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Cellular Cloud Patterns revealed by Tiros I[1]

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Abstract

In this report some satellite (TIROS I) photographs of cellular cloud patterns are related to conventional meteorological observations. These cellular patterns occurred at the top of convective layers which were heated from below; and through which there was little vertical variation in wind velocity.

1. Introduction

On April 1, 1960 the National Aeronautics and Space Administration placed a meteorological satellite, called TIROS I, into orbit around the Earth. The primary function of this satellite was to photograph the Earth's cloud cover between about 55° N latitude and 55° S latitude; and for this purpose it utilized two cameras, one a wide angle camera capable of viewing a swath 800 miles wide, and another, a narrow angle camera, capable of examining in considerable detail a smaller area located within the larger area. The experiment proved to be remarkably successful, and during its two and one-half-month lifetime TIROS I photographed many interesting cloud features, some of which have already been described (FRITZ and WEXLER, 1960; WEXLER and FRITZ, 1960; STAFF MEMBERS, 1961). For a description of the satellite and its components the reader is referred to a series of articles published in the June 1960 issue of Astronautics (STERNBERG ET AL, 1960).

One of the cloud features revealed by TIROS I was a cellular pattern having horizontal diameters as large as 30 to 50 mi and consisting of clear centers bounded by ring- or U-shaped cloud elements about 10 to 15 mi wide. Such features are too broad to be recognized by a single observer at the Earth's surface, and yet small enough to remain undetected by even the best distribution of standard synoptic reports.

Three examples of such a cellular pattern are shown in fig. 1. The first picture (fig. 1a) was taken while the satellite was over the Atlantic Ocean, 650 naut mi northeast of Bermuda at 1612 GMT, April 4, 1960; the second (fig. 1b) was taken over the central Pacific, looking north westward towards the Aleutians at 2341 GMT, April 1, 1960; and the third (fig. 1c) was taken from a point 750 naut mi northeast of Hawaii at 2250 GMT, April 4, 1960.

The primary aim of this report is to relate this cloud pattern to the available meteorological observations. Emphasis is mainly on the Atlantic case (fig. 1a) since more extensive observations were available for this case than for the other two. These observations consist of the standard surface reports, radiosondes, pilot balloon observations, and aircraft reports including several dropsondes. Later, the problem of cellular convection, as treated by laboratory and theoretical studies, will be discussed briefly in relation to these TIROS observations.

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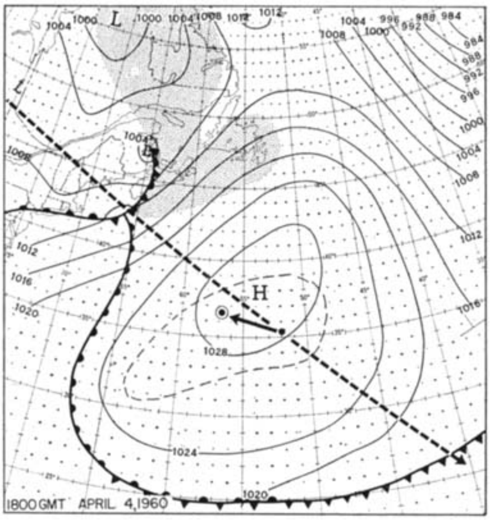

Fig. 3. Surface weather map for 1800 GMT, April 4, 1960. Track of TIROS I, subsatellite point (dot), and picture center (circled dot) are indicated. The area occupied by cellular cloud pattern in fig. 1a is outlined by dashed line.

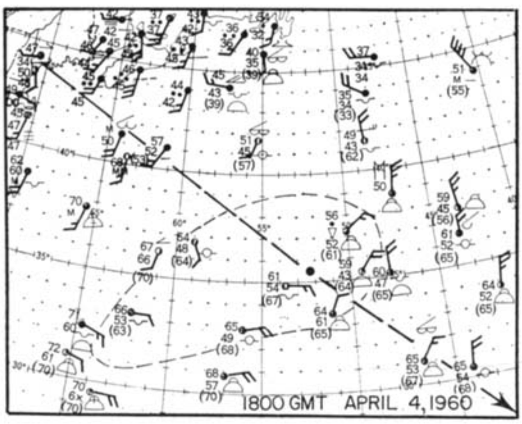

Fig. 4. Surface synoptic reports for 1800 GMT, April 4, 1960. Plotting model is abbreviated. Figures in parentheses are ocean surface temperatures. Track of satellite again indicated; and area occupied by cellular cloud patterns of fig. 1a is outlined.

2. Synoptic Analyses

The Atlantic Case.

