On the origin of certain symmetrical patterns of atmospheric convection[1]

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In a recent issue of this journal KRUEGER & FRITZ (1961) have presented a group of extremely interesting photographs obtained by the meteorological satellite TIROS I that show cumulus clouds arranged in remarkably uniform rings surrounding symmetrically distributed clear areas, thirty to fifty miles in diameter. Although, as these authors point out, the details of such large patterns cannot be recognized by observation from the earth's surface, some form of ordered periods of clear and cloudy skies over subtropical, oceanic locations has been detected in the past. High altitude photographs, among which the TIROS satellites have provided the most spectacular examples, indicate that these cycles result from the passage overhead of one of several organized convective systems. With the additional regime detected by TIROS I, these fields appear to include three mesoscale types: (1) cloud groups, (2) cloud bands, and (3) cloud rings.

Krueger and Fritz note that, although the regular appearance of the cloud ring pattern suggests an origin related to the "Benard" cellular mode of convective circulation, this comparison raises certain problems. For one, the diameters of the rings relative to their vertical dimensions exceed the same measure in Benard cells by an order of magnitude or more. For another, the rings are evidently not simple circulations, since their walls are seen to consist of many individual cumulus elements. Interestingly enough, these same characteristics of overall symmetry, relatively large horizontal scale, and fine interior structure apply to the grouped and banded convective regimes as well. The current note points out that such features need not be considered incompatible with the cellular hypothesis, since they can be interpreted as evidence that these patterns are generated by multiple-mode, "beat-frequency" mechanisms of a kind set forth in these pages some years ago as a tentative explanation of regularly spaced cloud groups (NAKAGAWA & FRENZEN, 1955).

In that earlier discussion it was suggested that a two-dimensional pattern of alternately reinforced and damped convection could occur, since a linearized theory for the laminar model had indicated that the presence of a basic rotation made it possible for a system to simultaneously attain the minimum conditions of instability necessary to excite both the ordinary and the "overstable"[2] convective modes. Because these two cellular fields have slightly different wave lengths, their superposition could be expected to generate the first type of organized convection, groups of cloud arranged in a larger scale version of the regular hexagonal tessellation characteristic of either cellular component alone. As shown schematically in Fig. 1, cumulus would form in roughly hexagonal groups centered near the vertices of equilateral triangles whose sides equal the least common multiple of the two fundamental component wave lengths. Within each group the tallest clouds occur in the central regions of maximum reinforcement, i.e., in the areas where the rising cores of the superposed cells would most nearly coincide. Surrounding these, the cumulus activity tapers off to the intervening clear space located where the two

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[2] An oscillating form of cellular convection predicted theoretically (CHANDRASEKHAR, 1953) and observed in the laboratory (FULTZ, NAKAGAWA & FRENZEN, 1954) but not as yet found in the atmosphere; more recently, these circulations have been shown to be elastoid-inertial oscillations (FULTZ, 1959).

cellular modes are least in phase. Recently cloud groups of this general configuration have been observed off Florida on days when the cumulus did not initially appear in rows (evidently because of insufficient vertical wind shear). They were described as "... large bunches, with the taller, more closely spaced clouds being in the central area" (PLANK, 1960). Unfortunately no comment on the arrangement of groups relative to one another was given, this detail perhaps being obscured by the large size of the groups and the fact that observations were made from only moderate altitudes.

The combined effects of stability, available moisture, and relative component amplitude could alter cloud distributions of this first type to patterns of semi-regular tesselation. Under conditions favorable to cumulus convection, adjacent cloud groups could grow to such large sizes that they would meet at their vertices in the manner shown by the shaded portions of Fig. 2. Clear areas would then be restricted to the relatively small triangular regions of maximum interference that remain between the cloud-filled hexagons. After further growth, clouds generated by one mode could attain a complete overcast with only a regular modulation of cloud top height revealing the presence of a second, longer wave component. On the other hand, in circumstances less favorable to cloud formation, cumulus might only occur in the small, widely separated hexagonal regions of maximum reinforcement.

