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Cloud Patterns over Tropical Oceans

Tropical clouds are arranged into characteristic "fingerprints" of the weather systems producing them.

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Tropical clouds are vital links in the radiation and water budgets of the planet, and they play an active role in maintaining wind systems, both locally and far away. But meteorologists have had surprisingly few opportunities to study low-latitude cloud sequences in their proper context of winds and other necessary meteorological measurements. A colleague and I found such an opportunity in the summer of 1957 when, hitching rides on regular Military Air Transport Service planes, we covered thousands of nautical miles above the Pacific, with moving-picture camera continuously operating. Later, with other colleagues, we made detailed analyses of the cloud systems recorded on the film and constructed cloud maps for the regions where the formations were of particular interest. These maps and what they reveal are the main subject of this article.

But before we look at them in detail, let us consider the general relationship of the distribution and structure of cumulus clouds to broad-scale features of the atmosphere in the tropics. Tropical circulations play a vital role in the atmospheric heat engine, whose main fuel is evaporated sea water obtained from the low-latitude oceans. Between latitudes 10 and 25 degrees in both the northern and the southern hemispheres, small unspectacular "trade cumuli" pump up the evaporated sea water and use some of it to drive the steady easterly trade winds in which they are embedded (*1*). Most of the fuel is not utilized here, however, but is shipped equatorward, still in the form of vapor. In a narrow equatorial zone, a few thousand giant cumulonimbus towers perform the main "firebox" function of the heat engine—that is, they recondense the vapor into liquid drops and lift the released heat to the high troposphere, ready for export aloft to great distances (*2*). Similar huge towers are essential in the operation of the destructive hurricane (*3*).

Attempts have been made to construct theoretical and numerical models of the mechanism by which an individual cumulus cloud develops and maintains its buoyant, moist updraft (see, for example, *4*). Specially calibrated research aircraft have been equipped with instruments to penetrate clouds in an effort to determine what physical processes are important. A severe obstacle in constructing a model is the interaction of the cumulus clouds with other motions of the atmosphere, both smaller and larger in scale. Observational studies are showing that wind systems on the mesoscale (10 to 100 km in horizontal dimension) and the synoptic scale (100 to 1000 km in horizontal dimension) control cloud formations and regulate their shape, size, and degree of development. Such interactions keep cumuli puny and stunted on most occasions, but under rare but important flow conditions the brakes are released. Then giant towers grow and penetrate the atmosphere to altitudes of 50,000 feet (15,000 m) and more—that is, into the tropopause region. Greater knowledge of the way in which the large-scale atmospheric conditions affect measurable cloud parameters is a prerequisite for modeling the mechanism of development.

It was in search of data illuminating these relationships that my colleagues and I made our photographic survey of the tropical North Pacific in 1957. Claude Ronne, an expert photographer, covered 15,000 nautical miles (27,800 km) along the routes shown in Fig. 1. I accompanied him on the last circuit (Fig. 1, bottom). Meanwhile, Herbert Riehl and his colleague William Gray collated the routine meteorological observations from all island and ship stations near the flight routes. They constructed streamline, pressure, and moisture charts for numerous levels from the surface to the tropopause and analyzed the vertical soundings of wind, temperature, and humidity. The main limitation of our study lay in the sparsity and poor resolution of these meteorological data. (A similar inadequacy of data is obstructing the interpretation of photographs taken from satellites.)

Ronne took his pictures on 16-millimeter Kodachrome film, with time lapse of exactly one frame per second. He aimed his camera straight out from the side of the plane, at right angles to the fuselage. Altogether, he obtained 8000 feet (2400 m) of good film. Its uses were threefold. First, it was projected slowly, and the cloud forms were interpreted in their flow-pattern context. Second, prints were made from the film at 15-minute intervals of flying time, and these were laid out in a strip along the flight path. A special "whole sky code" of 15 num-

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bers was devised to categorize them (*5*). Finally, the detailed cloud maps were made for many regions of special interest.

Overall Results

Most striking of the overall results was the high degree of cloud organization; this was observed on an ascending hierarchy of scales. On the small end, we found individual cumuli commonly lined up in rows, which occasionally intersected one another to make criss-cross patterns and checkerboards. More rarely the cumuli arranged themselves into "fairy rings," *y*'s, or polygons.

On the mesoscale these patterns were, in turn, arranged into "regimes," which often showed abrupt transitions or terminated as if cut off by a knife. The larger-scale planetary flows controlled the formation of these regimes and their succession in space and time.

In particular, penetrative giant towers and rainfall occurred only within so-called "disturbances." These are wave-like or vortical wind patterns, a few hundred kilometers across, which in the tropics occur at either low or high atmospheric levels. In "storm" situations they extend vertically throughout the troposphere. The circulations favorable to the building up of cloud towers are characterized by inflowing air at low levels and by outflow aloft; how this convergent-divergent flow facilitates the growth of cumuli is not yet fully clear, nor can it as yet be represented in quantitative models.

Within these areas of inflowing air, the high towers were further concentrated into characteristic patterns. The patterns have been classified, and from this classification, species of disturbances and of individual storms within these species can be recognized (*6*). The classifications may be used to determine the nature and intensity of a storm, and perhaps someday they may also be used to predict its future development.

The most common and most readily described type of cloud organization found in the photographs was the long row of cumuli. These rows were frequently from 80 to more than 160 kilometers long, and they appeared on 70 percent of our 308 prints. We used a simplified version of our cloud-mapping method, which is described later, to determine the direction of the rows in every 15-minute interval of film in which rows were observed. The results were plotted as arrows on the maps of streamline flow for low atmospheric levels as a means of comparing cloud lineup with wind direction. It is obviously impossible to determine, from the film, on which end of the arrow the head should be placed; this must be decided from wind data or other information.

An example is shown in Fig. 2. Here the aircraft, flying westward from Hawaii toward the Marshall Islands, passed from an undisturbed trade-wind regime through an "easterly wave." The low-pressure trough is denoted by the solid line. An easterly wave is a famous type of wavelike wind deformation that occurs in the lower half of the tropical troposphere. It exhibits convergent flow and active convection to its rear (to the east), whereas divergence and fine weather on its west side herald its arrival from the east. From 5 to 10 percent of these waves develop a closed central vortex, and about 1 percent may deepen to hurricane intensity.

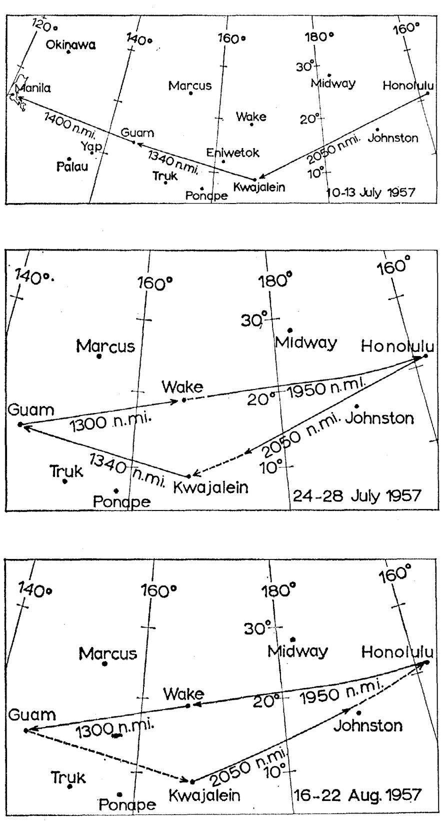


Fig. 1. Tracks flown in the Pacific during the summer of 1957. Dates are given according to Universal Time. Dashed lines indicate portions of the tracks flown in darkness.

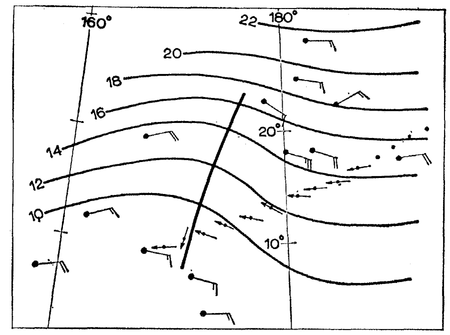


Fig. 2. Low-level winds [a half barb represents 5 knots (2½ m/sec)] and isobars (in millibars above 1000 mb), 10–11 July 1957. Solid near-vertical line is the easterly wave trough; arrows show orientation of cloud rows [indicated direction of arrowheads is arbitrary (see text)].

Figure 2 shows that almost everywhere the cloud rows (shown by the arrows) were lined up nearly along the direction of the wind, except just west of the trough, where the arrow is probably much more north-south than the airflow could have been. Figure 2 is typical of our findings. The cloud rows were nearly always parallel to the direction of the lower winds, but a sufficient number of exceptions occurred to show that simple wind direction was not the governing factor. From a practical standpoint, these exceptions were, unfortunately, just common enough to render cloud rows an unreliable indicator of wind direction.

