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BY SIGMUND FRITZ, U.S. Weather Bureau

Experiment and theory come to bear on the nature of the hydrodynamic and thermodynamic processes implicit in the cloud pictures that Tiros produced

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Chief of the Meteorological Satellite Laboratory, joined the U.S. Weather Bureau in 1937. A graduate of Brooklyn College, he received M.S. and Ph.D. degrees from MIT under Weather Bureau scholarships. Dr. Fritz served as an aerologist with the U.S. Navy for four years. He has published extensively, especially on solar-radiation problems and results of meteorological satellite observations.

There are already several review articles which summarize the results obtained from meteorological satellites.[1] In brief, clouds have been found to be highly organized, and the satellite pictures reveal atmospheric phenomena on all scales.

The satellite pictures often suggest that certain dynamical mechanisms are acting to produce cloud patterns. Here a few types of cloud patterns will be compared with laboratory experiment and theory to emphasize the hydrodynamical implications of the satellite pictures.

It should be noted, however, that any of the implied dynamical processes can only give necessary, and not sufficient, conditions for the production of cloud patterns. For example, the presence of enough water vapor, operated upon by a condensation mechanism, is always required also.

Cellular Clouds. The so-called cellular cloud pattern is frequently found in satellite pictures. Krueger and Fritz[2] discussed a few cases located over the Atlantic and Pacific Oceans. The Tiros picture shown at the top, from their paper, shows a cellular cloud pattern. Especially in the lower right quarter of the photo, the pattern suggests semicircular arcs of cloud, with clear areas in the center—a pattern similar to that found in the laboratory by Graham[3] and Avsec.[4]

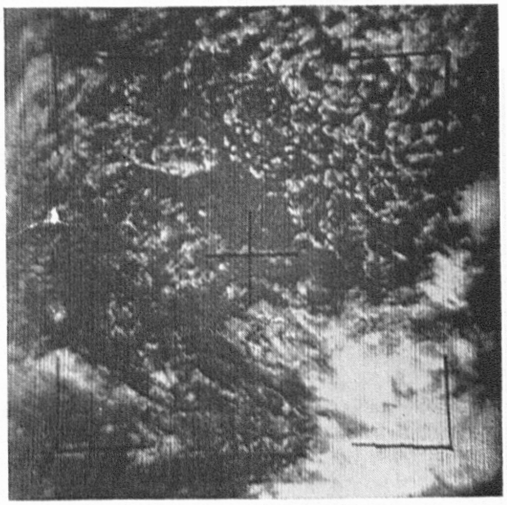
The clouds in this picture were imbedded in an atmospheric layer in which the temperature decrease with height was close to the adiabatic lapse rate. This relatively unstable layer was capped by a marked inversion, that is, an increase of temperature with height, at levels, which varied from 3000-9000 ft over the area.

In the laboratory these patterns are deformed from hexagonal Bénard cells by the superposition of vertical shear of the horizontal wind on the hexagonal pattern.[3] But there are important differences between the laboratory results and the results revealed by Tiros pictures. Among the most intriguing is scale.

In the laboratory, the characteristic ratio of width of the cells, w, to the height, h, is $w/h = 3$. By contrast, for the cells in the picture at top here $w/h = 30$, or about a factor of 10 larger. This value is computed from the fact that the cellular diameters in the picture range from 20 to 50 mi. If we take the height of the inversion as the depth of the fluid, then h varied from about 0.6 to 1.5 mi.

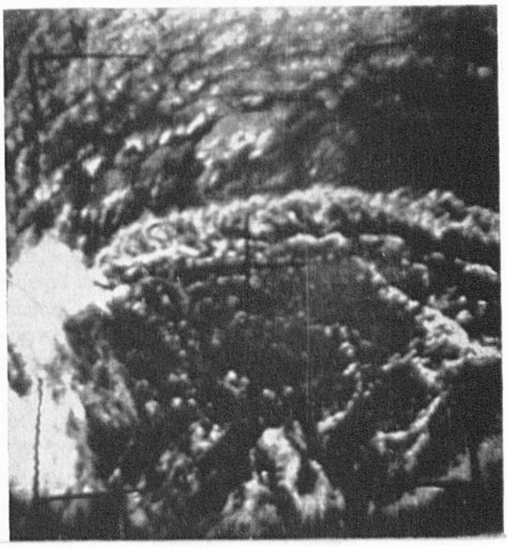
Several studies have attempted to explain or elucidate the conditions associated with the "flatter" cells observed by Tiros. For example, Fritz, Lipps, and Moore, working individ-

Cellular Cloud Pattern appears at lower right in this Tiros I picture taken 650 n. mi. northeast of Bermuda at 1612 GMT, April 4, 1960. From Krueger and Fritz.[2]



Cloud Mass from Precursor Hurricane Anna, as shown by Tiros III on July 16, 1961, shows only weak organization of cloud patterns, if any.