To establish location and scale, a latitude-longitude grid[2] has been superimposed on

[2] The method for calculating these grids is described in another report (STAFF MEMBERS, 1961) and will not be discussed here.

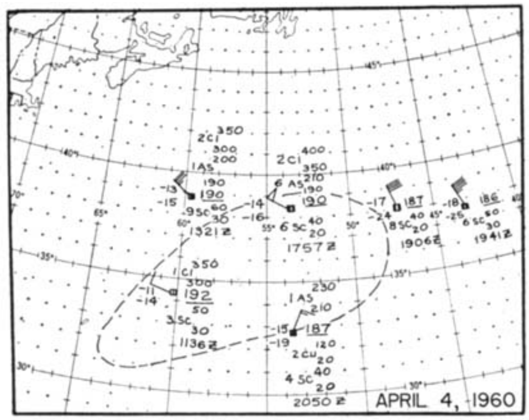

Fig. 5. Aircraft reports for period 1200 GMT-2300 GMT, April 4, 1960.

fig. 1a. This is shown in fig. 2, where it is readily apparent that the cellular cloud pattern in the foreground occupies a large area, extending in the picture about 650 naut mi in a west-east direction and 300 naut mi in a north-south direction. These cells have diameters ranging from 20 naut mi near the picture center to about 40 or 50 naut mi in the lower right portion of the figure.

The surface weather map corresponding most closely in time with this photograph is for 1800 GMT, April 4, 1960 (fig. 3). It shows an intense anticyclone with a maximum pressure of 1029 mb dominating the picture area. Northwest of this high pressure center, extensive middle and low cloudiness were reported with rain occurring near Nova Scotia and Newfoundland (fig. 4). This cloudiness, having the appearance of a stratiform type, is apparent toward the northwestern (upper left) portion of fig. 2. However, in the cellular cloud region of fig. 2 only low clouds, chiefly stratocumulus and cumulus, were reported (fig. 4). These observations were verified by a few aircraft in the vicinity which estimated these clouds to have bases around 2000—3000 ft. and tops ranging from 4000 ft. in the northern to 12,000 ft. in the southern part of the picture area (fig. 5).

The buoyancy of these cumuliform clouds arises in part from heating of the air mass at the ocean surface. Ships in this region, for example, reported ocean temperatures averaging about 3° C warmer than the air just above, with the smallest differences on the western