Clues from Cloud Maps

To unravel the mystery of orientation, cloud mapping proved essential. The map for the easterly wave of Fig. 2 is shown in Fig. 3, along with two frames from the motion-picture film taken near the wave trough.

The first question is, How do we go from the pictures, in which the clouds are seen from the side as the aircraft flies by at an altitude of 8000 feet (2440 m), to the map, which presents these same clouds in plan form, as if we were looking down on them from above? In this case the procedure was simple and schematic. We determined the orientation, extent, and lateral spacing of the rows of cumuli and the horizontal distances along the rows between the bunches of much taller clouds. These rows and bunches were then plotted on the map in the proper positions relative to the path of the aircraft.

The positions, within these rows, of the individual clouds were determined by counting the frames. The film was projected on a gridded screen at a distance from the projector which gave a prearranged magnification of the image.

Since the lens angle and speed of the aircraft are known, determination of the distance from a cloud feature to the camera depends only upon finding how many frames are required for the image to cross a grid interval. The speed of the aircraft was reported once an hour by the MATS crew, whose navigation was so accurate that estimated arrival times were rarely in error by as much as 2 minutes. Distances on our maps could be shown to be correct to within ± 5 percent.

The cloud pattern of Fig. 3*a*, with notable bending of the cloud rows across the trough line, turned out to be characteristic of the classical easterly wave (*7*). The lateral spacing of the rows was found to widen as the trough was approached from the east. It was about 4 kilometers in the area of undisturbed trade winds and in the outskirts of the wave, increasing to 25 kilometers just east of the trough and to 30 kilometers just west of it. In general, we found that the spacing of the rows increased in proportion to the vertical thickness of the clouds.

From about 150 nautical miles (280 km) east of the wave to the trough itself, a marked cross-wind organization was apparent, superimposed upon the parallel lines. That is to say, groups of extra-large clouds appeared along the lines at about 80-kilometer intervals, while intervening cloud segments were so small that the spaces were nearly clear. This gave the impression of large cloud groups lined up almost at right angles to the direction of the flow. These groups are shown schematically in Fig. 3*a* as a single large cloud. Within each group, individual clouds retain their organization parallel to the direction of the flow. The bending just west of the trough may be a manifestation of the cross-wind mode alone, but because data on the wind for that area were lacking, this is not possible to determine.

Since we suspected that the cross-wind lineup might contain the vital clue to the orientation problem, we studied it avidly by mapping every region where such a lineup was suggested on the film. The map and pictures of Fig.

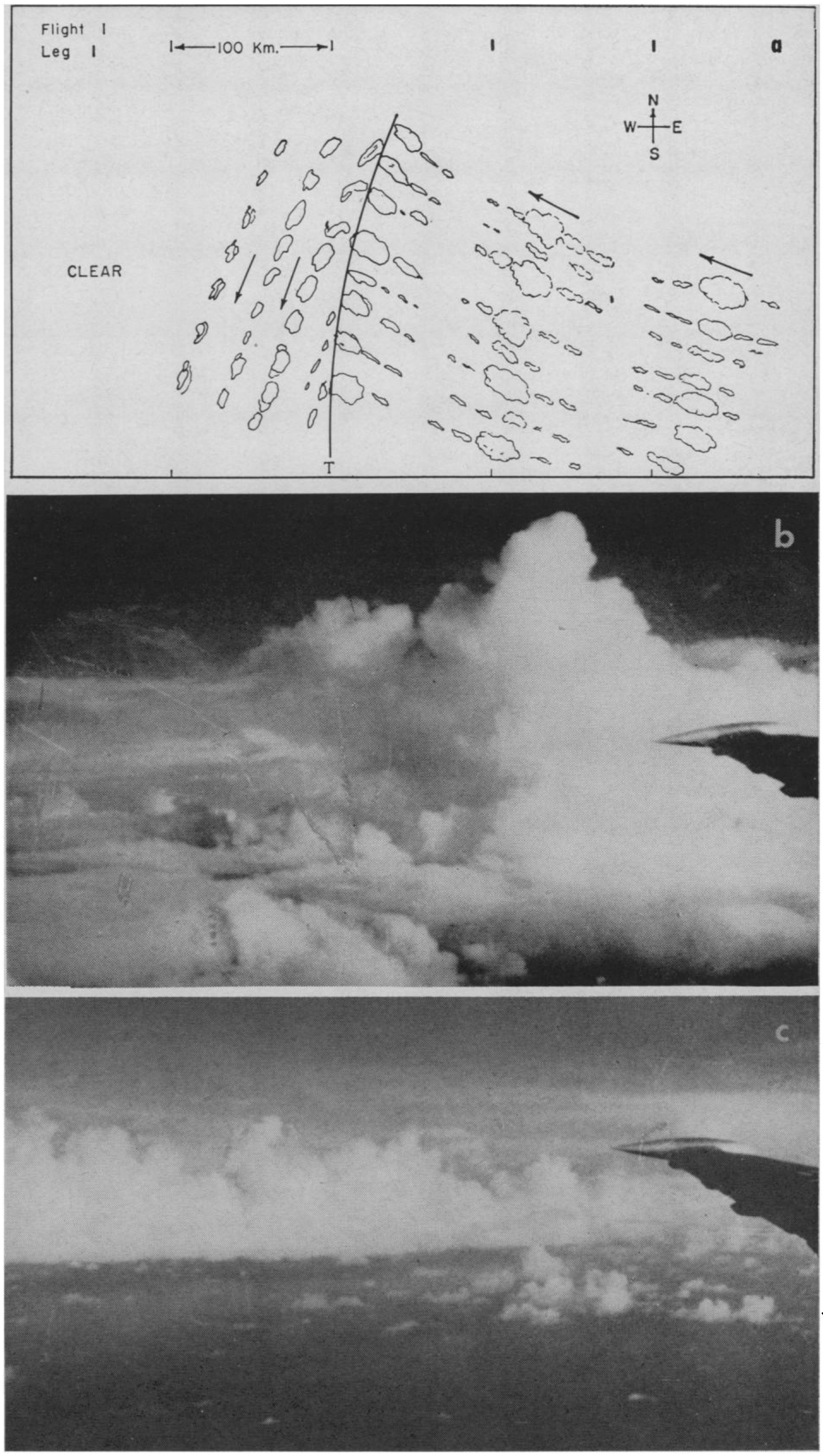


Fig. 3. Cloud map and selected moving-picture frames for the easterly wave of Fig. 2. *a*, Schematic map of cumulus clouds near the wave trough (solid line). The orientation of the cloud rows and the spacing between them was measured exactly from the film, as was the distance between the groups of larger clouds, shown schematically as single large clouds. Individual clouds have not been entered or drawn to scale. *b*, Frame from the film taken just east of the wave trough in the zone of active convection. The camera was aimed south; flight level, 8000 feet (2440 m). *c*, Frame from the film taken just west of the wave trough, showing the first cloud row to the west of the wave trough.

