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The Band Structure of the Atmosphere

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Abstract

A general characteristic of the atmosphere is its streakiness. It manifests itself in many phenomena such as the "cloudstreets" of polar outbreaks and tradewinds, the radar bands of hurricanes and certain precipitation patterns, the squall lines and the jet stream cirrus.

The banded structure can be traced back to convection in heated air flows with a curved velocity profile of rather uniform direction. The typical vertical curvature was found to be 10^{-7} (cm^{-1} sec^{-1}). A preliminary note deals with some theoretical considerations.

Synoptic cloud analysis by weather satellites will greatly profit from the wide spread existence of cloud bands.

1. Introduction

The advent of the jet and rocket age presents the meteorological observer with a revealing bird's eye view of the atmosphere. One of the most striking features of tropospheric weather as seen by a stratospheric observer is the streakiness of the cloud systems. Almost invariably a considerable fraction of cloud layers spreading under the observer is organized in bands running in the general direction of the flow (Figs. 3 to 5). With some practice one can estimate the wind direction at cloud level purely from looking at the cloud structure (a possibility to be exploited by meteorological satellites). The band structure of cloud systems is also apparent on many of the composite pictures taken from high flying balloons or rockets (Figs. 6 to 8). (BERGSTRALH 1947, HUBERT and BERG 1955).

That the meteorological literature contains so little on this widespread phenomenon of the "cloudstreet" may be in part due to the worm's eye view of the ground observer, in part it may be a consequence of the regrettable neglect, direct cloud observation in general and nephanalysis in particular have suffered in the last decade. A survey on the occurrence of cloudstreets indicates that they are frequent in all latitudes and, in some areas even represent the prevailing type of atmospheric convection clouds. Much information on the structure of cloudstreets has been supplied by glider pilots who are fond of this phenomenon and who introduced the term "wind thermals" to express their observation that a combination of thermal convection and strong winds is required to produce cloudstreets (KUETTNER 1949). However, the priority of their discovery that the tedious circling technique in columnar thermals could be replaced by a comfortable tailwind flight beneath the cloudstreets must be given to the sea gulls (WOODCOCK 1942) who seem to have enjoyed this technique for millions of years.

A more systematic study of the banded

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structure in the atmosphere is suggested by certain similarities with laboratory experiments. While a considerable literature exists on the artificial formation of "longitudinal rolls" or "strips" in flowing media heated from below, and on the analogy with certain cloud patterns in the altocumulus level (MAL 1931, AVSEC 1939, BRUNT 1951) no satisfactory theoretical interpretation has been offered so far. As the equations governing this flow embrace the effects of viscosity, buoyancy and vorticity, the silence in this matter may well be a reflection of some discouraging efforts of workers in this field.

A first step towards the solution of this problem is a more thorough understanding of the conditions under which bands form in the atmosphere. A general description of the phenomenon and the results of a special aerological investigation will be given in Part I of this study. Part II, to be published separately, will discuss the theory of organized convection in the atmosphere.

2. General Description and Definition of »Cloudstreets«

The most common type of cloudstreets may be defined as a system of long rows of cumulus clouds stretching in the general wind direction. The pictures, 1 to 8 give examples of convection bands as they occur in the atmosphere. From Fig. 1 and 2 it can be seen that the cloudstreets sometimes extend in parallel bands across the whole visible sky. Most of them show indications of individual cumuli lined up like pearls on a string. But the most spectacular cases of parallel cloudstreets resemble continuous roll clouds (Fig. 3). Such clouds form during a similar diurnal period as normal cumulus clouds do. Although individual cumulus streets sometimes originate over and downwind from a heat source, such as an industrial plant, a fire, a heated island, a warm lake or along a mountain range, the phenomenon discussed here is, in general, independent of orography. In fact, orography tends to disturb rather than to create cloudstreets and probably for that reason they are best developed over oceans. Interesting in this respect is the observation that cloudstreets are the prevailing form of thermal convection during the Arctic summer over Scandinavia (KUETTNER 1937). Here the terrain consists mostly of tundra, lakes and hills, but none of the features of the topography is reflected in the cloud picture. Even over the Arctic pack-ice convection in the lower levels forms regular cloudstreets as far north as 80° during the almost uninterrupted solar heating of the summer months.[1] Similarly, observations in the tradewinds show that cloudstreets are a characteristic form of convective activity over the tropical oceans.

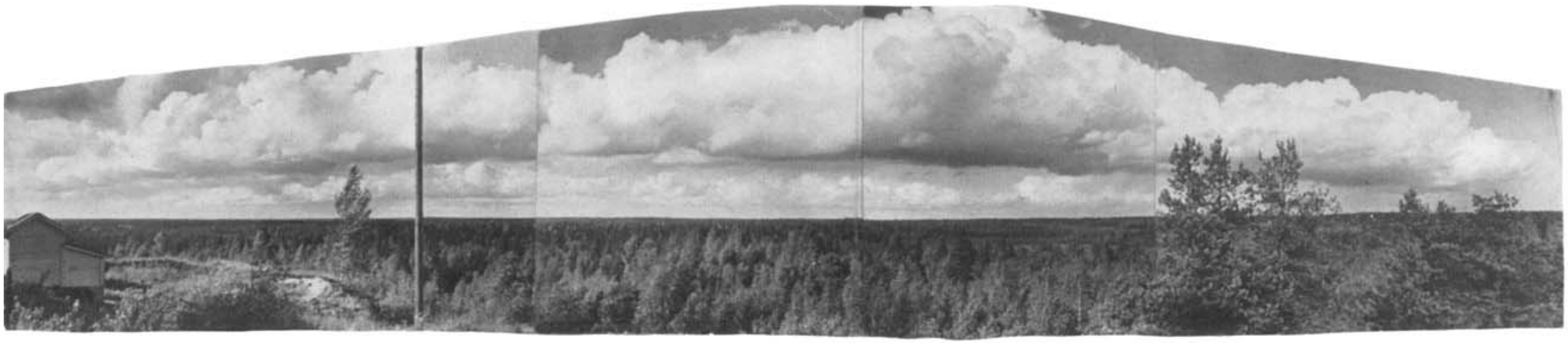
Frequently the cumulus tops of cloudstreets have a definite ceiling, indicating the existence of a temperature inversion which restricts vertical motion to a well defined layer over the ground. For instance, the cloudstreets of Northern Scandinavia form preferably in fresh outbreaks of Arctic air which is heated quickly from the ground during the long Arctic summer days. An aerological study of this process (KUETTNER loc. cit.) shows how an adiabatic layer establishes itself through a depth of 2 to 3 km, topped by a well defined inversion and maintained for as long as 15 hours daily. Most of these characteristics were already found in cloudstreet studies by the German Soaring Research Institute, DFS. (MALETZKE, 1953.)

Some estimates of the *length and spacing* of cloud streets may be appropriate. Typical values are: 50 km in length and 5 to 10 km spacing from axis to axis. However, cloudstreets of several hundred kilometers have been seen. With a characteristic layer depth of 1½ to 3 km the spacing of the cloudstreets lies frequently between 2 and 3 times the height of the convective layer. Occasionally isolated cloudstreets are observed.

Patient observations reveal that cloudstreets have a cycle with a lifetime of the order of one hour. They appear to build up and dissipate on both ends, sometimes in such a fashion that the street as a whole drifts slower than the elements in the street. This indicates that the street propagates upwind with respect to the mean wind and, in rare cases, even with respect to the ground. The dissipation is often seen to start through interference with other growing cloudstreets.

