infrequent to introduce significant error.

The integrity of the data after reduction to the one-half degree lattice concerns the formulation of equation (1). That equation follows the weighting technique of Taylor and Winston (1968), with slight modification to suppress the influence of sunglint. Taylor and Winston eliminated all brightness associated with the darkest subclass *v*. Equation (1) excludes the brightness of both subclass *iv* and *v* because experimentation revealed that this procedure filtered terrestrial reflection and all but the brightest sunglint without appreciably altering the brightness pattern of the cloud features. The experiments also showed that the additional elimination of subclass *iii* did degrade the cluster pattern. The principal reason for acceptance of equation (1) is that it yields a reasonably good representation of the cloud fields visible in the full resolution product (namely, fig. 3).

The most important aspect of reliability concerns the sensitivity of the cloud selection technique. It is quite exact in selecting isolated clusters but is less precise in treating patterns that are reduced to contiguous arrays. Figure 2 illustrates some of these difficulties.

Significant disturbances are selected on basis of size. For example, arrow IV represents retention of a category 4 cluster, while arrow III eliminates a category 3 cluster. But the latter may, in fact, have been the brighter, better organized, more active disturbance. Thus the size criterion might distort the statistics.

Sizes of clusters are determined by the size of a square that is completely cloud covered. Thus the size of real clusters that are elongated or circular will be underestimated. Notice, however, that size has no influence on the spacing statistics.

Spacing of clusters is measured after some clusters have been screened out (step 2 of fig. 2). Because some clusters are excluded if they are contiguous with clusters of the same or larger size, there is a tendency to eliminate some of the smaller separation distances.

In summary, the screening process tends to bias the statistics against small-sized clusters and short separation distances. Although there is no quantitative evidence, the bias does not appear to be serious. In the great majority of cases, the screened clusters correspond to what appear, subjectively, to be the most active disturbances (fig. 3). Because scale size may be slightly overestimated here, perhaps the scales that emerge from this analysis are dependable upper limits. That is, a grid mesh used for numerical analysis or forecasting must resolve disturbances at least as small as those implied by the cluster spacing.

ANALYSIS PROCEDURE FOR CLUSTERS

Presented in unmodified form, cluster population statistics are not easily interpreted. As would be anticipated, the smallest clusters are the most numerous, and the frequency of clusters decreases rapidly with increasing size. To enhance the two-dimensional aspect of the data, the simple frequency distribution has been converted to a new parameter, "relative dominance."

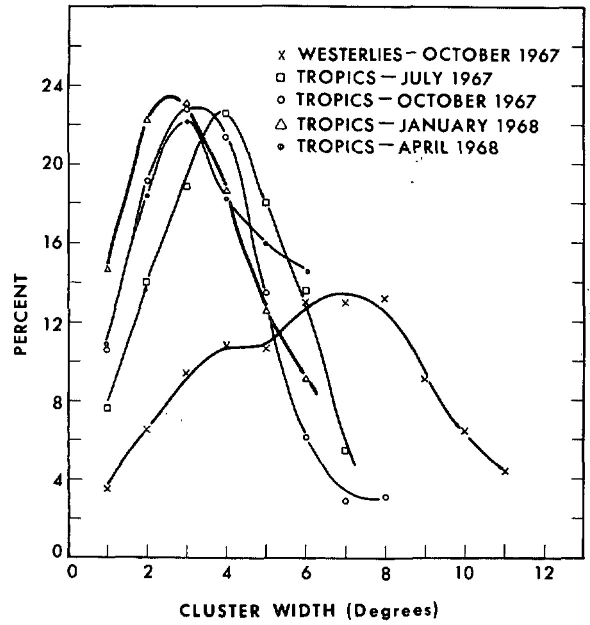


FIGURE 4.—Relative dominance by cluster size, monthly value, and brightest 10° latitude.

Relative dominance, expressed as a percentage, is computed by weighting the frequency of a cluster size by its area and dividing by the total area of all cloud clusters. For example, in a distribution containing a single cluster with a width of 4° and 16 clusters with 1° widths, both cluster sizes have the same relative dominance.