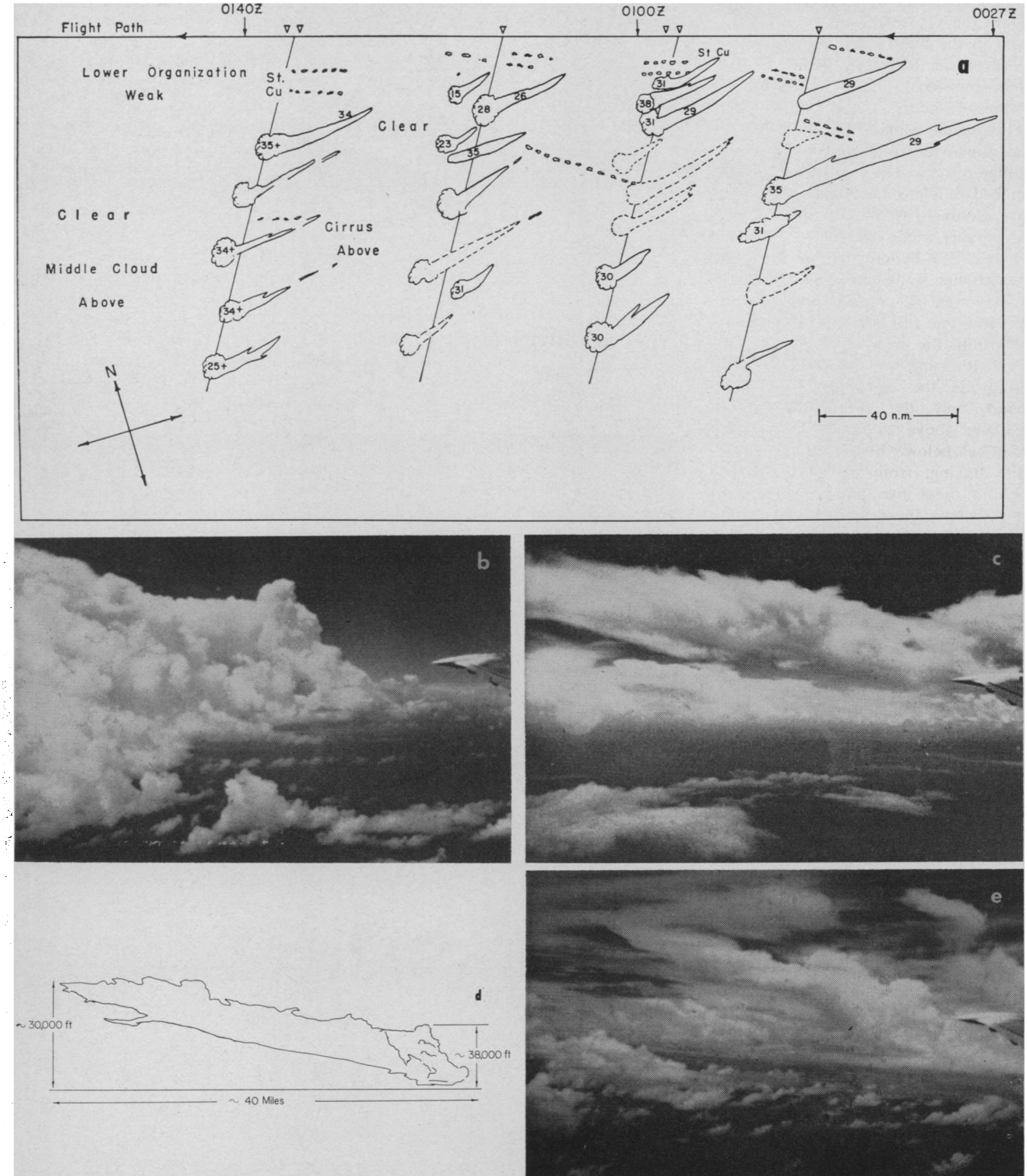


Fig. 4. Cloud map and photographs illustrating the cross-wind mode of lineup, 25–26 July 1957. *a*, Cloud map constructed from the film. All the large clouds [tops higher than 25,000 feet (7600 m)] are entered to scale. Solid outlines are clouds for which four or five points were plotted; dashed outlines, clouds for which at least one point was plotted. The carrot-shaped extensions are anvils. Numbers denote heights of the cloud tops in thousands of feet; the plus signs signify actively rising towers. The length of nearly all the rows of small cumuli is entered to the correct scale. Times are in Universal Time. Triangles denote showers. *b*, Western side of the cross-wind row second from the right, showing the highest tower [about 38,000 ft (11,500 m)] and small parallel rows of cumuli. *c*, Eastern side of the same cross-wind row, showing elongated carrot-shaped anvils and nearly clear seas below, with a few shelves of stratus. *d*, Composite tracing from several frames showing the tallest cloud in the second row from the east in Fig. 4*a* (photographs in Fig. 4*b* and *c*). The height scale expands to the left as the anvil slants toward the camera. *e*, Frame showing the nearest cloud in the westernmost row.

4 are a spectacular example, which contain the key to the puzzle. In Fig. 4 and in the figures that follow, times are given in Universal Time, which differs from local time in the flight area by about 12 hours.

This regime contained four, and only four, cross-wind rows of strongly slanting high towers. The tops of the towers stretched out into carrot-shaped anvils, some as much as 64 kilometers long. The parallel mode, nearly suppressed, was exhibited by only a few lines of small, stunted trade cumuli. Most striking here was the contrast between the west and the east sides of the cross-wind rows; the west side was like an abrupt, towering wall of icebergs (Fig. 4*b*), while the east side (Fig. 4*c*) showed only the sheared-off anvils streaming above a tunnel-like, nearly vacant sea below. Figure 4*d* is a composite tracing, from the film, of the cloud in these two photographs, and Fig. 4*e* shows the nearest cloud in the westernmost row.

Figure 4*a* is much more detailed than Fig. 3*a*. In the former, every large cloud has been entered to scale, and all the lines of small clouds are included; the only schematization is the omission of a few shelves of stratus (see Fig. 4*c*). Several points were plotted for each cloud drawn with solid lines, and at least one point was plotted for each cloud drawn with dashed lines.

The cloud heights (the numerals represent thousands of feet) were calculated, by trigonometry, from the distance of the image above the apparent horizon and from the previously determined distance of the cloud from the aircraft. A correction then had to be made for the earth's curvature, for the elevation of the aircraft, and for atmospheric refraction. The values for cloud tops may be in error by ± 2000 feet (600 m) for tall towers and by ± 10 percent for towers less than 10,000 feet (3000 m) high. Fortunately, a check of the value for the height could often be obtained by measuring the thickness of the cloud from base to top, since the bases of tropical cumulus clouds are almost always about 600 meters above the surface of the ocean (in extreme cases there may be a deviation of ± 300 m).

In Fig. 4*a*, the plus signs on some clouds denote growing towers. Clouds in the row farthest to the west were rising at a rate of 6 to 12 meters per second, while clouds in the easternmost row were mainly left-over anvils with dying cloud bodies below. This suggests that the whole pattern propagates by the growth of new rows on the forward edge and the death of the rearward rows. Thus, a disturbance can retain its cloud "fingerprint" despite hundreds of kilometers of travel, as we found in a similar study of an Atlantic hurricane (*6*).

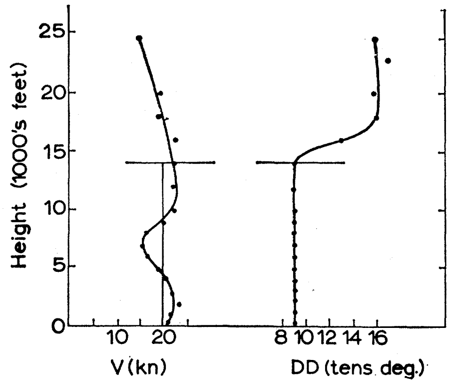


Fig. 5. Vertical distribution of wind speed and direction at Eniwetok, 26 July 1957, at 0000 hours. The horizontal lines mark the top of the trade wind layer. Eniwetok (see Fig. 1), in the Marshall Islands, is on the flight track near the cloud formations of Fig. 4.

In Fig. 4*a* we see three modes or directions of organization: (i) the parallel mode exhibited by the small cumuli; (ii) the cross-wind mode, this time at an angle of 75 degrees to the parallel; and (iii) the carrot-like anvils stretched out nearly due eastward.

The wind profile of Fig. 5 provided the hoped-for breakthrough in our effort to understand orientation. The wind speed remains nearly constant in the vertical, but the direction changes abruptly within a shallow layer just above 15,000 feet (4575 m), from nearly due east to southeast, with a shear vector (vertical difference) from south-southeast or just along the large-cloud rows. The anvils are stretched out along the shear vector between the level of the anvils (not shown in Fig. 5) and the wind in the lower cloud layer, where the air of the anvils originates (*8*). Thus, their direction can be simply explained as analogous to the direction of a smoke plume from the stack of a moving steamship. The orientation of the cross-wind mode requires a more sophisticated explanation. We postulate that it is governed by an upper shear imposed upon the convective layer; this hypothesis can be tested by reference to our other cloud maps and to results in the existing scientific literature.