From glider observations there is sufficient evidence that vigorous *updrafts* exist under certain sections of the cloud base while down-

[1] Observations by the writer on weather reconnaissance from Alaska poleward during June 1957.



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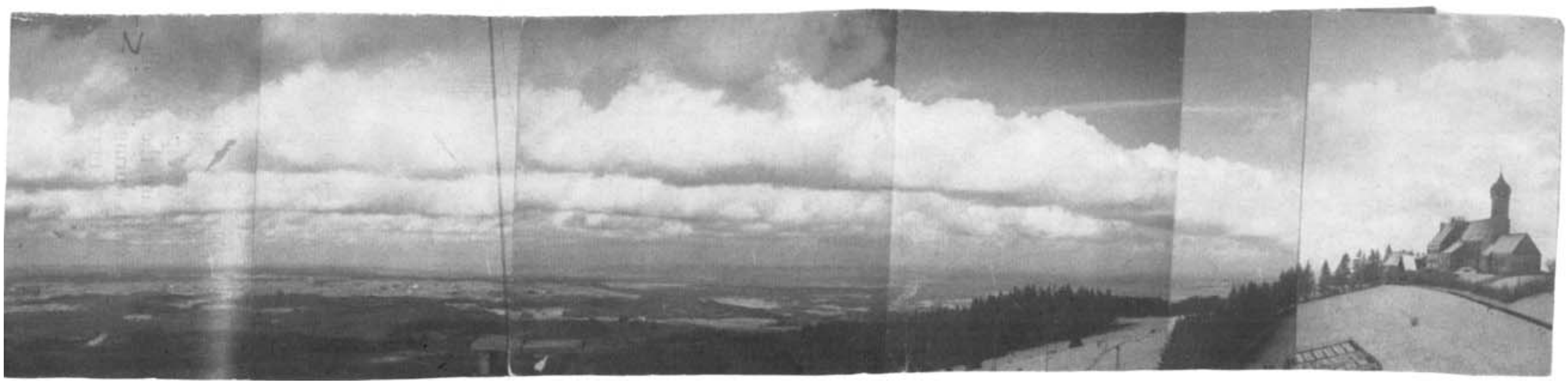


b

Fig. 1. Panoramic view of cumulus cloud streets lined up in flow direction.
a.: Hohen Peissenberg Observatory, Germany, 13 Feb. 1948. (Photo: H. Weickmann.)
b.: Ilmala Observatory, Finland, spring 1936. (Photo: Rossi.)

Fig. 2. Panoramic view of winterly cumulus cloud street oriented in wind direction. Blue Hill Observatory, U.S.A., 17 Dec. 1953. (Photo: C. F. Brooks.) For wind conditions, see Fig. 9.

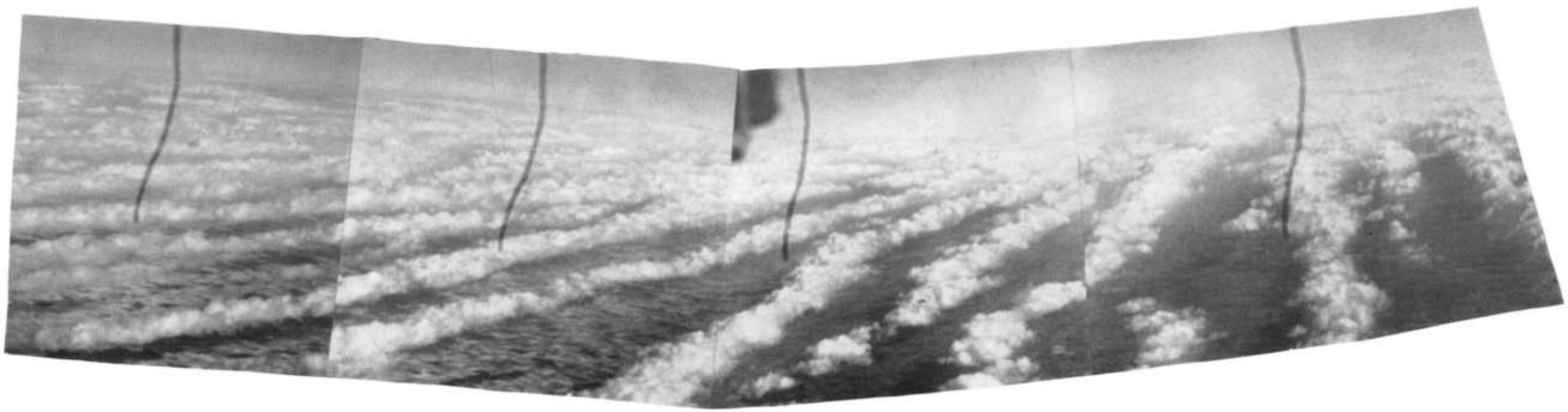


Fig. 3. Panoramic view of system of cumulus cloudstreets following low level flow over New York State taken from B-47 aircraft at 11 km altitude, 10 April 1957. (Photo: J. Kuettner.) For wind conditions, see Fig. 11. Note: The 4 black lines are due to a disturbance in the camera.

Fig. 4.

Fig. 5.