Same Cloud System a Day Later shows a pronounced organization of cloud lines, compared to picture above, with lines curving sharply into overcast.



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ually or in groups, considered among other things the distribution of cooling or heating in the cells.[5]

In the cells, clouds are produced where the motion is upward. In the cloudless portions of the cells, the motion is probably downward, at least near the upper boundary (at the inversion). Moreover, at least two heating or cooling mechanisms occur when the cloud is present. First, stratocumulus clouds are good radiators of thermal energy to space; they approximate black-body radiators at the temperature of the cloud "top." Evaporation from the cloud "top" may also contribute to cooling there. On the other hand, as the clouds condense they release the heat of condensation, and so act as heat sources.

Thus the clouds act as heat sinks at the top of the upward moving air. They also act as heat sources throughout the part of the cloud where condensation is occurring, also in the upward moving air.

In most cases examined, the cell size became *smaller* rather than larger, when these effects were added to the simpler classical problem. The main exception to this occurred when the air was *heated* near the top boundary in the upward flowing part of the cell. This suggests that condensation may be a factor in producing large cells. Even then, the effect on the cell size is probably small. Roy and Scorer also evaluated the effect of cooling throughout the cell and found the effect on cell size to be small.[7]

Thus, to find the explanation for the "large" cells seen by Tiros I, still other factors must be investigated.

Theoretical studies of Bénard cells usually employ molecular quantities for the coefficients of viscosity and heat diffusion. However, it is common to use the concept of "eddy" coefficients in studies of turbulent flow in real fluids. Priestly[6] and Roy and Scorer[7] have applied these to explain the flatter cells. Say that K_x and K_y denote the "eddy" coefficients for the horizontal direction and K_z for the vertical direction. Priestly then reasoned as follows: Assume that the cells rotate about horizontal axes, as in the case of Bénard cells. The upward flowing air, which produces the clouds, penetrates a short distance into the stable air above the base of the inversion. The airflow returns in the stable inversion and then descends where the air is cloudless. Since K_z acts to suppress velocity and temperature differences between the horizontally moving air at the top and bottom of the cell, K_z must operate across the stabilizing barrier of the inversion; therefore K_z is small. However for K_x and K_y there are no corresponding suppressions. From analogy with conditions in the boundary layer and in the general circulation, Priestly considers that $K_x/K_z = 100$ is plausible, and this leads to about a tenfold flattening of the cells, in agreement with Tiros observations.

Roy and Scorer also emphasize the variation of K_x and K_y as compared to K_z.[7] They note that K is greater in the turbulent cloudy areas than in the cloudless areas. They also consider that the cell motion acts as though the horizontal transfer of heat by eddies were large. With these assumptions they consider both isotropic and non-isotropic turbulence, and find that in either case a flattening of the cells occurs. They also show the ratio $w/h = 30$ can be achieved by various combinations of viscosity and heat conduction coefficients.

On the other hand Sasaki, mainly because of the difficulty of assigning numerical values to K (for eddies) objectively, prefers to consider K negligible.[8] He noted, however, that horizontal and vertical gradients of potential temperature existed in the area of the Tiros picture at the top of page 70, and that instability can be produced when the gradients exceed certain critical values. According to Sasaki's criterion, the horizontal and vertical temperature distributions, as given by radiosondes in the area of the cells correspond to cells which are even flatter than the ones observed by Tiros.

In summary, then, the insertion of variable values for K_x and K_y, which are larger than K_z, into a modified classical theory, can produce significantly flattened cells. Also baroclinic instability, introduced by horizontal temperature gradients, can apparently also produce flat cells independent of K. Eventually, all the significant factors will need to be combined into a unified theory.