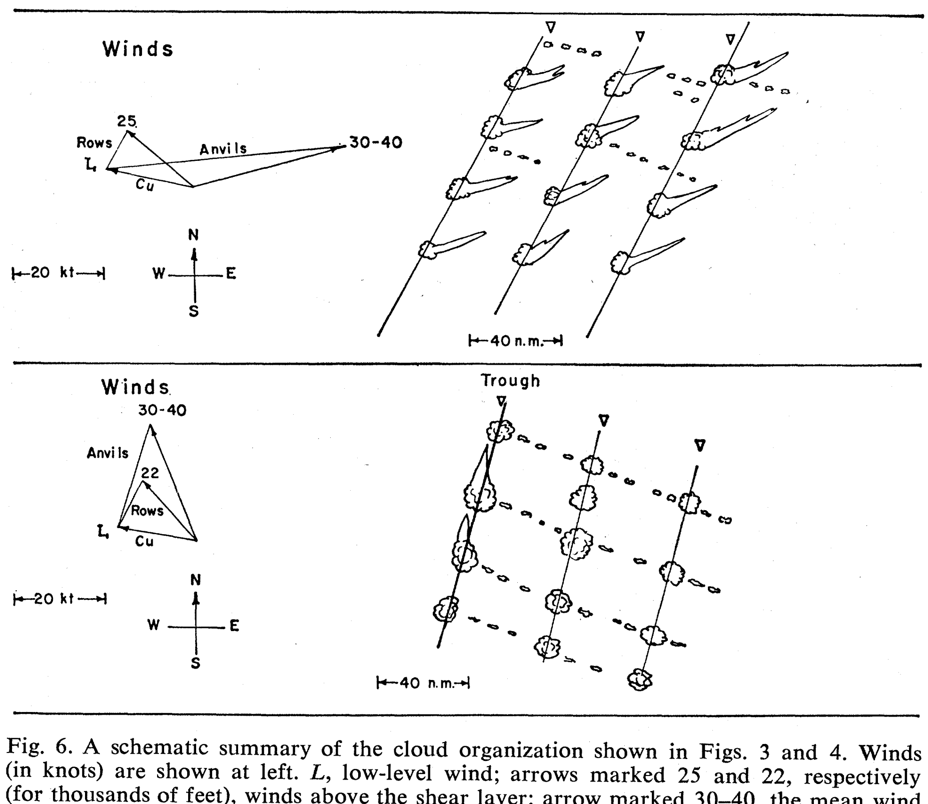


Fig. 6. A schematic summary of the cloud organization shown in Figs. 3 and 4. Winds (in knots) are shown at left. *L*, low-level wind; arrows marked 25 and 22, respectively (for thousands of feet), winds above the shear layer; arrow marked 30–40, the mean wind for the 30,000- to 40,000-foot layer, or anvil region. Note that cumuli (*cu*) line up in the direction of the low-level wind; the cross-wind rows line up along the shear vector between the low-level wind and the wind above the shear layer; anvils line up along the shear vector between the low-level wind and the wind at anvil level.

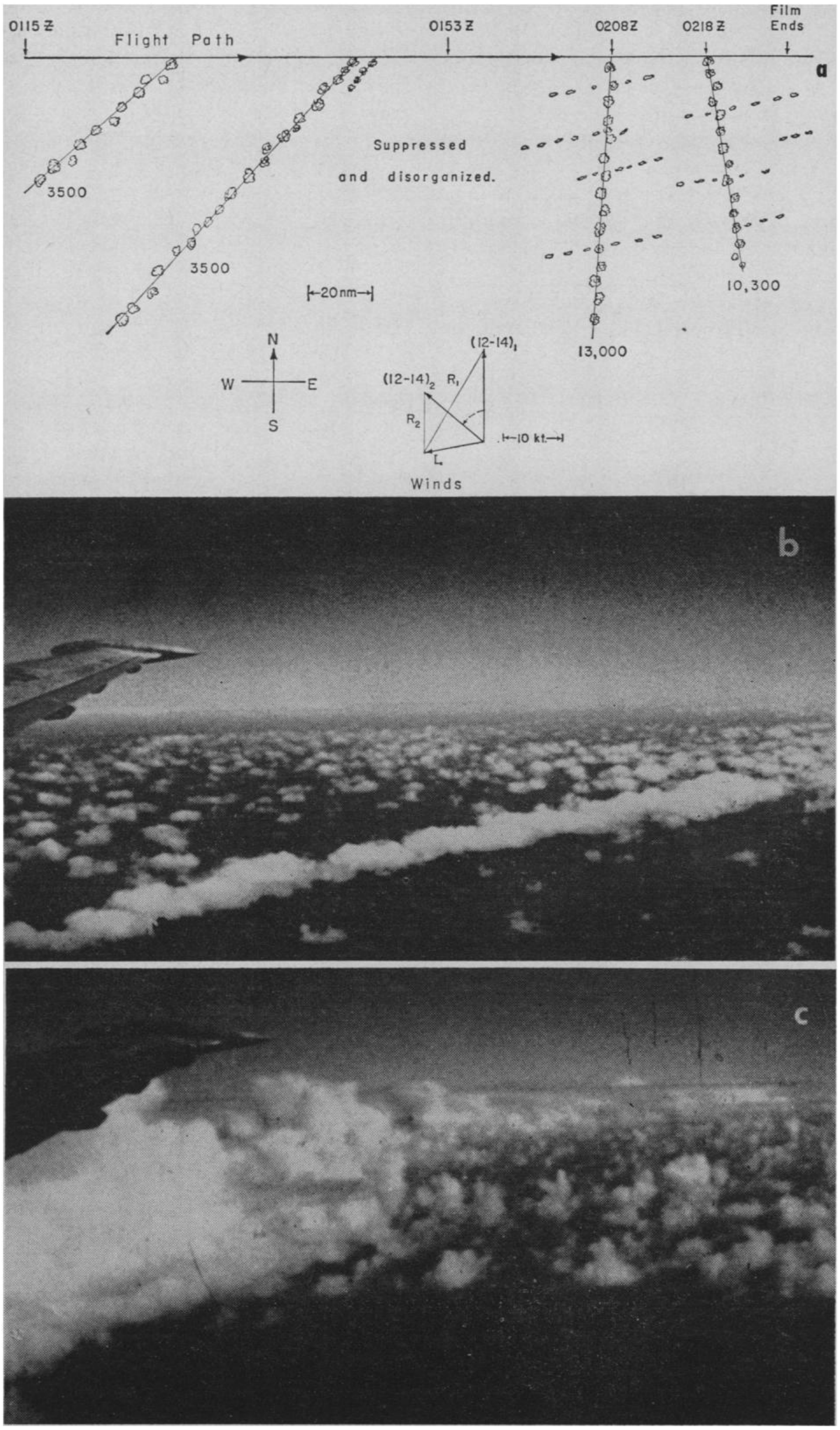


Fig. 7. Map and photographs illustrating the rotation of cross-wind rows in correspondence with the shear vector, 27–28 July 1957. *a*, Schematic cloud map, with many small cumuli omitted (see *b* and *c*). The lines represent the cross-wind mode; note the re-entry of the parallel mode as the right edge of the map is approached. Winds (in knots) are indicated at lower center. *L*, low-level wind; arrows marked 12–14 (for thousands of feet), winds above the shear layer. Subscript 1 denotes left side of map; subscript 2, right side. The corresponding shear vectors are denoted by R_1 and R_2, respectively. Note the corresponding rotation of the cross-wind mode. The numbers on the rows indicate average cloud heights (in feet). *b*, Photograph of the first cross-wind row (row at high angle to wind and flight path) encountered, near the left edge of the map. *c*, The next-to-last cross-wind row (0208 hours); its swing to a 90-degree angle to the flight path is obvious. One can also see the re-entry of the parallel mode exhibited in the smaller cumuli.

Interpretation of the Cross-Wind Mode

The suggested relationship of tower lineup and vertical wind shear led to comparison of our ocean cloud patterns with some beautiful experimental work by Avsec (*9*). He had made quantitative laboratory studies of the convective regimes in fluids heated from below, either initially at rest or in laminar motion in a channel. In the former case, Avsec had investigated the delightful polygonal regimes of Bénard (*10*); in the latter case, the convection took the form of long rolls. These were cells elongated infinitely in the direction of the shear between the channel bottom and the fluid motion—that is, parallel to the flow itself. The rolls consisted of long lines of alternate up and down motions, so the fluid particles moved downstream in a helical path; the lateral spacing between updrafts was proportional to, and about the same as, the depth of the convective layer.

In extending Avsec's results to the atmosphere, we must use caution. Among other complications, the atmosphere is fully turbulent—that is, many scales of motion are excited and interacting. In the laboratory study, on the other hand, the flow is laminar, with a single mode of circulation smoothly proceeding. The needed bridge is, however, built by some recent theoretical work on turbulent convection by W. Malkus (*11*). He showed that even when flow is fully turbulent, the mode of convection that is excited when the flow is laminar (as in the Avsec experiment) would still contain the most energy and predominate over its competitors.

In dealing with convection over the tropical oceans we are usually treating motions in a fluid that is fairly uniformly heated from below and that has fairly uniform boundaries. We therefore hypothesize, extending Avsec's results, that the orientation of the rows or cells will be governed by the shear between the layer of convecting fluid and its boundaries. If the convective layer is exposed to shear only at its lower boundary, then the cloud rows will line up with this shear, or with the low-level trade winds. This is the parallel mode, commonly dominant, since the uniform east-wind layer is usually deeper than the cloud layer.

If, however, the convective layer is exposed to shear from its top boundary as well, it may show two modes of row organization. The second mode then lines up with the shear vector between the motion of the convective layer and that of its upper boundary. Thus we may expect the cross-wind mode in tropical cumuli to be rarer than the parallel mode and to come in when either (i) the convective cloud layer is sufficiently deep to reach a strong shear region above the uniform easterlies, or (ii) a shear layer is abnormally low and invades the normal cumulus regime.