Organized convective fields of the banded type also exhibit features indicating the presence of superposed circulation modes, one of which very probably has a modified cellular origin. The large scale spiral bands first observed in hurricanes with the aid of radar and now known from satellite photographs to frequently extend for great distances over the oceans around extratropical storms as well, often show a fine scale interior structure of cumulus rows (FRITZ & WEXLER, 1960; WINSTON, 1960). In addition, radar reveals the presence of lines of more active precipitation cells that progress through the larger systems. This can readily be attributed to progression on the part of the regions of maximum reinforcement resulting from shifts in the phase of one fundamental component relative to the other.

When the vertical shear of the horizontal wind is sufficiently strong, fields of ordinary convection cells undergo conversion to parallel rolls, a mode of convection frequently observed in the atmosphere in the form of lines of cumulus lying parallel to the low level wind. Indeed, the suggestion that these "cloud streets" are involved in the formation of spiral convection bands dates from one of the latter system's earliest descriptions (WEXLER, 1947). But since rotation around each cell's vertical axis is necessary to the elastoid-inertial mechanism, similar vertical wind shear would be expected to destroy the overstable mode. A second component capable of combining with cumulus streets to produce the mesoscale bands requires a different origin.

One such mode has been shown by TEPPER (1958) in a theoretical hurricane model. His analysis contained circular gravity waves, which, while being propagated outward from the center of a developing storm, were modified into spirals by the forward movement of the system and structural inhomogeneities in the vortex. Combining this component with the roll convective mode, a pattern obtains in which lines of cumulus circulating around the storm in the low level flow are periodically damped and intensified as they pass through slowly expanding convergence zones associated with the gravity waves (cf. TEPPER, Fig. 1). When convection is so intense as to never be completely suppressed, the resultant spiral bands can be seen only on radar as zones of increased activity; with less instability, clear spaces appearing in the regions of divergence between the waves make the bands clearly visible. This model, however adequate it may be to band systems in the vicinity of active cyclonic centers, is less appropriate to those systems observed to extend long distances, because of attenuation of the gravity wave component. Evidently a supplementary modulating influence upon the cloud streets comes to the fore, perhaps, for example, one involving the horizontal wind shear.

At first thought the cloud rings listed here as a separate regime of organized convection might seem only special forms of a bi-cellular cloud group pattern of the first type. But in order to completely surround clear spaces, a semi-regularly tessellated distribution of this kind would have to occupy more than seven-tenths of the sky (Fig. 2), a greater cloud cover than the TIROS photographs show (cf. KREUGER & FRITZ, Figs. 1 and 2). Furthermore, secluded

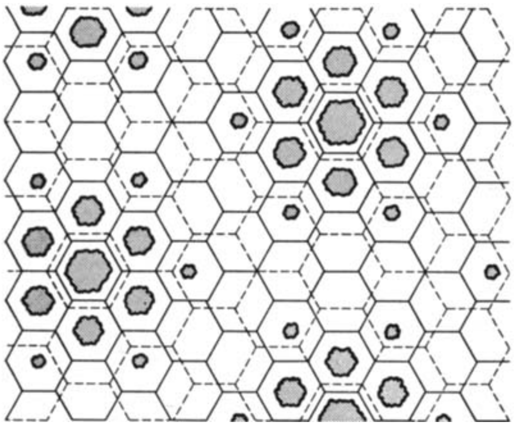

FIG. 1. Schematic representation of a "beat-frequency" pattern of cloud groups created by the superposition of two cellular fields of slightly different wave length. Lines depict descending walls of hexagonal cells; largest clouds are shown where their rising central cores coincide.

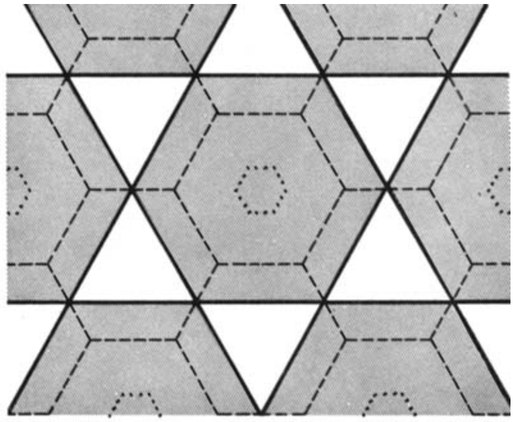

FIG. 2. Schematic representation of a semi-regularly tessellated distribution of cloud groups which have grown until they meet. Dotted central hexagons designate regions of maximum reinforcement where the last remaining cumulus can form during unfavorable convection conditions.

cloud-free areas produced in this manner should more nearly resemble triangles than do the near-circles observed. It is more likely that these unusual cloud ring patterns are symptomatic of a unique combination of meteorological circumstances all their own.