Tropical Vortex. Another occurrence which needs explanation was observed by Tiros during the formative stages of the tropical cyclone, which later became Hurricane Anna of 1961.[9]

On July 16, 1961 the cloud mass from which Anna developed was located near 10° N, 39° W, as shown in the middle picture on page 70. Although there may have been some organization present in the cloud patterns between latitudes 10° N and 20° N, it was, if present, weak. But by 1449 GMT on July 17, a marked change had occurred. The main cloud had moved to about 12° N., 43° W, and, by contrast, showed a pronounced organization of cloud lines, as the bottom picture on page 70 reveals, curving sharply into the overcast area from the east and north. The direction of such cloud lines usually lies near the direction of the vector of the vertical shear of the wind; and when the shear vector lies along the wind, as it often does in the tropical Atlantic at low levels, the cloud lines are also related to the wind direction. Thus, the curved, "spiral" cloud array indicates that the vertical wind shear vectors were arranged in a curved pattern, and that probably the wind was also curved cyclonically.

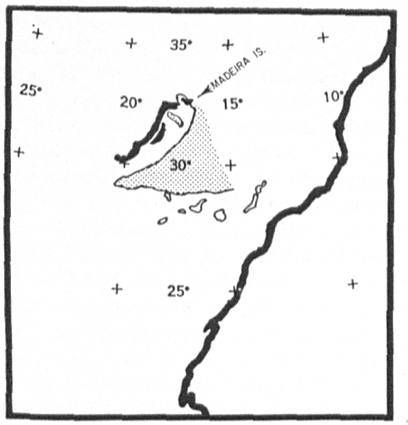
The marked change in cloud pattern suggests a corresponding change in airflow associated with the *onset* of instability. It is therefore interesting to compare these events with an experiment reported by Faller.[10]

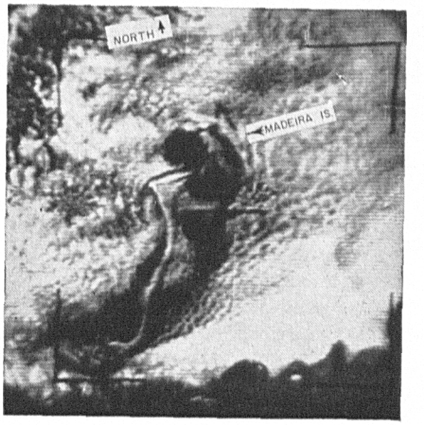
Faller used a rotating water tank, from which the water was withdrawn at the center. The water was pumped back into the tank along its perimeter. The tangential velocity, v, increased with radial distance from the center. Under the proper conditions of speed of rotation, Ω, and fluid velocity, v, instability developed in the Ekman boundary layer. (The theory of the Ekman layer is discussed by Haurwitz.[14]) This instability produced convective bands which spiraled toward the center of the tank. The onset of instability in the form of well-ordered spiral rolls was observed to occur at a critical Reynolds number, $R_{e_c} = 145$. There was a transition from well ordered rolls to more irregular rolls and fully-developed turbulence at $R_{e_t} = 177$.

Moreover, Faller found a constant relationship between the spacing of the bands, L, and the depth, D, of the Ekman layer, namely, $L = 10.9D$.

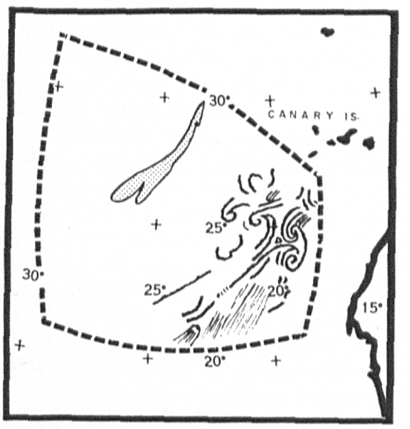
Now, the onset of instability may also occur in hurricane genesis. Hurricanes often begin as small cold-core disturbances in the easterly wind zones of the tropics.[11] In a cold-core disturbance the air is coldest near the center, where the air is rising. Such conditions cannot persist without forcing from the environment. Additional mechanisms must therefore act to produce the warm-core, self-sustaining convection of a hurricane. The heat released by condensation in the clouds can gradually change the cold core into a warm core. A stage in the development may then be reached, when the air is withdrawn vertically from the system rapidly enough, so that the associated low-level inflow may become unstable in the sense of Faller's experiment.