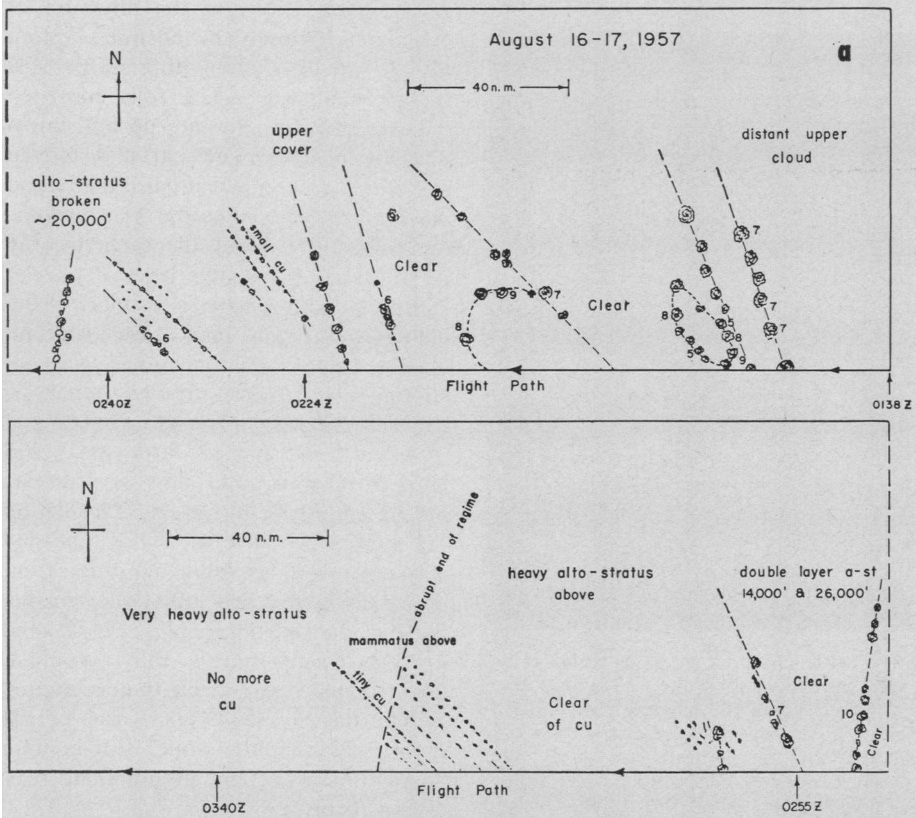
Figure 6 is a summary of this hypothesis, tested against the cloud maps of Figs. 3*a* and 4*a*. We documented several more cases, which worked out equally well; in each, the cross-wind mode showed a 40- to 50-mile (65- to 80-km) spacing which did not vary with latitude and which, so far, is unexplained. A fascinating example in support of this orientation rule is mapped in Fig. 7*a*, and shown photographically in Fig. 7, *b* and *c*.

The striking feature here is the rotation of the cross-wind rows along the flight path. The change in upper wind is shown in the inset at lower right; as the aircraft moved eastward (to the right), the shear vector indeed rotated from R_1 to R_2 in beautiful agreement with the rotation of the cloud rows. These wind data were taken from the aircraft navigator's calculations at flight level [9000 ft (2745 m)]; we see, at that level, a wind direction quite different from that at the surface, so it is evident that a strong shear is imposed upon the convective layer from the top.

By the time the aircraft left the area represented by the right edge of the map, it was again encountering a northeast wind—a finding which showed that the uniform layer of trade winds had regained normal depth. Thus, by 0208 hours, the shear layer was rising; as a result, the small trade cumuli resumed the parallel mode and only the towers that reached above 10,000 feet (3000 m) manifested the cross-wind mode. Any effort to deduce the direction of the low-level winds from the rows of cumuli would have met with signal failure in this case. Again, the 40-mile (65-km) spacing of the cross-wind mode is suggested, except for a "missing" row in the center of the map.

Clues to Other Patterns

Once the connection with wind shear and the Avsec experiments had been made, it was possible to arrive at a preliminary understanding of many of the other types of cloud patterns. For example, the cloud map of Fig. 8*a*



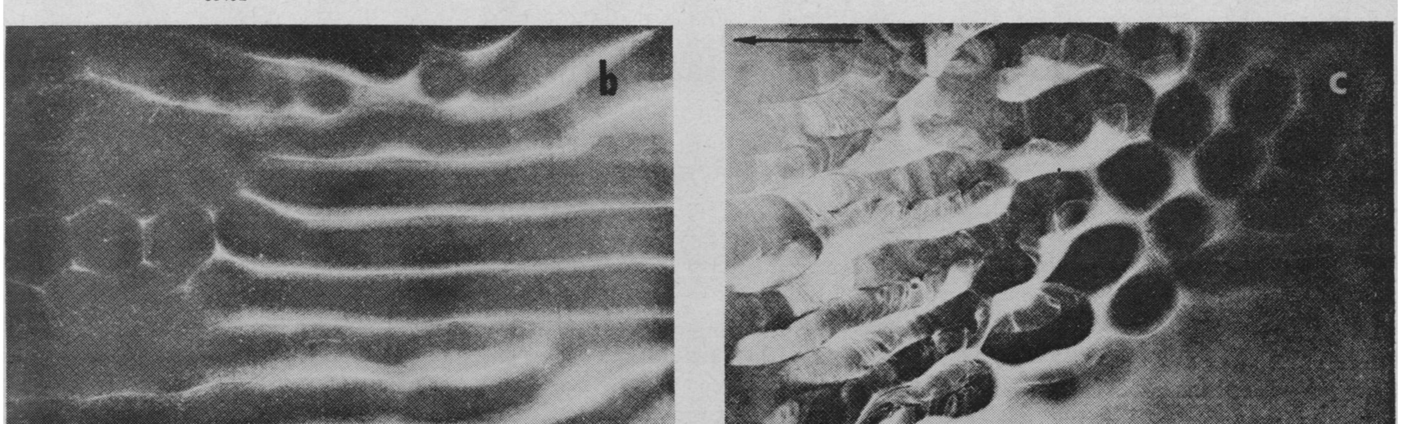


Fig. 8. Comparison of cloud configurations with laboratory results under conditions of very light winds, 16–17 August 1957. *a*, Cloud map. Heights (in thousands of feet) of some of the larger clouds are indicated. No attempt was made to map all the clouds viewed. Most of the large clouds to distances up to 70 to 80 kilometers from the aircraft were included. The spacing and lengths of the rows are drawn to scale. More polygons and ellipses were seen than are shown on the map. *b*, Photograph of the experimental transformation of polygonal cells into longitudinal bands by setting into weak translation a layer of air heated from below. Depth of layer, 20 millimeters [after Avsec (*9*)] *c*, Another photograph of the same experiment. The trajectories inside the rolls are plainly visible, especially on the left. A meter stick is shown at the bottom. [After Avsec (*9*).]

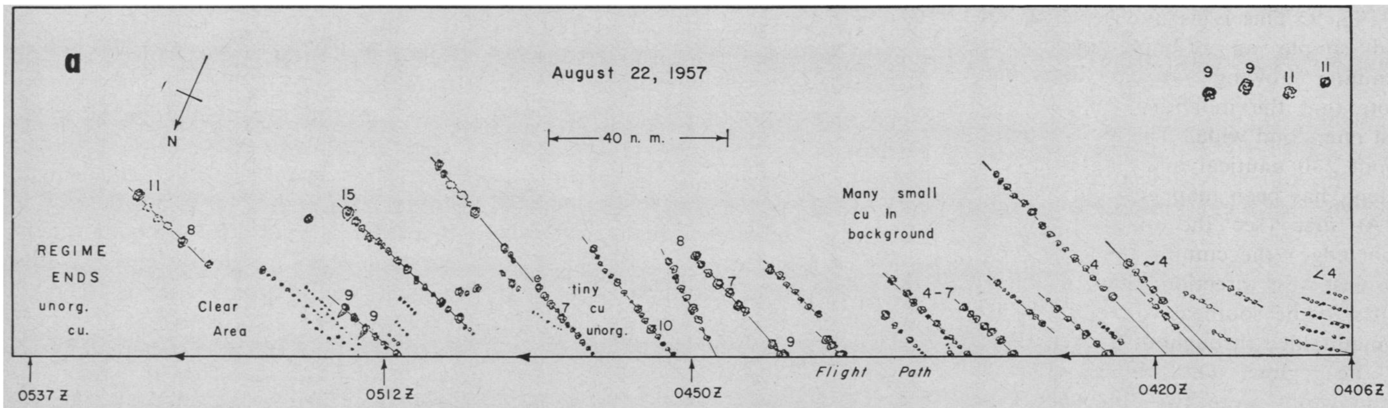


Fig. 9. The simplest case of the parallel mode, with cloud rows one cloud wide, occurring when trade wind and vertical shear are in the same plane. *a*, Cloud map, 22 August 1957. Cloud heights are in thousands of feet; when the height of an individual cloud is given, this cloud is generally the highest in its row. All the cloud rows and nearly all the clouds within 55 to 60 kilometers of the aircraft are shown. *b*, A still photograph showing the cloud rows mapped above. The camera was aimed just west of north (diametrically opposite to the direction in which the moving-picture camera was aimed, from the other side of the aircraft). This photograph was one of a stereo pair that confirmed the direction of cloud lineup and tilt. Note the leaning of the small clouds along the row, especially of the cloud in the foreground at right, which is "lying down" along the row.

at first sight appears to be rather chaotic and unordered. Then one begins to sort out wobbly cloud rows and to note the simultaneous presence of irregular elliptical or polygonal arrangements of cumuli. More of these formations were seen on the film but not mapped. The two components of our hypothesis fit together a bit differently here to explain this pattern.