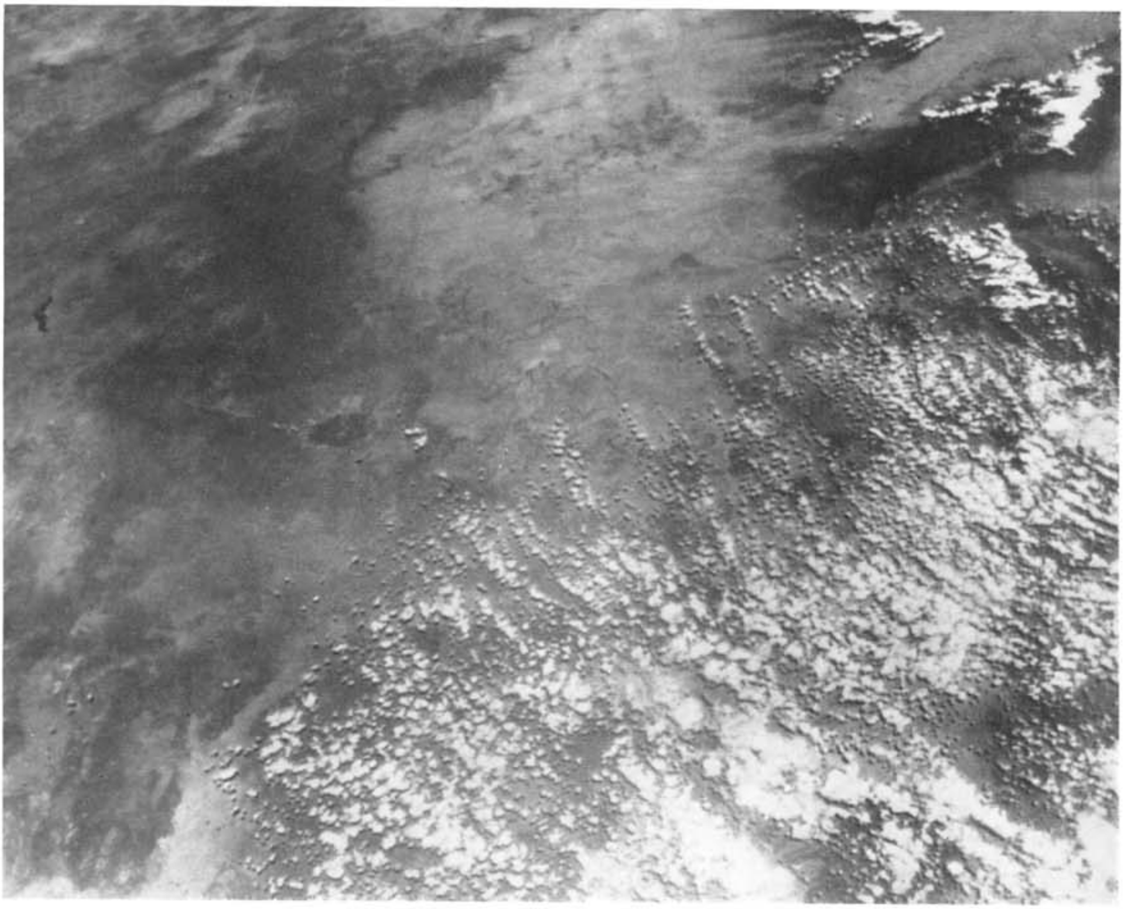
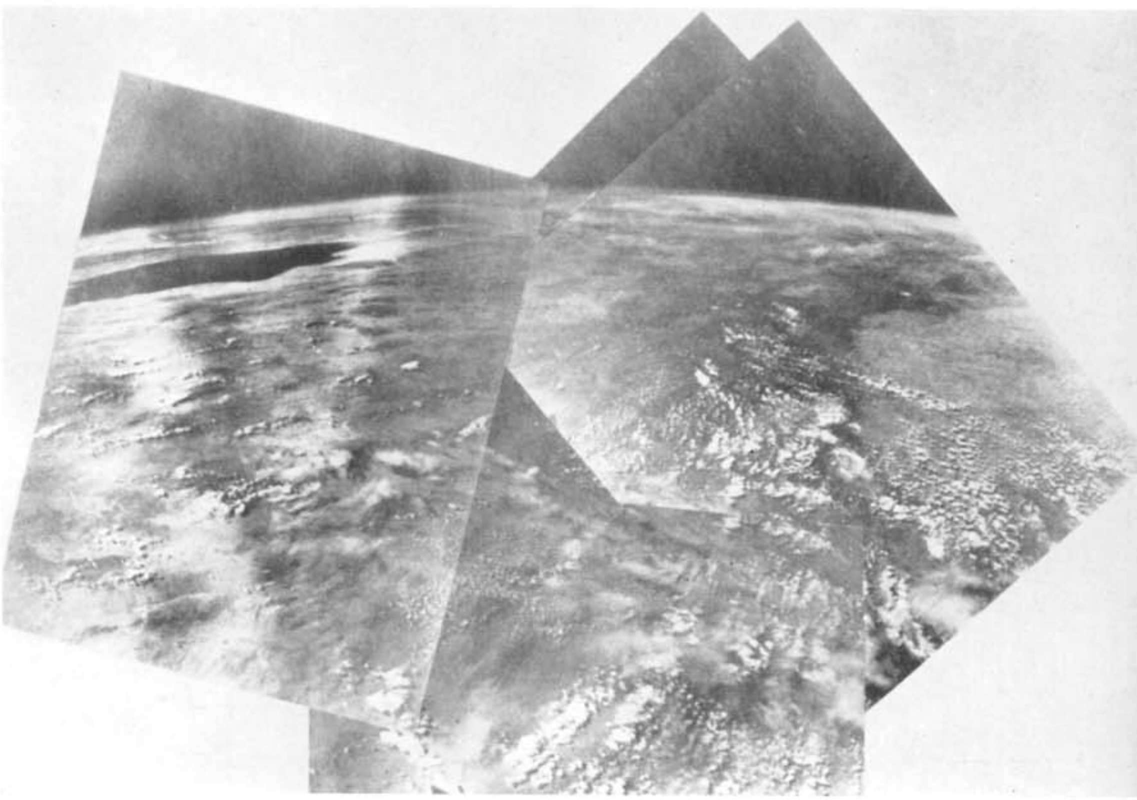


Fig. 7.



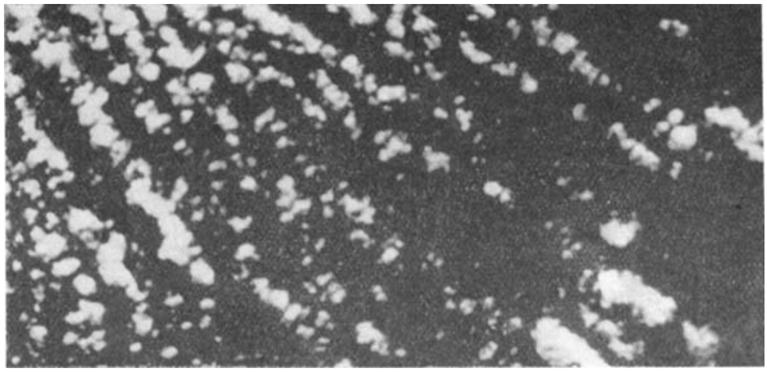


Fig. 6. Cumulus in bands over New Mexico, photographed from Aerobee rocket, 5 Oct. 1954. (Photo: Naval Research Lab.)

drafts occupy essentially the space between the bands. Compared to the flow in columnar thermals the updrafts in cloudstreets are generally estimated to be stronger under otherwise similar thermal conditions.

More information about these details is available from the use of whole-sky or wide angle time lapse pictures, as are now being taken at the Harvard Blue Hill Observatory near Boston under contract with the Air Force Cambridge Research Center. Another source of information lies in pilot's reports. A vivid glider flight account is given in the Appendix. Here Dr. Steinhoff describes his surprising experience when he encountered and recorded this interesting phenomenon for the first time in flight history. In the light of subsequent experience his observations on the distribution of drafts and turbulent zones are of special interest.

Fig. 4. Early morning cumulus cloud streets, oriented in the direction of low level winds, as seen from appr. 10 km height over Tampa, Florida, 12 August 1957. (Courtesy: V. Plank, Airforce Cambridge Research Center.)

Fig. 5. Cloudstreets lined up in wind direction near Tampa, Florida, 30 August 1957, as seen from about 5 km altitude. (Courtesy: V. Plank, Airforce Cambridge Research Center.)

Fig. 7. Cumulus bands as seen from 150 km altitude, 5 Oct 1954. (Aerobee rocket photo by Naval Research Lab.)

Fig. 8. Composite picture of more than one million square kilometers of Northern Mexico and Southwestern United States. (Photos taken from V2 rocket by Naval Research Lab.) Date: 7 March 1947. Altitude: 160 km. Cloudbands in lower right and center follow surface flow converging over Arizona.

3. Aerological and Synoptic Analysis of Extra-Tropical Cloud-Streets

This study was stimulated by the following thoughts. The reports by glider pilots that only the fast drifting "wind thermals" transform into streets and the corresponding evidence from laboratory experiments suggested an extension of Rayleigh's theory of cellular convection to flowing media. No effects of consequence are, however, obtained from an introduction of a uniform basic flow into the equations. Apparently additional characteristic parameters are required. Some authors, (see Brunt, 1951) have stated that wind shear is a decisive factor. But to the writer's knowledge a systematic investigation of the wind conditions connected with cloudstreets has never been made.