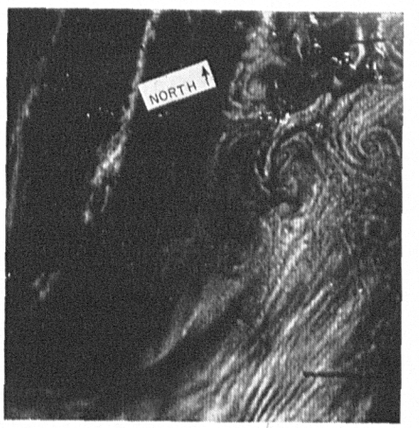
The spacing, L, between the cloud lines, in the bottom picture on page 70, was about 20–40 mi. If following





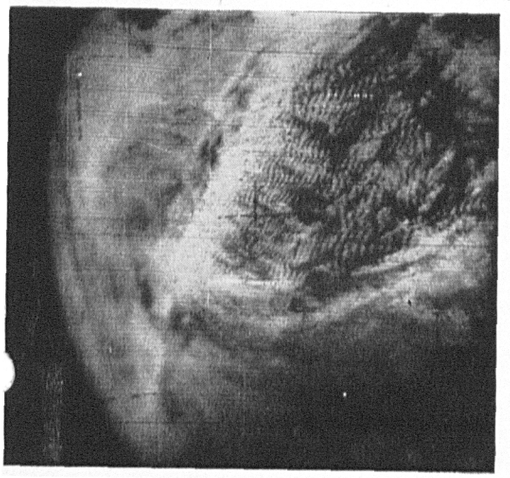
Cycloidal Cloud Pattern downstream from Madeira Island, photographed by Tiros V at 1650 GMT on June 21, 1962. The island has dimensions of 20 by 65 km, with mountains extending up to 1800 meters. From Hubert and Krueger.[12]



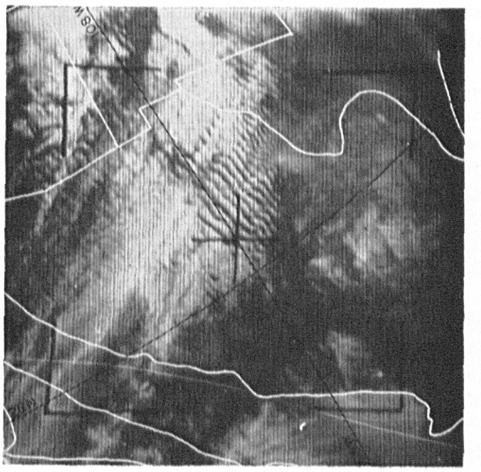


Complex Eddy Cloud Pattern downstream from Canary Islands, photographed by Tiros V at 1400 GMT on July 2, 1962. The Canary Islands range in size from about 30 by 12 km to 53 by 78 km and in height from 500 to over 3000 meters. From Hubert and Krueger.[12]

Wave Cloud Pattern in the lee of the Andes Mountains, as seen by Tiros I at 1738 GMT on April 18, 1960. Relatively uniform bright band, oriented N–S, is over the Andes.



Wave Cloud Pattern over northern Mexico and southwestern U.S., with a geographic outline superimposed. Taken by Tiros VI at 1706 GMT on Nov. 15, 1962.



Faller we take $R_{ec} = v\ D/\nu$, $D = (\nu/\Omega)^{1/2}$ (for an Ekman layer) and utilize the equation $L = 10.9D$, then $v = R_{ec}\ L\ \Omega/10.9$. Here ν is the coefficient of eddy viscosity. At latitude 15° N, Ω equaled 1.8×10^{5} sec^{-1}; then, taking $R_{ec} = 145$ and $L = 20$ mi., we find $v = 17$ knots. From the values of R_{ec} v, and D used here, $\nu \approx 1.5 \times 10^{6}$ cm^2/sec.

The wind speed was doubtless about 17 knots, or even higher, in the region of the cloud lines near latitude 16° N. Further, $D \approx 2$ mi., which seems quite reasonable, especially since, on the basis of experience, the appearance of the clouds was characteristic of a pronounced temperature inversion in the lower part of the troposphere.