First, we compare Fig. 8*a* with Figs. 8*b* and 8*c*, reproduced from Avsec's beautiful laboratory results. Avsec noted that when a convecting fluid was heated from below and at the same time subjected to a very weak translation (shear), an unsteady regime of combined wobbly rolls and transient polygonal cells was observed. Such a regime might occur over the tropical oceans when the horizontal velocities associated with the convection are comparable to the wind itself—that is, when the wind speed is less than about 2 meters per second. In the region mapped in Fig. 8*a*, the sea was quiet; the wind at flight level was only about 2½ meters per second.

Second, we note that the lines of large cumuli are at more of an angle to the flight path than the lines of small ones, the variation in the angle being roughly proportional to the variation in the height of the clouds. The surface wind was estimated to be from the southeast, or about parallel to the lines of small cumuli. At flight level, the wind was more southerly throughout the region represented by the map, but it abruptly returned to southeast at 0338 hours. Thus, the rows of larger cumuli which reached or approached flight level could have been affected by the upper shear, while the small cumuli were affected only by the shear between the sea and the lowest air.

Aside from this curious wind shift, there is no clue as to the cause of the abrupt ending of the regime. This had the appearance of a wall with one tiny row of cumuli protruding. A deck of altostratus above was gradually thickening but showed no change accompanying the disappearance of the cumuli. The tropical oceans usually continue to supply the air with heat from below even under conditions of overcast.

An important conclusion that was drawn from this map and confirmed from several others is that a minimum wind speed is required to generate parallel cumulus rows. A critical wind speed of about 6 meters per second for roll convection was deduced 23 years ago by Woodcock (see *12*), from observing the soaring behavior of herring gulls.

New Light on the Parallel Mode

The relationship of cloud lineup to wind shear also provided insight into the mechanisms of formation and maintenance of the dominant parallel mode. Here our earlier studies of cumulus (*13*) added something beyond analogy to the Avsec experiments.

On the last flight leg of our series (see Fig. 1, bottom: Kwajalein to

Honolulu) we obtained the cloud map of Fig. 9. This is as intense, clear-cut, and simple an example of parallel cumulus "rowing" as can be found. Note that the individual "streets" are just one cloud wide. The entire regime, about 280 nautical miles (519 km) in extent, has been mapped.

At first (see the map of Fig. 9, right edge) the cumuli are lined up in the east-west direction; then the lineup shifts to the southeast direction, which is maintained throughout the remainder of the regime. On this occasion the trade winds were two-dimensional up to at least 25,000 feet (7600 m). The surface wind was estimated, from waves and whitecaps, to be from the southeast. Individual clouds leaned in this same direction—an observation which indicated the important fact that there was no wind turning with height.

During the flight we had an oppor-

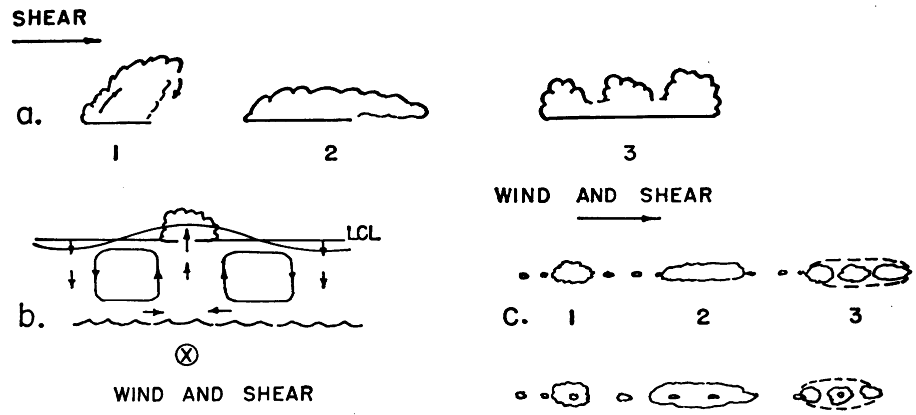


Fig. 10. Schematic illustration of the hypothesis regarding the formation of rows of cumuli when the low-level wind and the shear in the lower cloud layer lie in the same plane. *a*, The effect of shear in three stages: (1) Little growing cloud tilts downshear, and (2) lies down downshear as updraft dies; (3) new little cloud grows from the prostrate body. *b*, The effect of Avsec rolls, wind, and shear at right angles to plane of diagram (blowing into the paper). The wavy line denotes the top of the mixed layer, raised in zones where the roll motion is convergent and upward, depressed where the roll motion is divergent and downward. Cloudlets break out where the mixed layer reaches condensation level—that is, at roll crests. *c*, Combination of the direct shear effect in *a* and the Avsec rolls in *b* produces cumulus rows parallel to the flow, which elongate downshear.