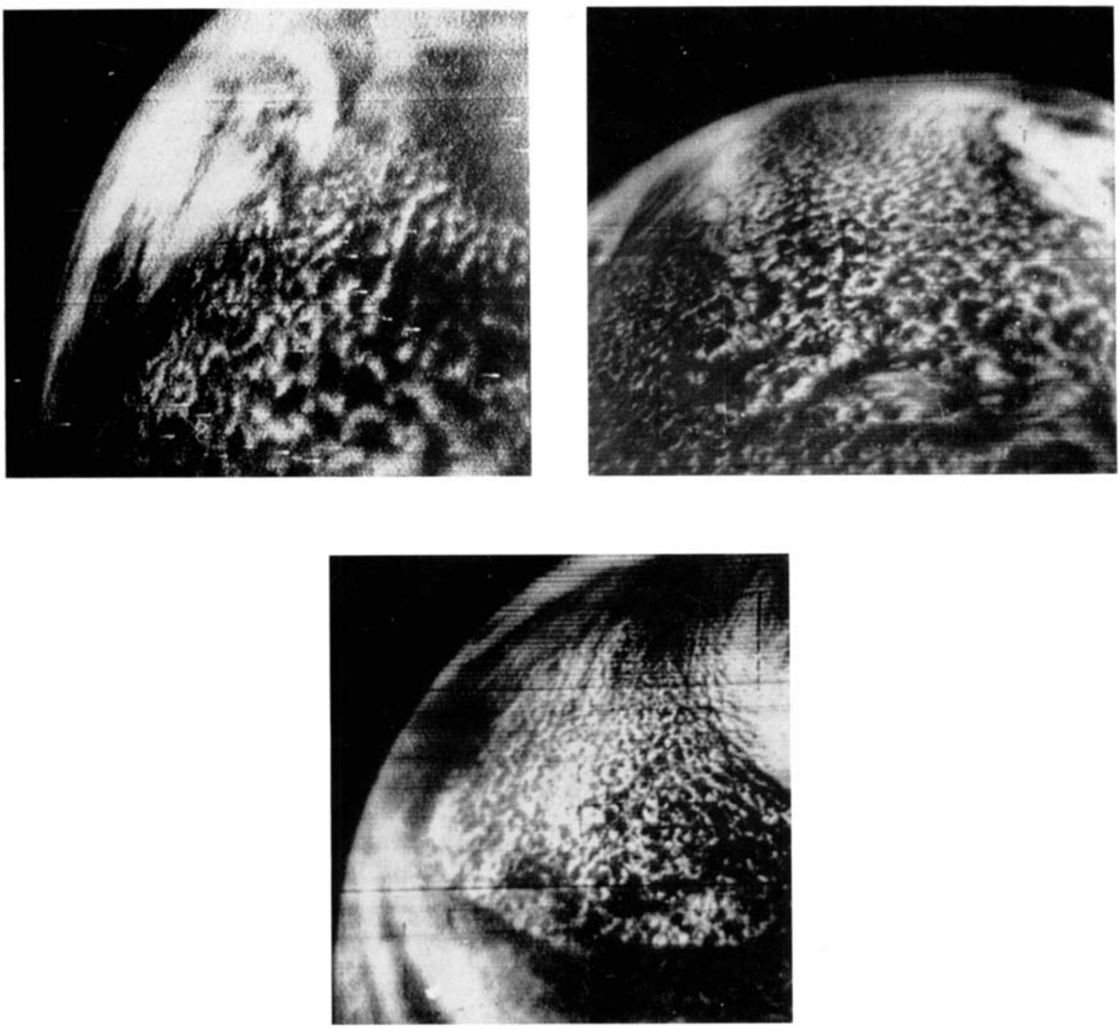

Fig. 1. TIROS I photographs:

a) taken 650 naut mi northeast of Bermuda at 1612 GMT, April 4, 1960.
b) taken over the Pacific looking northwestward at 2341 GMT, April 1, 1960.
c) taken 750 naut mi northeast of Hawaii at 2230 GMT, April 4, 1960.