Under these circumstances an aerological and synoptical study was undertaken in the fall of 1953 in the Boston area which has covered over 50 cloudstreet days so far. Routine observations of wind and temperature were used in this preliminary investigation. Data included pibal soundings of the Weather Bureau Airport Station at Boston and, if available, radiosonde and rawins taken by the Air Force at Bedford, a suburb of Boston, and by the Army Signal Corps at Ft. Banks in Boston's harbor. When required use was made of other New England upper air stations such as Nantucket (ACK) 90 miles SE, Portland (PMW) 90 miles NNE, and Mitchell Field (HEM) 175 miles SW of Boston.

Consistently a striking feature was found—a strong *curvature* of the wind profile containing

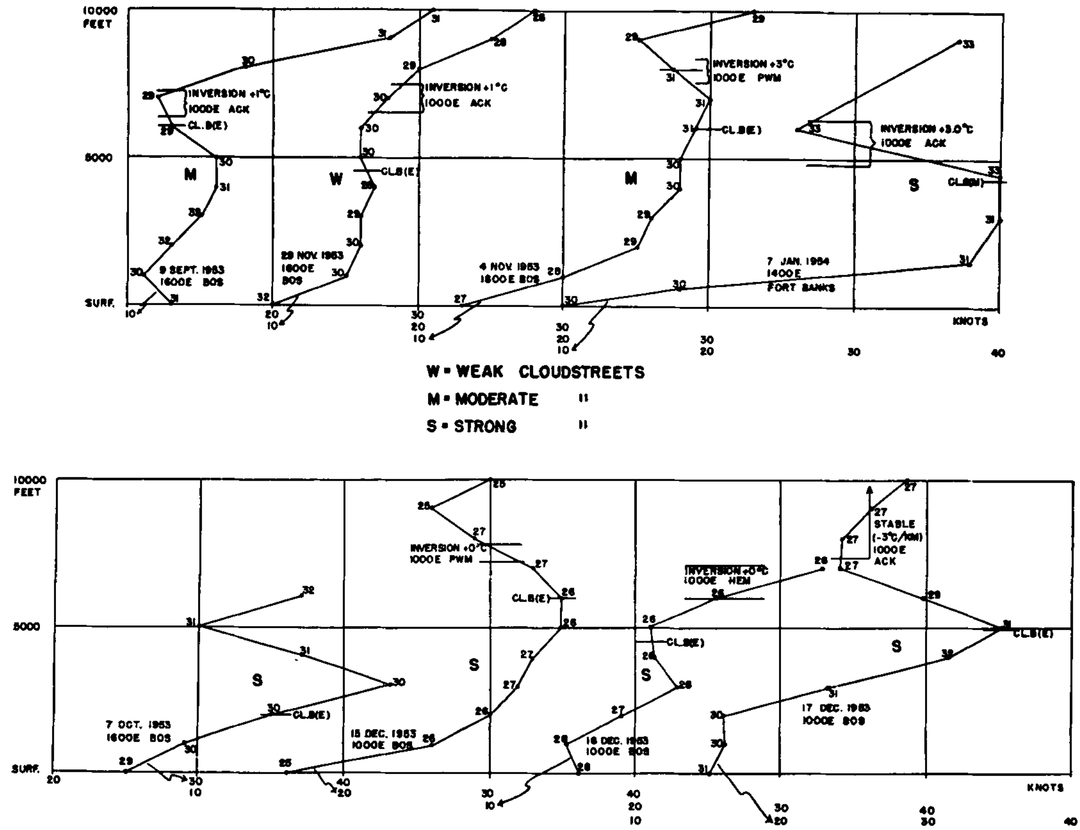


Fig. 9. Vertical wind profiles on days with cloudstreet development as observed near Boston, Mass. Windspeed in knots (running scale) vs. altitude in feet. Small numbers along curves denote wind direction in tenths of degrees. CL. B. = Cloud Base. E = estimated. Cloud photo, Fig. 2, corresponds to sounding at lower right (17 Dec. 1953).

in most cases a definite wind maximum within the convective layer. There is very little indication of a linear wind shear or uniform flow, Fig. 9 to Fig. 11. The illustrations also show that variations of wind direction with height are quite small, in fact, they permit replacing the vector wind profile with the scalar wind profile without appreciable error. This calls for discussion in a later section. It is evident from the figures that the mean variation of the vertical wind shear with height throughout the convective layer is of the order of -10^{-7} (cm^{-1} sec^{-1}) corresponding to a negative curvature of about 10 m/sec per km^2. However, in extreme cases, values as high as the threefold and as low as one-third of this figure are observed.

With rare exceptions the wind speed in the lower atmospheric layer is considerably higher than normal. The average scalar surface wind on days with cloudstreets in the Boston area was about 70 % above the 60 year scalar climatological mean. (15 knots as compared to an annual mean of 9.0 knots and a maximal monthly mean of 10.2 knots in March according to the Weather Bureau's Climatic Summary of the U.S.). This situation seems to justify the use of the term "wind thermals" by glider pilots.

In some cases with low level cloudstreets we find a jet-like wind maximum close to the ground (Fig. 10 upper part) which will be discussed in connection with the synoptic interpretation of the wind profile. Our findings on the wind have been summarized in Fig. 25 (left curve), by averaging height and wind velocity for the 3 levels: ground, wind maximum and upper wind minimum. (In this

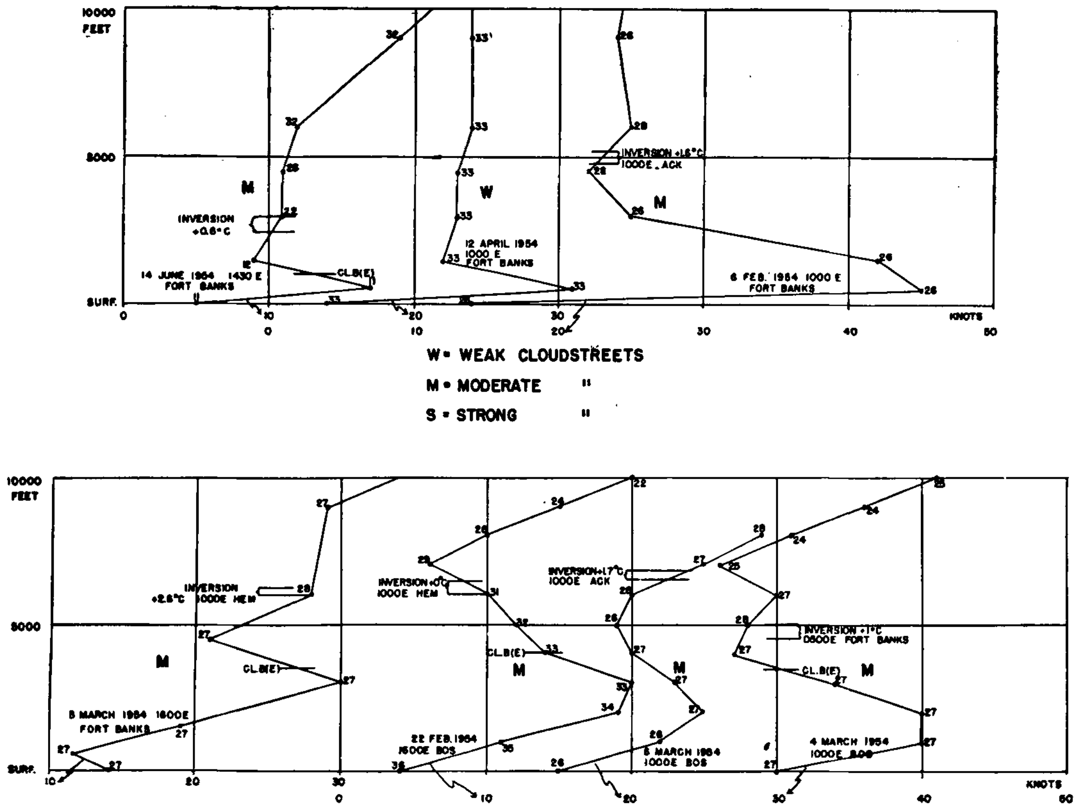


Fig. 10. Same as Fig. 9. Upper series shows cases of "low level jets".

figure the forementioned shallow "ground jets" have not been included.)