Separation distances for cluster sizes 5×5 (half-degree grid squares) and larger have been compiled in the form of daily frequency distributions with a resolution of 2° of latitude. That is, for clusters at least 5×5, a daily count was made of all separation distances between 0°–2°, 2°–4°, 4°–6°, etc. Spacing increments less than 2° were not used because of the uncertainties implicit in the cluster selection technique. For the same reason, spacing statistics for the smallest arrays (3×3) are not included in the results. In general, the smaller the cluster size, the more likely the occurrence of contiguous clusters. In consequence, the positions of small clusters were less reliable. With the smallest clusters, this uncertainty becomes important; but it did not appear to be significant for larger sizes.

It was mentioned earlier that relative dominance and separation distances were derived for the brightest 10° latitude band and for the entire 30° region. The former is considered to be the ITCZ. The statistics for the two areas are quite similar because the majority of clusters occurred within the 10° ITCZ. For this reason, and also because the ITCZ always occurred at low latitudes and thereby excluded the persistent low stratus cloud off the coast of California, only the ITCZ results are presented below.

FOURIER ANALYSIS OF BRIGHTNESS

In addition to the screening procedure, brightness values (B) were subjected to Fourier analysis. For consistency, this analysis was applied to the ITCZ band. Brightness values were averaged latitudinally over the brightest 10° band selected each day. Fourier analysis was performed on the resulting line of mean brightness values, representing 120° of longitude of the ITCZ.

3. RESULTS

CLUSTER SIZE

Monthly averages of the relative dominance for the ITCZ are presented in figure 4. For comparative purposes, the same parameter is shown for 1 mo for the brightest 10° band included between 30° and 60° N. Three aspects of the figure deserve special attention.

It is readily seen that in all seasons the dominant cluster size in the ITCZ is only half the size of that in higher latitudes. After pursuing the hypothesis that cloud cluster size is related to dynamic scales, this result is relevant to a minimum grid length suitable for the Tropics.

The peak in the relative dominance in the westerlies occurs at a cluster width of approximately 7° of latitude. This corresponds to the average size of cloud shields associated with well-developed cloud vortices generated by the cyclone scale. Systems of this size can be successfully analyzed and forecasted with the 381-km grid spacing presently utilized by the National Meteorological Center. Analogy suggests that the tropical grid distance should be reduced by at least a factor of 2 to resolve the smaller dominant size. Although the analogy may be questioned on grounds that the dynamics of the two regions are quite different, its interpretation agrees with numerical studies. Experimental tropical forecast models indicate that spatial resolution must be greatly reduced in the Tropics (for example, Baumhefner 1968).

Second, figure 4 shows a distinct seasonal variation in the size of the dominant cluster in the ITCZ. In July, the size is largest with a width of approximately 450 km; whereas in January, it is smallest with a width of perhaps 275 km. Sizes for April and October fall between the extremes. The variation is believed to reflect changes in the intensity rather than in the scale of disturbances creating the cloud clusters. This conclusion is suggested by the fact that the separation of cloud clusters (discussed below) shows almost no seasonal dependence.

Finally, the curves of relative dominance are more sharply peaked in the Tropics than in the westerlies. This demonstrates that cluster sizes are less varied in the Tropics, or equivalently, that there exists in each season a size which is distinctly preferred. Whatever the dynamic mechanisms creating an organized cloud system, they appear to be of both small and discrete scale as compared with midlatitudes.

CLUSTER SPACING

Separation distances between clusters were computed (but not shown) for each month separately. There was no significant seasonal variation, so only the 4-mo aggregate appears in figure 5.