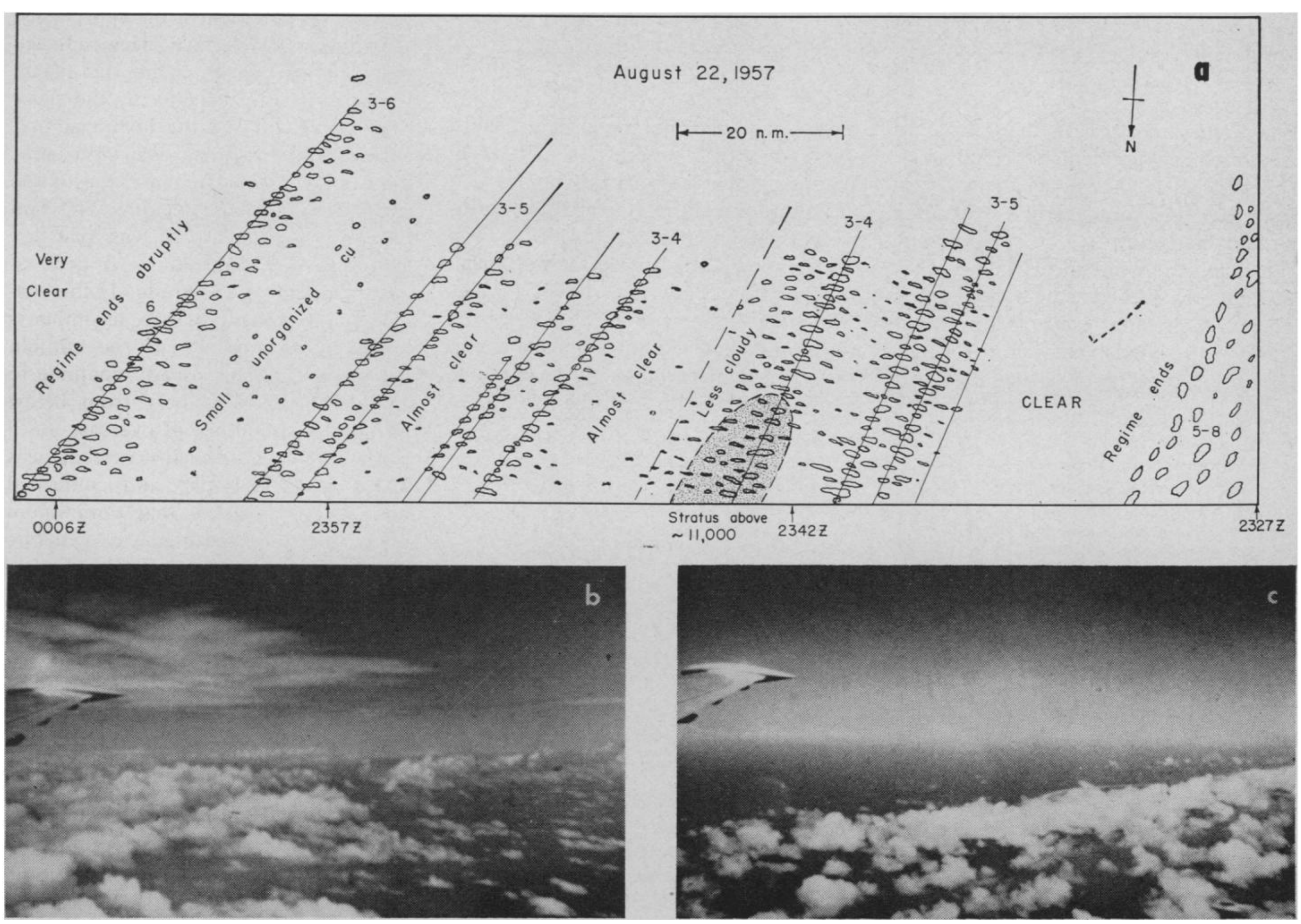


Fig. 11. Parallel mode with rows several clouds wide, occurring when the trade wind and the vertical shear in the cloud layer are at a high angle to each other. *a*, Cloud map, 21–22 August 1957. Not all the clouds photographed were included. The length and spacing of the rows are to scale. The height ranges are in thousands of feet. The shaded region denotes a patch of stratus above the cloud row. *b*, Frame from the film taken 21 August at 2342 hours. Note the rows running from left foreground to right background (the solid lines on the map). Note the individual clouds shearing and lying down from right to left (approximately east-west). *c*, Frame showing the abrupt ending of the mapped regime.

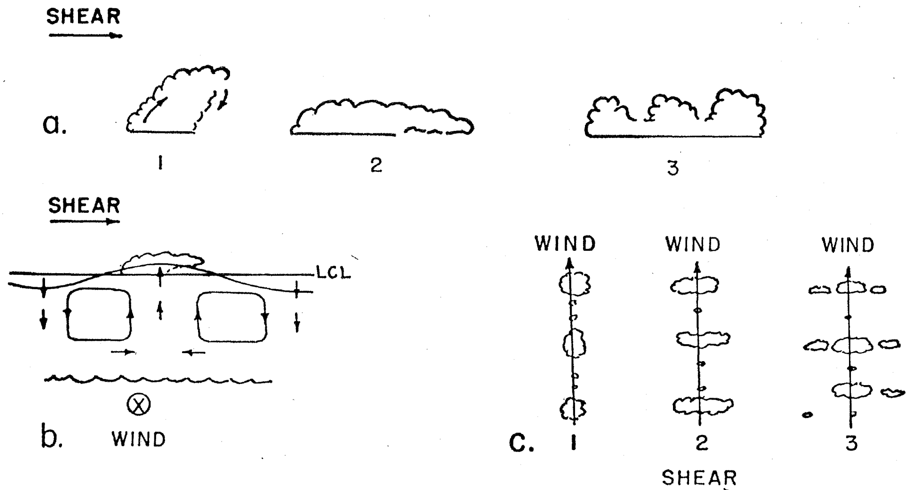


Fig. 12. Schematic illustration of the hypothesis regarding the formation of rows of cumuli when the low-level wind and the shear in the lower cloud layer are at right angles to each other. *a*, The effect of the shear elongates the cumuli downshear, as shown in Fig. 10*a*. *b*, Avsec rolls lined parallel to the wind (which blows directly into the diagram) but at right angles to the shear (which points from left to right in the plane of the diagram). Cloud rows develop along the direction of the wind, as suggested in Fig. 10*b*, but the individual clouds are elongated normal to the rows. *c*, Combination of *a* and *b*, showing the clouds stretched downshear normal to the Avsec rolls. The clouds are most likely to break out along the roll crests, but there is some spreading into the interstices.

tunity to watch closely the formation of several new segments of cloud rows. This process is shown schematically in Fig. 10. As our earlier work on cumulus had shown (*13*), small cumuli lean along the wind shear; that is, they tilt along the shear vector between their top and their base levels, so that if the speed of the wind increases with height (as in the case of Fig. 10), they lean downwind, and vice versa. Furthermore, they become increasingly more slanting as their updraft is exhausted. We noted that these small cumuli lay flat along the shear (toward the northwest) but remained visible. Then several new little towers sprang from the prostrate body, as shown in Fig. 10*a*, stage 3. Sometimes these separated into individual cumuli, or sometimes they amalgamated into a bigger cloud, which could go through the cycle on a larger scale. Frequently another small cloud formed downshear at stage 3, the process was repeated, and a segment was added to the row, which often thus elongated rapidly in the downshear direction.

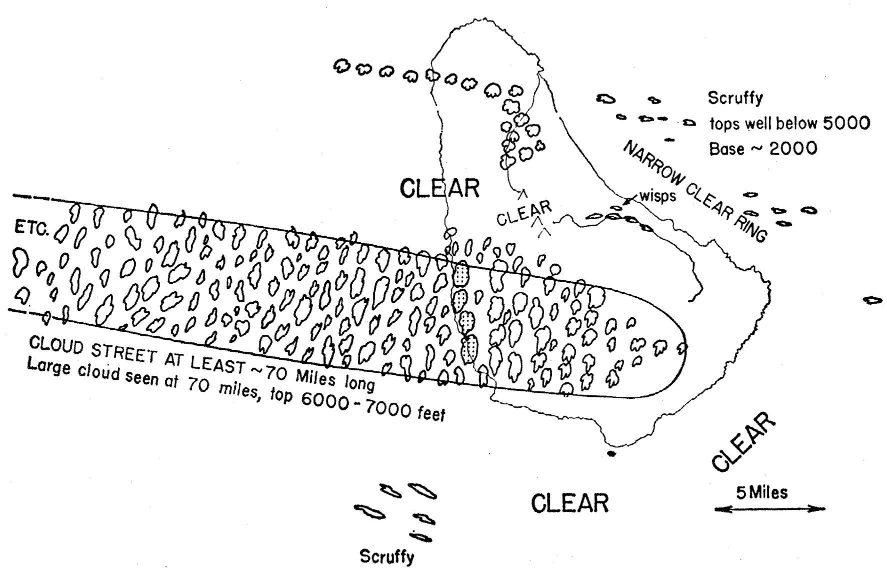


Fig. 13. Cloud patterns near Barbados on 7 April 1963 between hours 1320 and 1420, with wind east-southeast and shear vector from the north. Cliffs and mountains (maximum height, 335 m) are indicated by the thin solid lines; the rest of the island is flat.

Thus we could expect that there would be some tendency for cumuli to form in parallel rows under these wind conditions, even without the roll convection studied by Avsec. However, as Fig. 9 shows, the rows of cumuli may be 100 kilometers or more long, with few or no clouds between them. Furthermore, the spacing between the rows widens with increasing cloud height (see the map of Fig. 9, right edge and center), as one would expect from the Avsec experiments and the accompanying roll theories of convection. Finally, all the clouds in the long rows were sometimes observed to spring into being almost simultaneously.

We therefore postulate that Avsec rolls occurred in the convective layer, lined up along the shear between the flow and the ocean boundary—that is, in the direction of the low-level wind. This is shown schematically in Fig. 10*b*. In the region of local convergence and ascent, the mixed subcloud layer is thickened up to, or a little beyond, the level of water-vapor condensation (usually near 600 m) and clouds break out. In the intervening regions of divergence and descent, the mixed layer fails to reach the condensation level, so the turbulent moist eddies swirling around in the subcloud layer cannot condense and no cumuli form. In previous work (*14*) my associates and I have shown that the top of the mixed layer is commonly within 30 to 100 meters of the condensation level, hence that only a small variation in thickness of the layer is needed to control the formation of the cumuli. Figure 10*c*, a combination of *a* and *b*, shows how the process described in *a* is confined to the roll crests.

A test of this hypothesis is needed. We would have such a test in a situation where the wind shear in the cloud layer differed markedly from the wind direction itself. Then, if the hypothesis is valid, the small clouds should lie down at an angle to the Avsec rolls. Such wind turning with height is not common in the tropical cloud layer, but by good fortune we found an example during a portion of the last leg of our flight (see Fig. 11). Though the clouds were rather small, this was one of the most remarkable patterns we photographed.

At the right side of Fig. 11*a* there is a region of unorganized cumuli with tops up to 8000 feet (2440 m). This regime suddenly ends in a clear stretch about 25 miles (40 km) wide. Then the organized pattern, which is the main subject of interest, sets in. This regime lasts for 100 nautical miles (185 km) along the flight path and then terminates abruptly (Fig. 11*c*).

There is little doubt that the main direction of organization, shown by the solid lines in Fig. 11*a*, is the parallel mode. The whitecaps were from about northeast at 0000 hours, and in the remaining two-thirds of the map the direction of the cloud rows has changed from just north of that direction into conformity with it. The average shear in the cloud layer was from barely north of east, or almost perpendicular to the cloud rows.