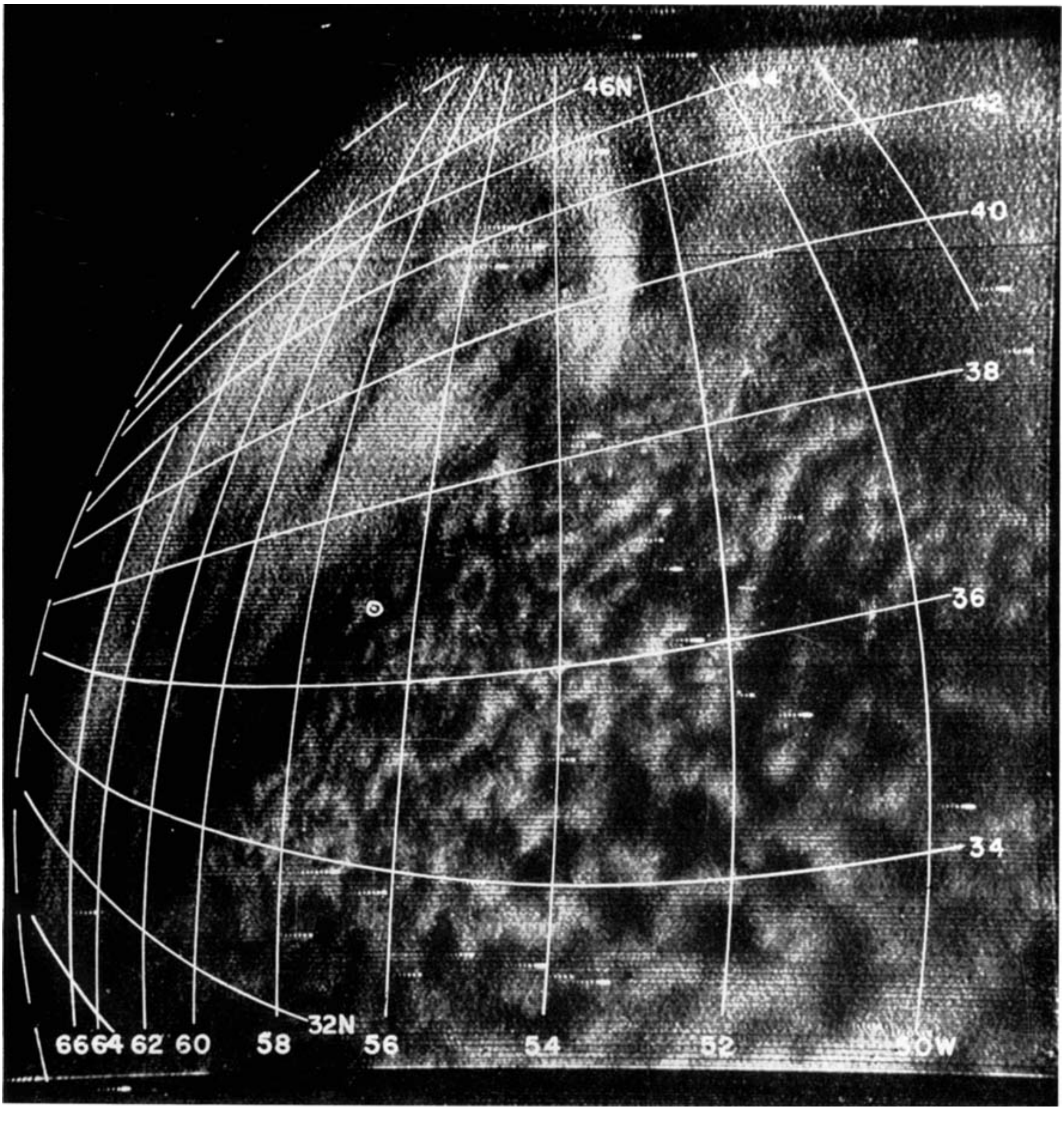

Fig. 2. Same as fig. 1a with 2° latitude-longitude grid superimposed.

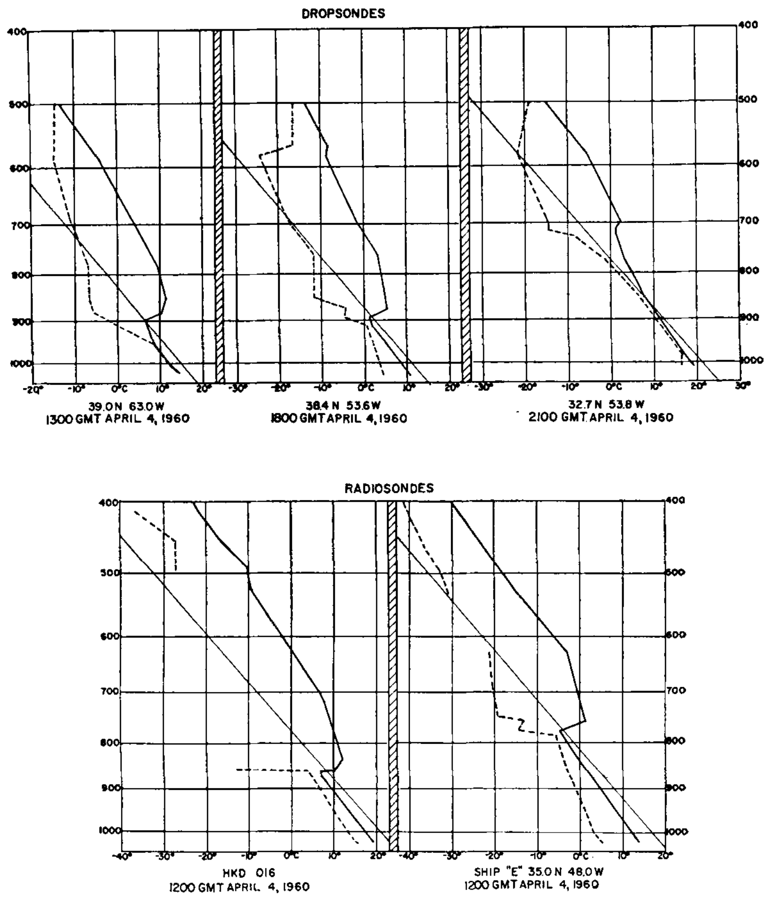

Fig. 6. Aircraft dropsonde observations at locations indicated and radiosonde observations at Bermuda and ship E between 1200 GMT and 2100 GMT, April 4, 1960. Solid lines show temperature distributions; dashed lines, dew point distributions.

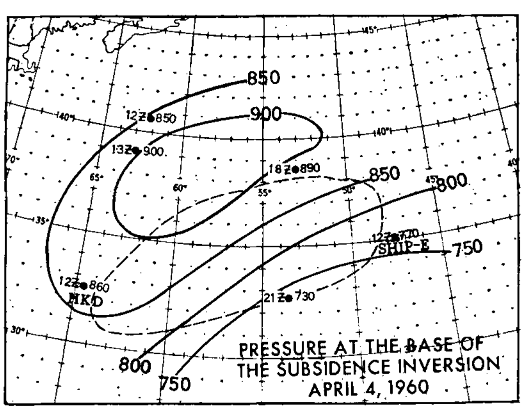

Fig. 7. Topography of the base of the subsidence inversion from data primarily in fig. 6. Analysis is for intervall of 50 mb.

side of the high pressure center and the greatest on the east where the surface wind had a northerly component (fig. 4). Radiational cooling at the cloud tops should also contribute to the destabilization of this air mass.