The earlier observations that cloudstreets are topped by a stable layer or *inversion* are borne out by most of our data. On the average, this lid was found at about 2 km above ground, quite close to the level of the upper wind minimum. See Figs. 9 and 10.

In a few cases it has been possible to take some rough measurements of the cloudstreet *dimensions* by checking cloud shadows with land marks in the lowlands around the Blue Hills Observatory. For example, on Dec. 16, 1953, the three nearest cloudstreets had a mutual spacing of 7.2 and 8.5 km respectively (from axis to axis) while the mean width of each cloudstreet was 2.3 km and their length more than 40 km. With a cloud top around 2.5 km the spacing-depth ratio was about 3. Evaluation of Fig. 3 indicates an average spacing of 8 to 10 km at a layer depth of 2.5 to 3 km and a length of 50 to 80 km.

The actual flow pattern in cloudstreets is not sufficiently known. Its measurement represents a major problem and the method used to explore a tradewind cloudstreet in flight (described in Section 6) may give some suggestions how it should be done. The quasi-steady state of cloudstreets facilitates somewhat the study of the airflow in comparison with that of the isolated columnar convection for which the instantaneous flow pattern is largely unknown. The flight report of Steinhoff (Appendix) gives some evidence that under the base of the cloudstreet the draft distribution is not symmetrical with respect to the axis and further that there are definite zones of strong turbulence imbedded in this draft structure. As to the circulation near the cloud top an interesting observation by AUF'M KAMPE, WEICKMANN and KELLY (1953) indicates that there is horizontal divergence towards both sides of the cloudstreet. These authors write (p. 22)

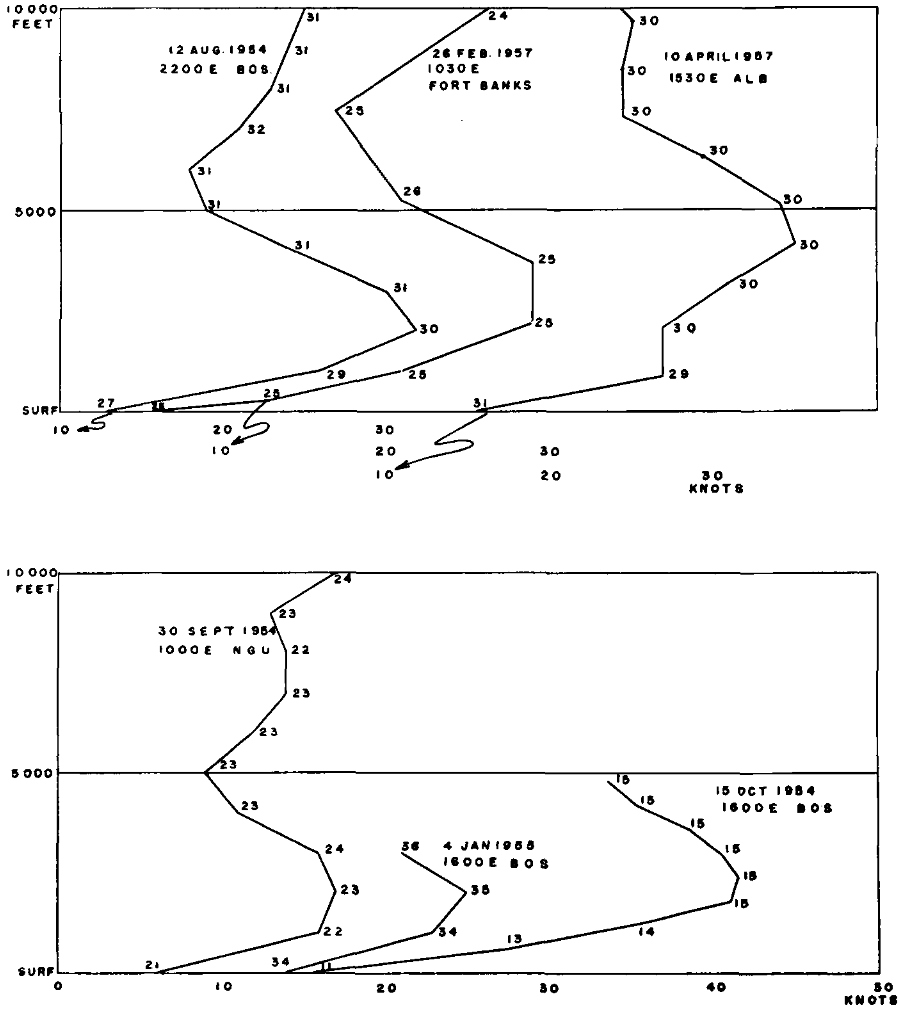


Fig. 11. Same as Fig. 9. Observations over Eastern United States. Panoramic cloud photo, Fig. 3, corresponds to sounding in upper right (10 April 1957).

"... we had some dry ice left which we dispersed at a rate of about three pounds per mile for eight miles along the middle ridge of a cloud line consisting of supercooled water clouds. After the seeding was finished nothing happened immediately, but nine minutes later ice crystals appeared left and right of the cloud line but none underneath. The cloud line itself was not modified. This experiment indicated that the circulation which formed the cloud line consisted of an up draft under the ridge, diverging horizontal flow near the top of the cloud line and downdrafts at some distance left and right of the cloud edges. The velocity in the updraft must have been higher than the fall velocity of the generated crystals which was about $\frac{1}{2}$ meter per second. Thus, they did not stay in the cloud and were carried away horizontally."

Time lapse pictures of cloudstreets do not give a clear impression about the circulation as horizontal and vertical motions cannot easily be separated visually. Stereoscopic motion pictures will be required.