Figure 12 shows schematically how the high wind-to-shear angle accounts for the elongation of the rows—why each row is many clouds wide. Actually, some of the rows show up as just a greater concentration of clouds along the lines than in the intervening spaces, which merely contain fewer and smaller cumuli. Fig. 11*a* thus supports the hypothesis that elongation along the shear and Avsec rolls may both contribute to the rowing of trade cumuli. In the regime of Fig. 9 these effects combined to produce clear-cut parallel rows, while in that of Fig. 11 they seemed to have worked at cross purposes, making the stippled pattern.

Conclusions and Future Outlook

These maps, considered in connection with the wind field, have apparently provided an initial insight into cloud patterning. When the trades are strong and heated from below, rows are common and their orientation is governed by the vertical wind shear.

Our hypotheses may be summarized as follows. When there is a single shear between a cloud layer moving fairly uniformly and its lower boundary, the parallel mode develops by a simple superposition of Avsec rolls and individual clouds leaning downshear. When there is wind-turning within the cloud layer, the individual clouds lean across the rows, which may then be several clouds wide.

A marked shearing imposed aloft upon the convective layer brings in the cross-wind mode, oriented with the upper shear. It may be superposed on the parallel mode to make a checkerboard, or in extreme instances it may appear alone, so that the only cloud rows are at a high angle to the wind. The 40- to 50-mile (65- to 80-km) spacing of the cross-wind mode in all our examples of it may be coincidental, or it may provide a clue to the dynamics of this mode that we do not yet know how to read. The factors that govern the relative degree of development of the two modes are still unspecified, as are those that govern the abrupt regime transitions exemplified so dramatically in Fig. 11.

These problems cannot be clarified simply by obtaining more and more pictures like those of our survey or more and more pictures from satellites. This is because the existing meteorological networks do not provide data of sufficient quality, quantity, or resolution for determining the atmospheric and boundary conditions and their mesoscale variations. Moreover, aircraft observations (*15*) show that cloud regimes alter much more abruptly than does the temperature and moisture structure of the air. It follows that these transitions must be regulated dynamically (by air motions) or by the oceanic boundary conditions, or—and this is the most likely—by the two in interaction.

Thus, specially designed observational programs with special measuring tools must be undertaken. These programs can be most fruitful if we seek a site where nature itself is experimenting upon the tropical atmosphere in a semicontrolled way—that is, where the usual delicate balances are undergoing reproducible and describable alteration.

Such "experiments" are being performed daily by tropical islands as they warm in the sunshine by day and cool off at night. That even small atolls create distinct cloud patterns was well known to the ancient Polynesians, and, in less ancient times, dynamic models of the airflow over heated islands have been made by meteorologists.

Guided by these, we have chosen the island of Barbados (13°10′N; 59°30′W) in the West Indies as the site for our next intensive observing program, to be carried out in August 1963. Barbados is nearly ideal for this type of meteorological study. A lopsided triangle, 15 by 20 miles, it is almost flat, and surface and boundary-layer measurements may readily be made from all parts of it. It is far from the influence of continents and other islands.

To obtain unmodified oceanic conditions upwind, a research vessel will be stationed about 400 kilometers east of the island. It will make soundings to determine the structure of the air and the sea; it will make a detailed examination of the air-sea interface, under disturbed and undisturbed conditions; and it will obtain cloud pictures by camera and radar. The crucial connection between ship, island, individual cloud, and cloud pattern will be made by a research aircraft. It can examine the wind field by means of a Doppler radar and can determine details of sea-surface temperature by radiation thermometer. It can also penetrate and record the properties of individual cumuli. All these measurement procedures will supplement a photographic program of the type described here.

The cloud map of Fig. 13 is from a preliminary study made from Barbados in April 1963. It bears a remarkable resemblance to the cloud pattern of Fig. 11, suggesting the exciting result that many of the oceanic cloud patterns I have described here will be reproduced by the island. From Fig. 13 we might deduce, for example, that the wind is from the east-southeast along the main cloud street (the parallel mode) and that the shear in the cloud layer is from the north, along the direction of elongation of the individual clouds. These deductions proved to be correct. The presence of the island removes the ambiguity of wind inferences from cloud photographs, since the island provides a point of reference: if the wind were in the opposite direction, the cloud street would extend off the island in the other direction.

Thus, the island experiment can help us to deduce air structure from cloud photographs—perhaps even from satellite photographs of clouds surrounding other planets. However, our goals go beyond this, and we aspire to learn how to make the reverse deduction: to predict cloud structure and patterning from initial and boundary conditions imposed on the atmosphere. The island of Barbados provides a laboratory where measurable cause can be linked to reproducible consequence, in a setting where theoretical and numerical modeling have already made progress (*17*).

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17. My colleagues Claude Ronne and Professor Herbert Riehl made this study feasible. Professor Riehl provided the initial inspiration, collated and analyzed the meteorological data, and drew on his vast experience in tropical meteorology at all stages. Mr. Ronne made all the flights, took all the pictures, and spent endless hours in the labors of reduction and mapping. We are all grateful to the Pacific Division of the Military Air Transport Service, whose officers and men often went far beyond the call of duty in making the research both possible and pleasurable. The work was supported by the Office of Naval Research, whose cooperation in all phases we deeply appreciate. We also thank the Woods Hole Oceanographic Institution for the use of their facilities during the long period of data reduction. This article is University of California (Los Angeles) Department of Meteorology paper No. 89.

Neutrinos, Old and New

The neutrino, discovered several years ago, is a curious particle now believed to exist in four states.

Frederick Reines

Thirty years have passed since Pauli (*1*) suggested the neutrino hypothesis in order to extend the validity of the principles of conservation of energy and momentum to include the process of beta decay. Nuclear beta decay is a process in which a nucleus spontaneously changes to another which differs by one unit in electric charge, simultaneously emitting a positive or a negative electron. It was noticed that, despite the existence of well-defined nuclear energy states—that is, a definite amount of energy available for the process—the emitted electrons only rarely carried off all the energy. Pauli hypothesized that the missing energy was in fact embodied in an unobserved particle which interacted weakly with matter. This particle was concluded to be electrically neutral because of the equality of the charge on the initial nucleus and on the final nucleus-plus-electron. In the years since this conjecture was made, the particle (named the neutrino by Fermi) has, primarily on the basis of Fermi's brilliant theory of beta decay (*2*), become an indispensable, if peculiar, member of the family of elementary particles. Symbolically we can describe nuclear beta decay by the equation

$$[A, Z] \rightarrow [A, Z \pm 1] + \beta^{\mp} + \nu_{\beta\mp} \quad (1)$$

where A is the number of neutrons plus protons in the nucleus, Z is the number of protons in the original nucleus, and $\beta^{\mp}$ and $\nu_{\beta\mp}$ refer, respectively, to the emitted electrons and neutrinos. The upper signs on the exponents go together, and the two subscripts on the neutrino indicate the two neutrinos associated with nuclear beta decay ($\nu_{\beta-}$ is the antineutrino, $\nu_{\beta+}$ is the neutrino).

Until 1956 the evidence for the existence of the neutrino was based on observations made on the other particles which participated in the act of beta decay—that is, the electron and the residual nucleus. This indirect evidence, though impressive and consistent with the neutrino hypothesis, was not logically conclusive because it represented no more than a restatement of the original premise that energy and momentum are conserved in beta decay.

However, in 1956, after a series of experiments carried out over a period of 5 years, a Los Alamos group (*3*) observed the free neutrino—that is, the occurrence of a reaction induced by a neutrino at a location other than its point of origin. This direct observation removed any doubts as to the existence of the neutrino, and it became as "real" as any other elementary particle. In 1962 a significant advance was made in neutrino physics when it was discovered, by a group of Columbia University and Brookhaven physicists working at the Brookhaven National Laboratory (*4*), that there is a second class of neutrinos, those associated with particle decays involving mu mesons. An example of a process in which neutrinos of this class are emitted is the decay of a pi meson to a mu meson

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu\pm} \quad (2)$$

Pi mesons, predicted by Yukawa and first discovered in the cosmic radiation by Powell and his collaborators (*5*), are produced in processes involving the bombardment of nuclei by high-energy protons. The decay process shown has a mean life of 2.5×10^{-8} second, and the masses of the meson are 270 and 207 times the mass of the electron.

Studies of the interactions of free neutrinos, though difficult because of the extreme rarity of the interactions, are aimed at the elucidation of fundamental questions about the nature of the weak interaction, which, along with interactions of the other three types—that is, strong (the type responsible for nuclear forces), electromagnetic, and gravitational—is considered to be responsible for the universe as we know it.

A further field of neutrino research, still in a very speculative stage, has to do with the neutrino's cosmic and astrophysical role. What makes the neutrino a subject of special fascination for physi-

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