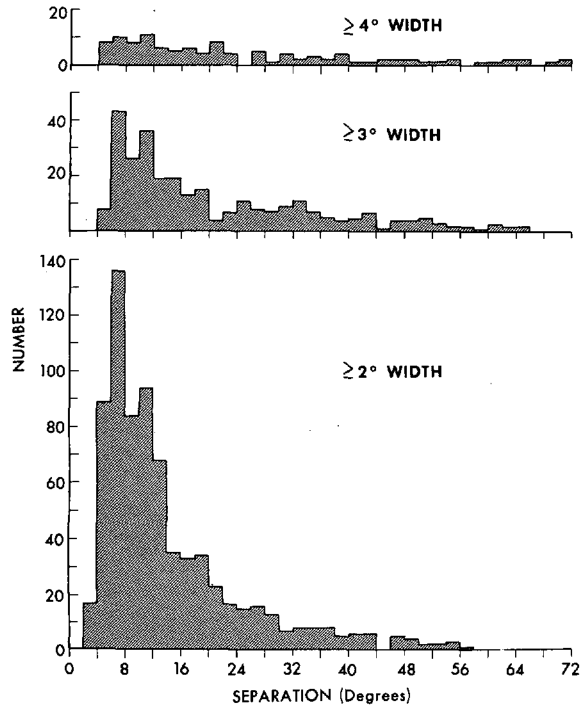


FIGURE 5.—Frequency distributions of cloud cluster separation distances as (bottom to top) smaller clusters are excluded. Distributions are aggregate of 4 mo for the ITCZ.

Frequency of separation distances was derived to examine the relation between cluster size and spacing for sequentially larger categories. First, the spacing was computed for all clusters of 1° and larger; second, the 1° clusters were excluded and the spacing computed for those 2° and larger; and sequentially, 3°, 4°, etc. This sequential process is represented in figure 2, steps 3a through 3d.

Figure 5 presents only the frequency distributions of the second through fourth computations. As discussed above, the first was considered unreliable, and the fifth was disregarded because only a small number of clusters remained after those of 4° and smaller were excluded.

Two separation distances appear to be significant: 6°–8° and 10°–12°. Both distances appear as relative maxima in all three distributions of figure 5. At first glance, the maxima corresponding to the greater spacing might be questioned because it is not prominent. However, it is argued that it is real because it appears in each of the individual month's statistics and because it becomes more prominent as the smaller clusters are excluded.

It is the opinion of the writer that the 10°–12° separation distance corresponds to a principal synoptic scale of the Tropics; whereas the shorter 6°–8° separation corresponds to a faster-moving secondary scale that is enhanced by interaction with the larger scale. The midlatitude analogy to this interpretation is the shortwave feature moving through the large-scale trough-ridge pattern. This interpretation is based on the following argument.

It is apparent from figure 5 that the shorter separation distances tend to be associated with smaller cluster sizes. If clusters of all sizes were similarly distributed, the frequency distribution of separation distances would retain the same shape as smaller clusters are excluded. This is not observed. In particular, the 6°–8° maximum is preferred by the smaller scale clusters.

The inference that the smaller scale is enhanced by the larger primary scale is not so apparent. Subjective evaluation of the brightness fields showed this to be true. The smaller clusters occurred frequently as:

a) groups of clusters or individual clusters in the neighborhood of large clusters,

b) an individual cluster distant from a larger cluster (this condition of no-enhancement was observed only rarely), and

c) groups of clusters distant from a larger cluster.

The latter resulted from large cloud areas that contain holes causing the selection technique to break up the larger area into groups of small clusters. Both a) and c) are interpreted as enhancement of the small scale by the larger scale.

The condition of no-enhancement was observed only rarely. That situation is defined to be the occurrence of small clusters.

Apart from the subjective interpretation, some evidence of enhancement is shown by figure 5. Assuming no enhancement, b) elimination of small clusters would decrease the frequency of short separation distances but would *increase* the frequency of larger separations. For example, the elimination of a small cluster midway between two larger clusters 16° apart would reduce by two the number of 8° separation distances but increase by one the number of 16° separations. Figure 5 does not display that type of change and consequently suggests that enhancement exists.

The characteristics of disturbances revealed by figure 5 suggest that the grid mesh in the Tropics must be finer than that now used for the midlatitudes. This is in accord with the results of cluster size analysis. The NMC Northern Hemisphere analysis grid might barely discriminate the 10°–12° disturbance, but the smaller scale would be lost. There is no a priori reason to suggest that the smaller scale is any less important than the larger.

Figure 6 illustrates the longitudinal distribution of cloud cluster population in the band 15° N. to the Equator. This zone includes the ITCZ band every day. Shading reveals the proportion of large and small clusters. Considering the year as a whole, the clusters are distributed quite uniformly over all longitudes, but there are variations for individual seasons (or months).