Radiosonde observations for Bermuda and ship "E" (35° N, 48° W) for 1200 GMT, as well as dropsondes from reconnaissance aircraft are illustrated in fig. 6, while the position of the soundings are shown in fig. 7. The sounding closest in time (1800 GMT) was a dropsonde at 38.4° N, 53.6 ° W taken near the edge of an altostratus deck (see figs. 2 and 4). This sounding showed a marked subsidence inversion at 900 mb (about 3000 ft.) capping a moist lower layer in which the temperature lapse-rate was close to dry adiabatic. Any con-

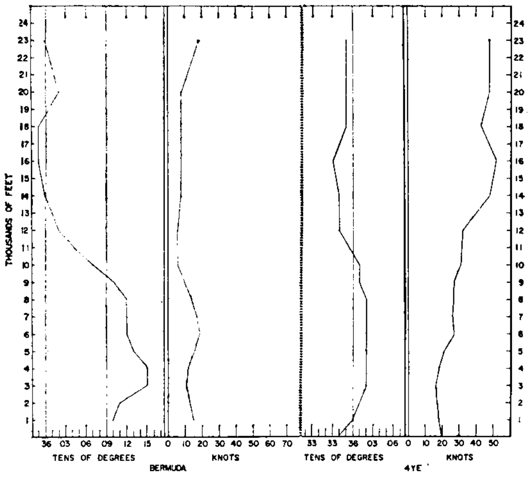

Fig. 8. Upper-wind soundings for Bermuda (1200 GMT) and ship E (1800 GMT), April 4, 1960.

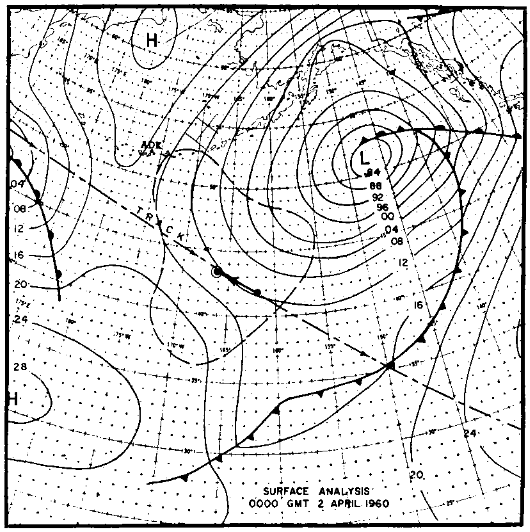

Fig. 9. Sea-level isobars and fronts, 0000 GMT, April 2, 1960. Track of TIROS I, sub-satellite point (dot), and picture center (circled dot) are indicated. The area occupied by cellular cloud pattern is outlined by dashed line.

vective clouds below this inversion presumably would be shallow since the condensation level was only 20 mb below the inversion. The presence of a higher cloud deck was indicated by increasing moisture with height above 600 mb.

A similar low-level structure, but with considerable variation in the height of the inversion and also convective cloud thickness, was indicated by the other soundings. The highest inversion (730 mb or about 9000 ft.) occurred in the southern part of the picture region (32.7° N, 53.8° W) with the thickest clouds also indicated (bases about 2000 ft, tops about 12,000 ft.). This seems to be connected with larger cloud elements and also larger clear spaces in the lower right portion of fig. 2.

The systematic spatial variation in depth of the moist lower layer is seen in fig. 7 which is an analysis of the topography of the subsidence inversion based on the few soundings available taken during the period 1200—2100 GMT. The average depth of this layer was about 850 mb, or approximately 5000 ft. Thus, if the cellular pattern is considered to include the entire convective layer rather than just the visible cloud, the horizontal scale is about thirty times the vertical scale.

Upper-wind soundings (fig. 8) were available only for Bermuda (1200 GMT) at the western extremity and ship "E" (1800 GMT) at the eastern end of the region. These showed a