A study of the *synoptic situation* reveals that most of the extratropical cloudstreets occur in vigorous outbreaks of polar air which is heated from below during its progress towards warmer regions. An intense cold High is almost invariably found on the surface map. Along the low level trajectories the flow is from cold to warm with the cold center to the right and the warm center to the left. The temperature gradient *across* the flow calls for a pressure gradient decreasing with height. By the time the 700 mb level is reached, not

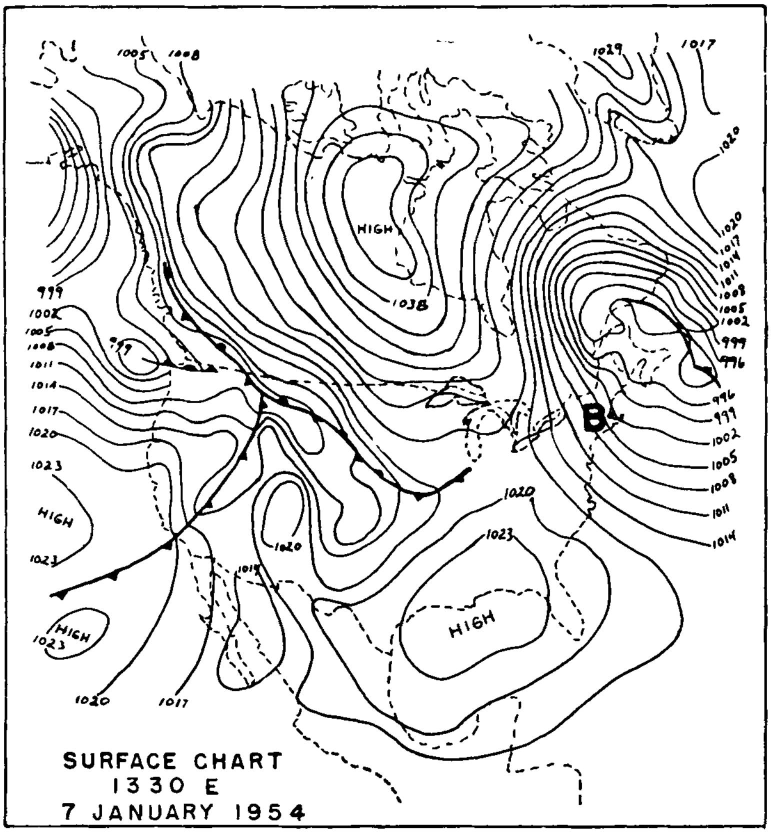


Fig. 12. Surface weather map during strong cloud street development over Boston (= B). For vertical wind profile near Boston, see Fig. 9, upper right (7 Jan. 1954).

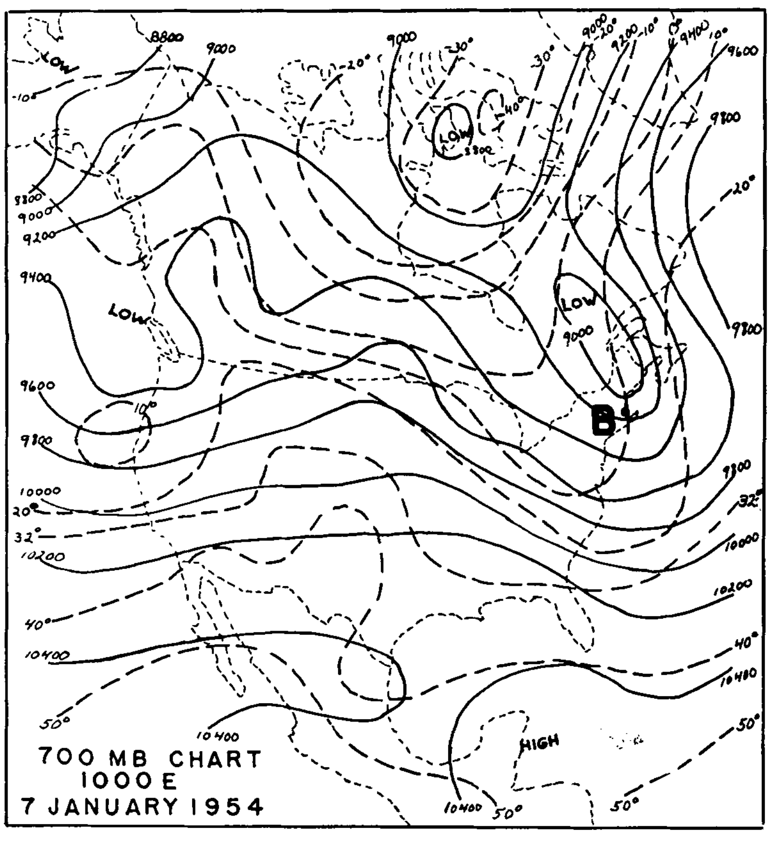


Fig. 13. Upper air map of same day as in Fig. 12. Solid lines: contours of 700 mb surface. Dashed lines: temperatures.

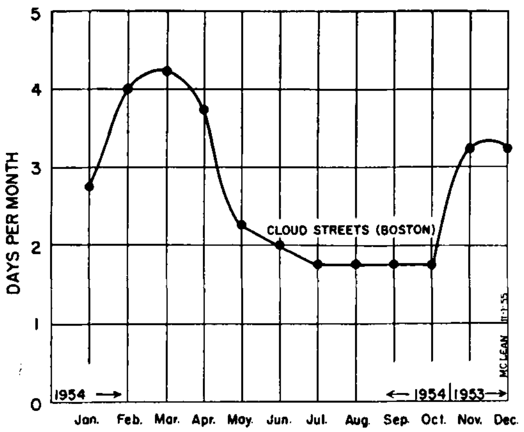


Fig. 14. Seasonal march of cloudstreet development, as observed in Boston (USA) during 1953 and 1954, indicating that this type of cloudstreet (formed in polar outbreaks) is primarily a winter phenomenon.

much of the surface High is left and, were it not for friction, the (geostrophic) wind would be a maximum at the surface.

The temperature gradient *along* the flow indicates cold air advection and hence calls for backing rather than veering of the wind with height. This vertical variation of the wind direction tends to line up the vector of the upper (geostrophic) flow with that of the lower (frictional) flow giving a uniform direction throughout the layer. Fig. 12 and 13 give an example.

It can be stated then that the curved wind profile owes its existence to a *frictional wind increase with height in its lower portion and to a thermal wind decrease in the upper portion*, while the almost two-dimensional uniformity of the wind direction follows from the cold air advection of the low-level flow which gains heat during its progress. This situation will be encountered again in our discussion of the tropical cloudstreets. Occasionally the strong flow in the lower troposphere, between the deep low and the cold high, is straight over a horizontal distance of the order of 1,000 km. The conditions favorable for cloudstreets extend into the area where the flow is anticyclonically curved and where subsidence inversions exist with relatively clear skies. This confirms earlier conclusions by MALETZKE (1953) who considered the Middle West and "Texas Northerns" as optimal situations for cloudstreets.

As a phenomenon of cyclonic activity extratropical cloudstreets occur preferably in winter except in high latitudes. This is demonstrated by the (smoothed) *frequency* curve of Fig. 14 which, however, should be considered with reservations in view of the small sample. In the year Oct. 1953 to Sept. 1954, cloudstreets over the Boston area were observed on 35 days. As complete coverage was not ensured, a figure of 40 to 50 days per year may have been closer to reality. In other latitudes cloudstreets are far more common.

As to the "low-level jet" profiles of Fig. 10 mentioned earlier, it is doubtful if they are of the same type as the other profiles. In some cases these data represent a shallow sea breeze with easterly winds. Again we have heating of a cold air current flowing over warm ground. In other cases the "low-level jets" are most pronounced during the night and resemble the strongly supergeostrophic type discovered during the Great Plains Project. (BLACKADAR 1957, LETTAU and DAVIDSON 1957.) The wind conditions encountered during the day may, in this case, represent just what is left over from the "night jet".