The western Pacific contains the greatest number of larger clusters, probably because this area is where most typhoons develop. Not so readily understood is the low frequency of clusters in April or the absence of large clusters from 150° E. to 175° W. in January. Of course the individual months analyzed here may be quite abnormal, so the differences cannot be ascribed to normal seasonal influences.

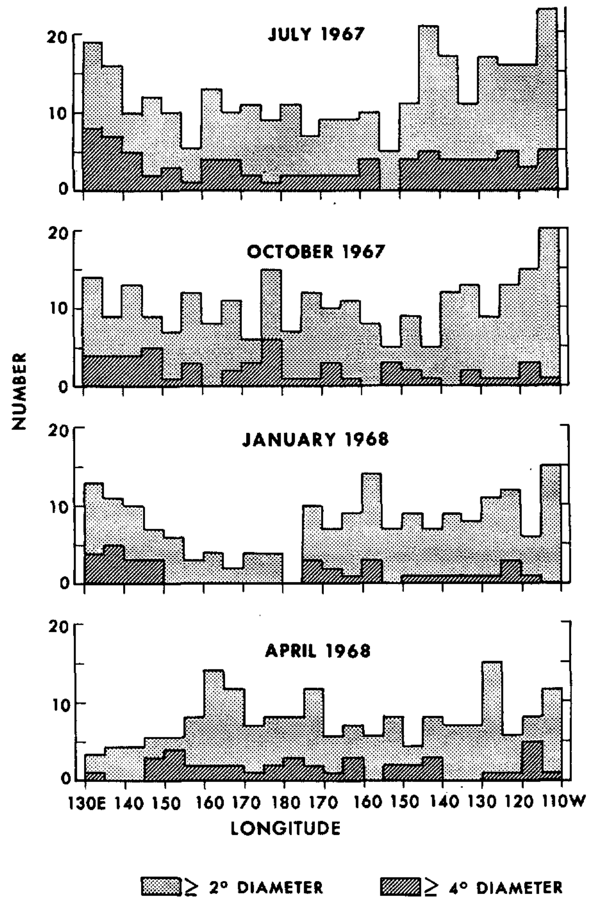


FIGURE 6.—Zonal distribution of cloud clusters by month for the latitude band 0°–15° N.

FOURIER ANALYSIS

Brightness of each ITCZ band was averaged over the 10° latitude width and the longitudinal distribution subjected to Fourier analysis. The results were somewhat disappointing.

A general scale difference is evident between the tropical ITCZ and the brightest 10° band in the westerlies. As would be anticipated, more variance is contained in the smaller scales in the Tropics. This result is shown in table 2 for a 1-mo average of the daily spectra. In neither region, however, did peaks in the daily spectra persist long enough to define a dominant scale for any month.

There is evidence in the tropical data that peaks corresponding to wavelengths 15° to 30° longitude persist for several days. This phenomenon is not observed in the westerly data. Because this interval conforms to a commonly accepted scale of tropical waves in the easterlies, it is tempting to stress its significance. However, careful examination of the cluster-spacing statistics for the same periods gives no support for this scale. In view of this, and recognizing that latitudinal averaging and aliasing both detract from the validity of the spectral analysis, little significance can be attached to the occurrence of these peaks.

TABLE 2.—*Percentage of brightness variance explained by small, medium, and large scales in maximum cloud zones of Tropics and midlatitudes, October 1967*

Wavelength	Explained variance	
	Tropics	Midlatitudes
(km)	*(percent)*	*(percent)*
>3000	56	65
1000–3000	36	28
<1000	8	7

4. SUMMARY

The objective screening technique devised for this investigation of cloud clusters in the Pacific ITCZ shows that the dominant cluster widths range from 275 to 450 km, with larger sizes favored in the summer. Distances separating those cloud clusters do not show seasonal variation. Cluster spacing has two preferred maxima, 6°–8° and 10°–12° latitude. The larger separation becomes more significant as smaller cloud clusters are excluded. This has been interpreted as evidence that the two scales are discrete. The smaller separation and cluster size may represent a secondary scale that is enhanced by the larger scale.

What is most disturbing is that even the larger scale is rather small in terms of extratropical synoptic scales. If, as seems probable, resolution of this order is required for realistic numerical analysis and forecast procedures in the Tropics, both data networks and grid lattices will require twice the resolution presently employed in midlatitudes.

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