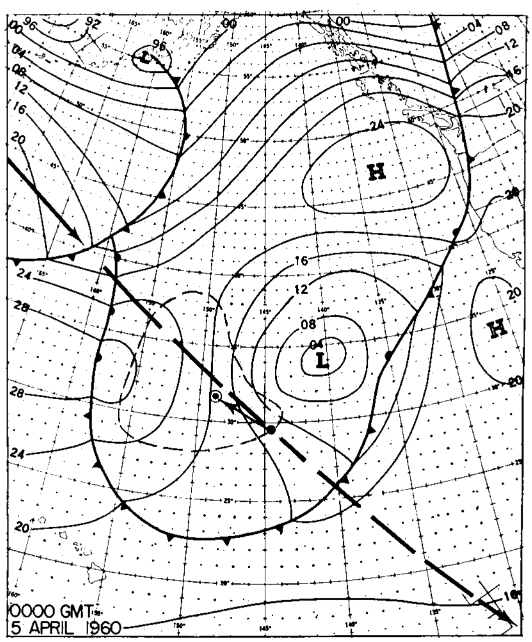

Fig. 10. Sea-level isobars and fronts, 0000 GMT, April 5, 1960. Track of TIROS I, sub-satellite point (dot), and picture center (circled dot) are indicated. The area occupied by cellular cloud pattern is outlined by dashed line.

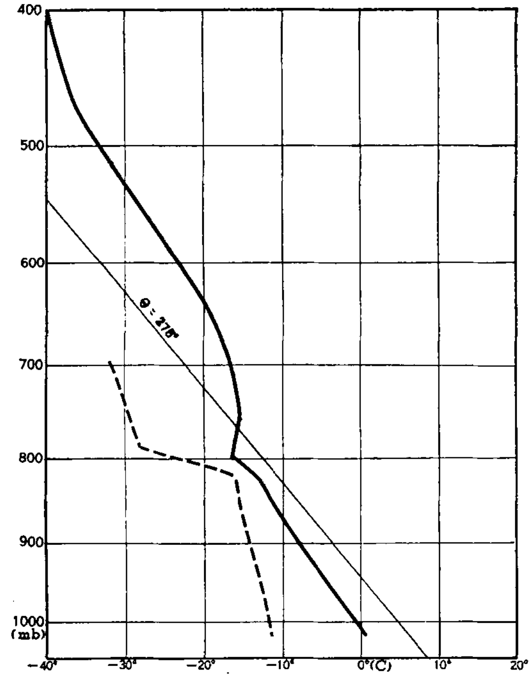

Fig. 11. Radiosonde observation for Adak, Alaska, 0000 GMT, April 2, 1960.

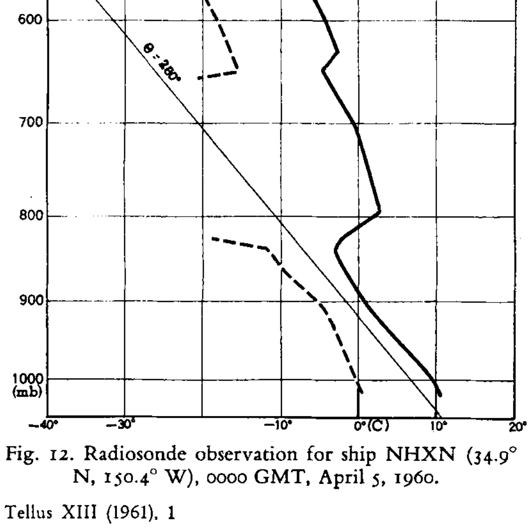

Fig. 12. Radiosonde observation for ship NHXN (34.9° N, 150.4° W), 0000 GMT, April 5, 1960.

veering of the wind up to 3000 ft. with a small decrease in wind speed. Above 3000 ft. the wind speeds increased about 10 kt to 6000 ft, while the wind direction remained uniform up to the base of the inversion (4000 ft. at Bermuda, 7000—8000 ft. at "E"). Above the inversion the winds backed to a northerly direction indicating cold air advection.

The Pacific Cases.

The surface map corresponding with fig. 1b is shown in fig. 9, and that for fig. 1c in fig. 10, again with the track of the satellite indicated and the area occupied by a cellular cloud pattern outlined. The synoptic conditions accompanying fig. 1b will be discussed first.

As may be seen in fig. 9, the surface flow in the region outlined varied from anticyclonic to cyclonic, in contrast to the anticyclonic flow accompanying fig. 1a. But surface reports in the area, except for the Aleutians, were almost non-existent. The available reports did, however, indicate considerable amounts of stratocumulus clouds. Such a northerly current from the Bering Sea, as was observed over the area, would also be expected to undergo considerable heating at the ocean surface. The only radiosonde observation available was from Adak, 730 mi to the northwest of the picture center, and was quite similar to those for the Atlantic case. Here the subsidence inversion was at 800 mb (fig. 11). Whether this sounding was representative of conditions in the central part of fig. 1b may be questioned, for it is generally expected that cyclonic flow is more unstable throughout a deeper layer than anticyclonic flow (PETTERSSEN, ET AL, 1946). That this may not be the case here is suggested by the JNWP vertical motion computations (not shown). That chart, applicable at 600 mb, showed subsiding motion over the picture area; thus an inversion should have formed at the base of this subsiding layer with the cellular pattern confined to the convective layer at some level below 600 mb. Some indication of greater vertical development, however, is suggested in the immediate foreground of fig. 1b, where a blurred appearance may have represented either anvil cirrus or patches of altostratus clouds.