In the latitude of Central Europe early spring offers the most favorable conditions for the development of cloudstreets when the circulation is still strong and solar heating already intense. Especially the cold north or northeasterly flows, known as "Bise" in the Northern Alps resemble the observations in the Boston area and have been utilized successfully by numerous glider pilots. For example, seventeen French pilots on April 16 to 18, 1954, flew motorless 500 to 650 km between Paris and Bordeaux using cloudstreets. They repeated the same feat on precisely the same dates in 1955 when cloudstreets covered considerable portions of German and French territory. Under similar conditions, the Russian Soaring Champion Iltschenko flew his sailplane from Moscow to Stalingrad on May 26, 1953 over the astonishing distance of 830 km. (ILTSCHENKO, 1954.) A good description of a 500 km glider flight under long cloudstreets was given by COMPTON (1957).

4. Dry Streets

It is not surprising that the banded structure of atmospheric convection is also in existence

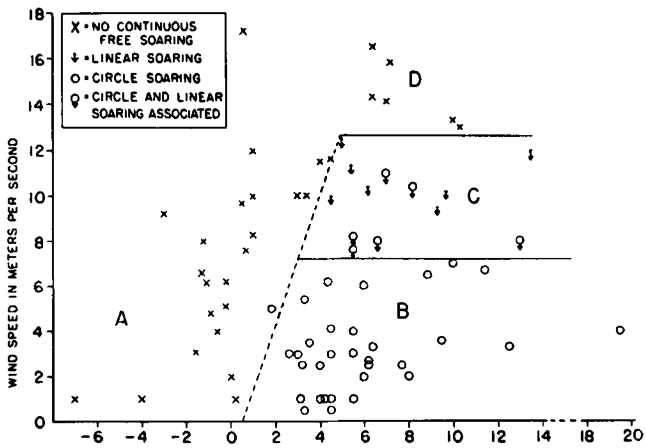


Fig. 15. Soaring techniques of sea gulls over the ocean inresponse to surface wind velocity and temperature difference between water and air, as observed by A. Woodcock (1942).

when the humidity is too low for cloud formation. The writer well remembers how an invisible "Highway of the air" once saved him in a desperate situation when the sailplane he was flying had been carried out many miles over the open sea by an easterly gale over the Swedish west coast.

Of interest to our problem are WOODCOCK's (1942) observations over the oceans. In connection with studies on cellular motion Woodcock, in a fascinating piece of work, explored the conditions under which the sea gulls change their soaring technique from circling to straight flight. Fig. 15 gives his results. As a first condition for straight flight the ocean surface has to be more than 4° C warmer than the air above it. Furthermore, Woodoock states, "Below a wind velocity (at the surface) of 7 meters per second the birds circle about in columnar thermals drifting along with the wind as they rise... At wind velocities of 7 to 13 meters per second, birds soar straight to windward in a fast flight in which they gain altitude and over-the-water distance much more rapidly than in circling flight at lower wind velocities. While moving against a wind of 28 mph birds have been seen to disappear high to windward in a few minutes... Both the columnar and strip thermals (as described by the gulls) start within 100 to 300 feet of the sea surface and extend to an unknown height. Soaring altitudes of 2,000 feet have been measured with a small rangefinder. Gulls are seen at much greater heights." Again we seem to have the conditions of "wind thermals". Above 13 meters per second surface winds, no soaring was observed by Woodcock.

In further studies on the band structure of the ocean surface WOODCOCK and WYMAN (1947) found the spacing of longitudinal rolls about twice the height of the atmospheric layer in which mixing takes place. This layer is generally isentropic and covered by an inversion. The pattern on the ocean surface is thought to be due to a concurrent structure of the surface wind. The similarity between these and our results suggests that the same phenomenon was observed.

5. Precipitation Bands

Radar Meteorology has become increasingly interested in the band structure of radar echoes seen on the PPI scope. (CLEM and MOXON 1950, AUSTIN and BLACKMER 1956, LEACH 1957, many more interesting observations are hidden in scientific progress reports.)

In identifying these bands with the phenomenon here under discussion one has to exercise caution for two reasons:

1. Since radar reveals precipitation rather than clouds, important modifications may have been introduced into the dynamics of normal convection by the action of the precipitation.

2. As precipitation falls relative to the air and as the radar beam generally intercepts a layer of considerable vertical depth, banded

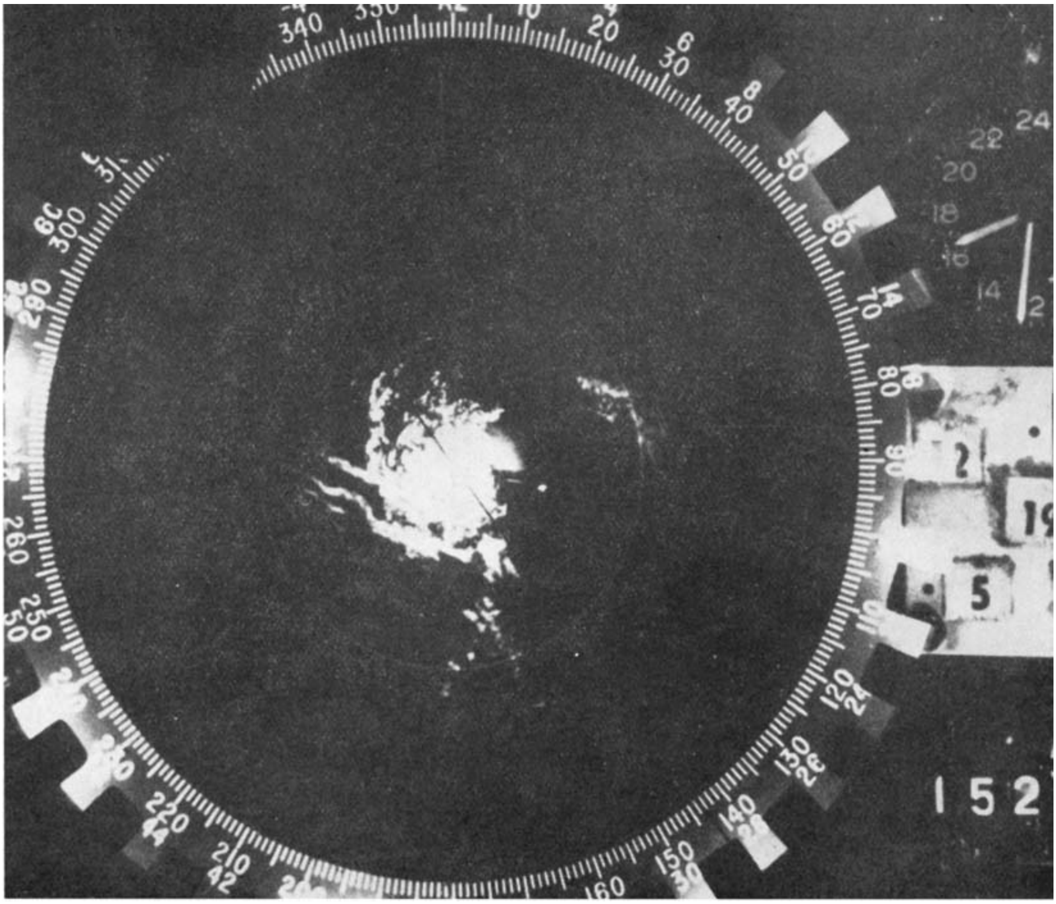


Fig. 16. PPI radar scope photo of banded echoes southwest of Boston, as observed from Blue Hill Observatory in the afternoon of 19 Dec. 1955. Total range: 200 miles. For wind conditions, see Fig. 18. (Courtesy: D. Atlas and A. Chmela, Air Force Cambridge Research Center.)

radar echoes may be produced by a number of different things.