Thus, the Tiros pictures, such as the one on page 70, are consistent with laboratory results and suggest the onset of instability in the friction layer during the early, formative stages of a tropical cyclone, at least, for this one case of the forerunner of Hurricane Anna.

Mesoscale Eddies Produced by Islands. Another class of interesting phenomena are the mesoscale spiral and cycloid patterns produced in the lee of elevated islands under suitable atmospheric conditions. Several examples of these were discussed by Hubert and Krueger.[12] Two of their figures are reproduced at the left. The top one shows a general field of cellular clouds, doubtless under a strong, low inversion, with very little vertical shear of the horizontal wind. But starting in the vicinity of Madeira Island and extending downwind for about 150 mi. is a long cloud pattern arranged more or less like a series of arcs in a cycloid. The general area of the cycloid cloud is surrounded by relatively cloudless air in some places, suggesting that the air was shaded from the main wind by the island, or that subsidence of the air was occurring, or both.

Hubert and Krueger point out that the presence of the inversion favors the production of inertial oscillations in the air. The frictional influence of the islands modifies the balance of forces which existed in the airflow upwind from the islands. And the unbalance of forces produced by the presence of the island introduces inertial oscillations which take the form of cycloids, if the oscillations are stable. Furthermore, the wavelength of the pattern depends on the speed of the mean flow, and on the horizontal shear. They find that the cycloid pattern in the top figure corresponds to a wind speed of 10 knots and a period of between 17 and 24 hr.

The pattern in the lower figure,

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however, is rather different from the other. The spiral patterns are much more developed. The cloud patterns suggest that more "eddies" exist, and the appearance is one of greater instability. Also the cloud pattern downwind (to south) of the eddies shows pronounced streakiness, rather than the cellular pattern of the top figure. Such streakiness often suggests a marked vertical shear of the horizontal wind, rather than the absence of shear indicated by the cellular pattern. The eddies suggest a von Karman type of vortex introduced by an obstacle, such as the complex grouping of the Canary Islands. Moreover, the existence of vertical shear can be another destabilizing influence, which may have been present in the bottom but not the top figure.

However, Hubert and Krueger suggest that the eddies in the bottom figure are not von Karman vortices, because the eddies were found too far downstream from the islands, in their view. For example, they calculate that the eddies could have existed for, *at most*, 8 hr even if one considers only the vertical shearing stresses of the horizontal wind. Nevertheless, for a reasonable value of the mean horizontal wind, and the observed distances of the eddies from the islands, they estimate that the eddies had been in existence for 10–20 hr from the time of their formation. However, the numerical value of the eddy stresses which they used are doubtless uncertain by a factor of 2 or 3; and if so, the eddies appearing in the bottom figure could have been mechanically produced by the islands, without the need for additional destabilizing mechanisms.

However, having rejected the view that the eddies of the figure on page 72 are merely mechanically produced by the islands, Hubert and Krueger apply a criterion for instability appropriate to the mean flow in which the eddies are imbedded.

Although they do not arrive at this result, one can show that from their assumptions, $V/R < -f/2$ where V = tangential velocity, R = radius of trajectory curvature, f = Coriolis parameter $= 2\,\Omega \sin \phi$, Ω = angular velocity of the earth, and ϕ = latitude. For $V = 15$ knots (7 m/sec) at latitude 25 deg, $R < 145$ mi. (= 230 km) indicates a rather marked anticyclone. Moreover, the horizontal shear, $\partial V/\partial R > V/R$.

They also assume that perturbations on the inversion may decrease the depth of the fluid by 30%. If so, it can be shown that $\partial V/\partial R$ could become cyclonic.

If it were practical, it would be interesting to observe the island-produced eddies from their inception, and to note the meteorological conditions required for the onset of the eddies.

Wave Patterns in Clouds. Rather regular wave patterns are observed fairly frequently in clouds. They may be formed in several ways. One type of such waves is the pattern produced by flow of wind over and perpendicular to a mountain range.

The Andes Mountains represent a rather narrow, high mountain range, which extends for great distances north and south. Wind from a direction of 250 deg (from the southwest) blows almost perpendicular to the mountain; and when the temperature and wind vary in a certain manner with height, waves will form. These waves become visible when clouds form in the upward moving part of the wave.