The second Pacific case (fig. 1c) shows the smallest cellular pattern of the three cases. These are located in northerly flow with the isobar curvature again varying from anticyclonic to cyclonic across the area and occur to the rear of the cutoff low discussed by WINSTON (1960, see also STAFF MSL). In this area stratocumulus clouds were reported, and surface heating was indicated from the sea-air temperature difference. One radiosonde observation available in the area was quite typical of the others cited earlier (fig. 12). Another significant difference of this case from the Atlantic case was in the surface wind velocities. Here they ranged up to 30—35 kt compared with 12—20 kt for the Atlantic case. Pilot balloon observations were not available except from a ship about 300 naut mi to the south and this indicated little variation in direction or speed up to 5000 ft.

Summary

A study of the synoptic observations accompanying the three satellite pictures of cellular cloud formations described in this report indicated that: (1) a layer of moist air about 5000 ft. deep was heated at the ocean surface resulting in an adiabatic lapse-rate, (2) superimposed over this layer was another of greater stability which served to inhibit the convection and (3) throughout the convective layer there appeared to be little variation in wind speed and direction above that portion influenced by s urface friction.

These distinctive cloud patterns, especially those in fig. 1a, have the appearance of Benard cells. There are, however, many important physical differences between the patterns observed by TIROS I and those observed in the laboratory.

3. Physical Nature of Cellular Convection

Cellular convection was studied in detail by Benard early in the century (cf BRUNT, 1951). The patterns he observed in unstable liquids consisted of cells with upward motions in the center and descent at the periphery. His findings led him to suggest that certain cloud patterns, such as cirrocumulus, might represent cellular convection. Stimulated by his pioneering, other investigators undertook the study of these Benard cells and attempted to relate their findings to atmospheric cloud patterns. Theoretical work was originated by RAYLEIGH (1916) who determined the criterion for the onset of convection. This criterion indicates that Benard convection will not occur unless the density at the top of a fluid layer exceeds that at the bottom by an amount that varies directly as the molecular heat conductivity and viscosity, and inversely as the cube of the depth of the fluid.

The cloud patterns illustrated in this report, presumably with upward motion and cloudiness at the periphery and descent in the clear centers, are more typical in general appearance to cellular patterns obtained from convection experiments with an unstable layer of air (CHANDRA, 1938; GRAHAM, 1933). In these experiments smoke-laden air confined within a suitable container is destablized, usually by heating from below. If no shearing motion in the vertical is present, it is found that the mixture breaks up into a series of polygonal cells that have the intracellular motion just described. The observed polygonal pattern is an unsteady one, displaying a tendency for the cells to join into long rolls and the rolls in turn breaking up into polygonal cells. Increasing the depth of the chamber results in an increase in the cellular diameter, but the ratio of this diameter to the depth of the convective layer remains about two or three to one (AVSEC, 1939). This cellular configuration with its characteristic intracellular circulation has hitherto rarely been observed in natural cloud patterns, and consequently the reverse type, characteristic of cellular convection in liquids, has been the expected one (BRUNT, 1951).

Although observations of cellular convection by TIROS I have the appearance of experimental and theoretical studies of Benard cell convection, significant differences are evident. If the observations presented here are to be compared with Benard phenomena, then certain problems suggest themselves. One of these is related to scale. For example in laboratory and theoretical studies a diameter to depth ratio of three to one is obtained (BRUNT, 1951; NAKAGAWA & FRENZEN, 1955). In this study a value ten times as large was obtained—a ratio that is, interestingly, comparable to that found by WOODCOCK and RILEY (1947) from a study of cellular patterns in pond ice. Clearly, further investigation into the physical parameters that determine scale is required.