Conditions in the lower troposphere during cloud ring situations are evidently similar to those associated with regimes of the first type in that they favor the formation of quasi-steady fields of regular convection cells. In four cases described by Krueger and Fritz, uniform heating from below was always available as was shown by the air-sea temperature differences. Further, the low level wind shears were markedly reduced, this precluding the conversion of cells to rolls. Hence, one component of ring convective systems is probably a cellular mode, its relatively high wave number corresponding to the observed distribution of individual cumuli within the ring walls.

On the other hand, upper tropospheric conditions during cloud ring occurrences appear to be unlike those prevailing in either cloud group or cloud band regimes, for the rings are evidently associated with broad regions of increased subsidence aloft. This suggests that some form of interaction between the subsiding upper currents and the convective layer beneath the inversion might periodically suppress cumulus formation in such a way that the observed circular clear spaces result. For example, if subsidence were to occur in the form of symmetrical distributions of relatively more intense downdrafts surrounded by slower descent, then the inversion would be selectively intensified in a manner that could produce a pattern of relatively warmer regions distributed over the top of the convective layer below. When there exists only just sufficient heating to maintain convection (a marginal condition incidentally favorable to the preservation of a cellular field in a quasi-steady state), such relative heat sources aloft would create clear spaces by their thermally stabilizing influence. Thus, a tessellated pattern of intensified subsidence above the inversion could be duplicated by a pattern of circular holes in the cloud cover below. In a somewhat similar mechanism given consideration by KRUEGER & FRITZ (personal correspondence), the clear spaces were conceived to form as the result of periodic mixing of drier upper air downward through the inversion.

Each of the foregoing suggestions implies the existence of a symmetrical pattern of intensity modulation in the subsidence inversion, the one postulating local degenerations sufficient to allow dry upper air to periodically penetrate to the layers below, while the other requires local intensifications that result in a distribution of relative heat sources atop the convective layer. Unfortunately, questions as to the existence and nature of these hypothetical mesoscale inversion variations cannot be resolved with the available information; data of higher resolution are required. Adequate coverage might be obtained if reconnaissance aircraft were to make a number of closely spaced, abbreviated drop-soundings through inversions over cloud-ring systems located by satellite observations.

As meteorologists are aware, once even a simplified model of a complex natural phenomenon has been discovered, significant gains are achieved in both the theoretical understanding of the prototype and in the practical interpretation of sparse data relative to its occurrence. In the era of satellite meteorology now begun, models for mesoscale convective systems will not only facilitate the rapid interpretation of cloud photographs, but they will also enable the full potential of these graphic data to be realized by making it possible for the meteorological conditions each observed system infers to be accurately incorporated into the reports of the existing synoptic network. This note has sought to indicate one direction in which the search for these models might proceed.

Two additional articles concerning symmetrical mesoscale convective systems have recently appeared in the literature. L. F. WHITNEY (1961) describes the generation of cloud band regimes by a process evidently similar to the bimodal mechanism listed above, namely through "the enhancement of some cloud streets and suppression of others". He shows a TIROS I photograph of one such system as an example and cites several earlier reports of similarly distributed cloud-street patterns. In another paper, C. H. B. PRIESTLEY (1962) contributes an hypothesis concerning the origin of the third type of organized convection, cloud rings. He suggests that, provided the rings can be assumed to indicate the presence of a single Benard cellular mode that penetrates the inversion from below, then the exaggerated horizontal scale can be attributed to the reduction of the vertical component of eddy diffusion in the stable air aloft. However, such a single modal mechanism does not account for the observed fine scale cumulus structure within the ring walls.

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