Döös[13] has considered such a case based on the Tiros picture at the bottom left on page 72. This shows the Andes Mountain as the rather wide N-S band, caused by rather uniform cloudiness and some snow on the mountain. In the lee of the mountain a remarkably regular and widespread wave pattern appeared in the clouds. The wave pattern extended about 200 mi. downwind from the mountain and for at least 250 mi. in a N-S direction. The measured wavelength of the cloud pattern, although not exactly the same everywhere, was about 7 mi. Fortunately, one of the few radiosonde stations, Puerto Montt, is located just to the west of the mountain. This station showed a fairly uniform wind increasing with height from about 20 knots near the surface to about 100 knots at a height of 30,000 ft. The temperature decreased rather uniformly, from about 10 C near the surface to about −50 C at 30,000 ft, although a slight inversion existed near 13,000 ft. With these distributions, Döös found theoretically that the computed wavelength should also be about 7 mi.—in close agreement with observation.

It should be noted however that more than one wave pattern seems to exist in the picture on page 72. Superposed on the main short wave pattern is another less well-defined wave with a wavelength of about 30 mi. This wave pattern is oriented more NE-SW than the first wave train. It is interesting to note that Döös' theoretical development yields two solutions for a certain, rather arbitrary, choice of parameters. For example, if he takes the average height, H, of the terrain near the base of the mountain as 2625 ft (= 0.8 km), he gets two solutions for the wavelength, namely, L_1, = 6.8 mi. (11 km) and L_2 = 44 mi. (70.3 km). As already noted, L_1 agrees well with the wavelength for the picture on page 72. But L^2 = 44 mi. seems too high to explain the longer "waves" seen in the picture. It is possible, by adjusting the parameter, H, to get closer agreement with L_2; but then the agreement with L_1 becomes poorer.

However, the pattern of the longer waves in the picture on page 72 is not very well defined, and even the suggested wave begins far from the mountain. Thus, there may be other causes for this poorly defined pattern, such as the influence of irregularities in terrain downwind from the main mountain ridge.

Another example of waves discovered over Mexico and the southwestern U.S. by Tiros VI appears at the bottom right on page 72. This pattern may have been formed by the flow of air over the Sierra Madre Occidental Mountains, but no analysis of the cause has yet been attempted.

Conclusions and Further Speculations. From the few examples presented, we see that the cloud pictures from Tiros present challenging problems. Hydrodynamical and thermodynamical processes produce the observed cloud forms when an adequate supply of water vapor is present. The problem is to deduce the nature of these processes and the state of the atmosphere, in as much quantitative detail as possible.

Very regular cloud patterns are produced by the interaction of airflow with a mountain. It is interesting to speculate, however, to what extent one can deduce a consistent set of wind and temperature distributions which could produce regular wave patterns, such as the ones in the pictures on page 72, when other information is not available.

With regard to cellular patterns, numerous pictures from many parts of the world are available. It seems likely that a measure of the horizontal dimensions of the cells, provided by the pictures may offer an estimate of the height of the inversion which we postulate to be present. Moreover, the presence of well-formed cells suggests absence of vertical wind shear.

Instability in the Ekman boundary layer has been invoked as the cause of the appearance of the clouds shown in the picture on page 70. If this is so, we should perhaps expect to find a transition to such a pattern whenever a tropical disturbance changes from a cold-core to warm-core system of sufficient intensity. With the exception of Hurricane Anna, no other examples have yet been investigated for this effect.

Many of the cloud patterns discussed do not occur as often as one might expect if the mechanisms postulated for their cause were the only determining factors. These mechanisms, such as the flow past Madeira Island, or the Canary Islands, in the presence of a strong inversion, probably occur more often than we find the associated patterns in the satellite pictures. But to make the dynamical phenomena visible enough water vapor must be present. Moreover, in many cases there must be regions of local convergence so that upward motions can condense the water vapor. And these convergent zones must themselves be arrayed in a pattern consistent with the airflow postulated.

In spite of all these requirements, it is fascinating to find that the atmosphere does organize itself into a myriad of patterns made visible by clouds. And the need to infer the physical significance of the numerous cloud patterns observed from satellites poses interesting questions.

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