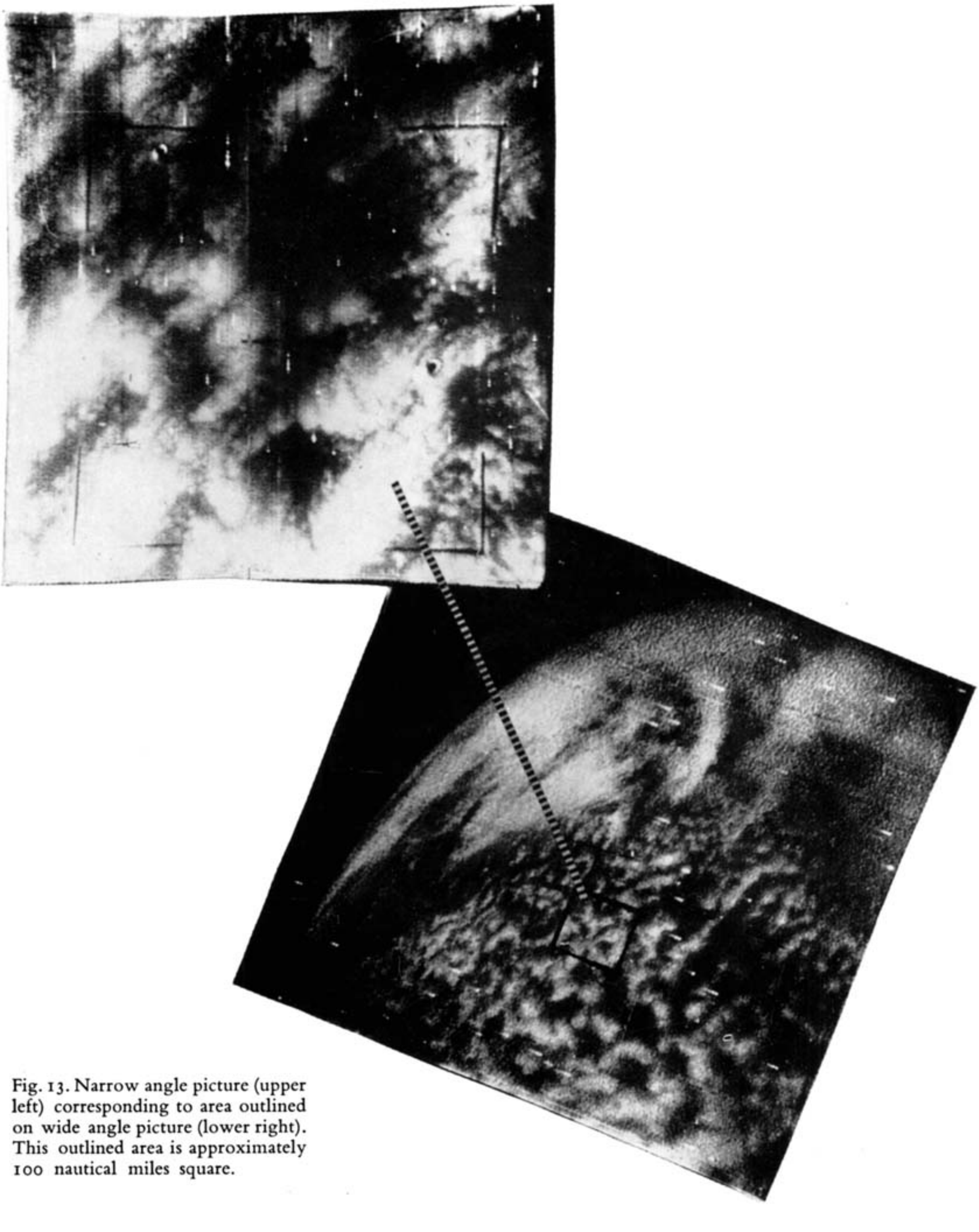

Fig. 13. Narrow angle picture (upper left) corresponding to area outlined on wide angle picture (lower right). This outlined area is approximately 100 nautical miles square.

Another problem is related to the detailed structure of the convection cells. This is apparent from an examination of the narrow angle TIROS I picture corresponding with fig. 1a (fig. 13) where it is seen that the cell walls are often made up of individual cloud elements. This is verified by surface observations of stratocumulus in the area (fig. 4). Thus the TIROS cellular cloud pictures indicate several scales of motion, while in contrast the typical Benard cell as obtained in the laboratory appears to possess a very simple structure and circulation.

Further difficulties involve the treatment of heat conduction and viscosity; for, on the scale of motion in fig. 13, the use of eddy coefficients is required, and these vary widely in space and time. Also, the release of latent heat, compressibility and perhaps the spatial variation of heating should be considered. Some of these problems have been discussed by Malkus (1952) in an interesting review of the convective cloud problem.

The observations presented in this report are but a few examples of cellular convection obtained during the lifetime of TIROS I. Many other examples remain to be studied. For, among its many findings, TIROS I has indicated that cellular convection occurs at a larger scale, and over a greater portion of the Earth's surface, than heretofore realized. These observations should serve to stimulate an increase of interest in this challenging problem.

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