For example, they may represent the deformation pattern of virga in a non-uniform velocity field or they may depict the "seeding path" of an overrunning "generating cell". (GUNN and MARSHALL, 1955.)

Although only a minority of these bands is likely to be of the type discussed above, radar can, in certain cases, disclose meso-scale features of convection which otherwise would escape observation. This is particularly true when, on cold winter days, low-level convection creates enough ice crystals (Fig. 2) to produce radar echoes. Two cases of this type are illustrated in the radar scope pictures of Fig. 16 and 17 which, together with the following information were kindly supplied by Dr. Atlas and Mr. A. C. Chmela of the Air Force Cambridge Research Center. On two consecutive days (19th and 20th Dec. 1955) the northeastern United States were under the influence of a severe outbreak of Arctic air from Canada where surface temperatures averaged —20° to —30° C. Northwesterly winds carried this very cold air through New England and out over the warm ocean waters of the Atlantic where vigorous convection developed. Radar bands running in the general wind direction (300°) formed southwest of Boston (Fig. 16, 19 Dec. at 17E) and on the next day over the ocean waters 100 miles east of Cape Cod (Fig. 17, 20 Dec. at 14E). Ship reports the morning of Dec. 20th indicate surface water temperatures to be

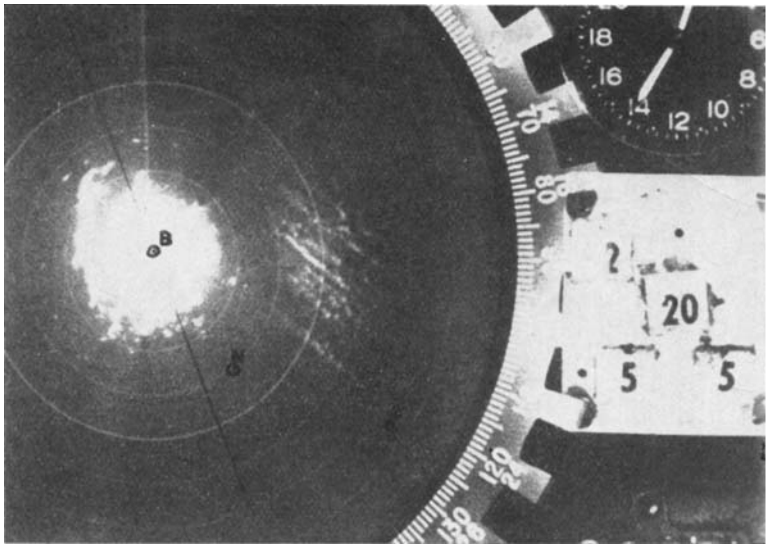


Fig. 17. Radar echoes of convective bands over the Atlantic Ocean, east of Boston, in the afternoon of 20 Dec. 1955. PPI radar scope photo from Blue Hill Observatory. Range markers: every 25 miles. Total range: 200 miles. B = Boston. N = Nantucket. S = Ship. For wind and temperature soundings, see Fig. 18. (Courtesy: D. Atlas and A. Chmela. Air Force Cambridge Research Center.)

more than 9° C warmer than the surface air. From considerations of the beam elevation angle the tops of the furthest radar echoes can be estimated to be not higher than 3 km m. s. l. The Nantucket (ACK) temperature sounding of 4 hours earlier and the ship temperatures of 7 hours earlier (see Fig. 18) suggest the same value. The length of the bands may well exceed the portion (about 100 km) intercepted by the radar beam. The large bands in Fig. 16 exceed 150 km in length. In both pictures the minimum spacing between bands (axis to axis) is of the order of 8 to 10 km, the spacing-depth ratio being about 3 or a multiple thereof.

The wind soundings from Nantucket, Fig. 18 (the position of ACK and the ship is marked on the radar photo, Fig. 17) show the familiar profile with a negative mean curvature of about 10^{-7} cm^{-1} sec^{-1} in the layer between surface and 8,000 feet.

Here as in all other aerological studies of convection over land we are handicapped by

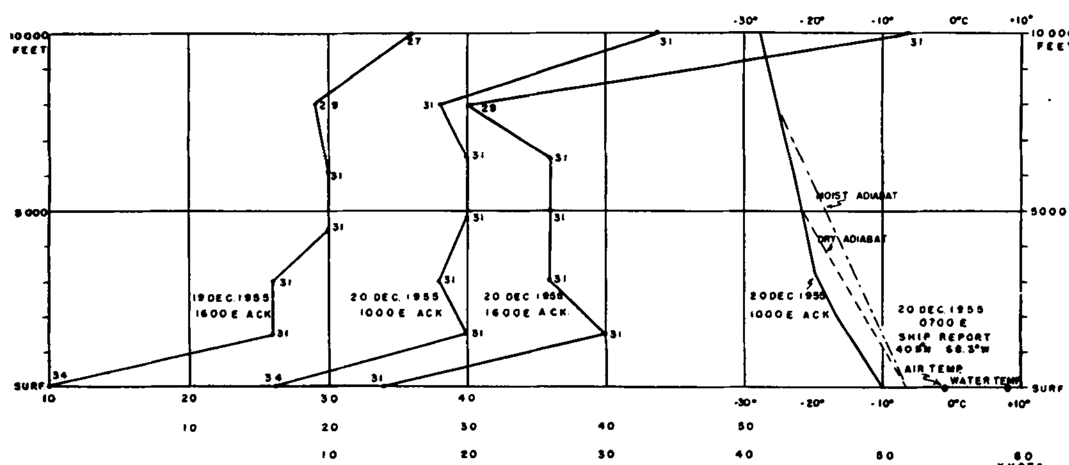


Fig. 18. Aerological conditions observed near Nantucket (Ack) during radar band observations of Fig. 16 and 17. Left: winds (knots, running scale) vs. height (ft). Right: temperatures (°C) vs. height (ft). Small numbers along curves denote wind directions in tenths of degrees. Note: ship report (marked "S" in Fig. 17) gives air temperature 9° C colder than water surface.

Fig. 19. Tradewind cumuli organized in bands parallel to tradewind direction, as seen from 20,000 ft halfway between Puerto Rico and Bermuda, 24 July 1955. (Photo: J. Kuettner.)

the fact that the 12 hourly schedule of international upper air soundings provides no data from midday for the U.S.A.

Finally, we may mention the earlier synoptic studies of "hail-streaks" and shower bands (PROHASKA, discussed in WEICKMANN 1953, SCHIRMER 1951). The fact that they run in the general direction of the wind over a distance of about 100 km suggests possible relations to the phenomenon under study here, even allowing for reservations expressed in the beginning of this chapter. The repetition of hail showers along such line (apparently from distinctive cells within a shower band) is a well-known fact. A new case study by YASUDA (1957) of precipitation stripes forming in cold front showers confirms these observations and establishes the connection with a low level jet.

6. Cloud Streets and "Spiral Bands" over the Tropical Oceans

Cumulus lines stretching in the general wind direction are a characteristic feature of convection over the tropical oceans occurring specifically in the trades and in tropical cyclones.

Tradewinds

Little has been written about this striking cloud formation which is familiar to most tropical meteorologists. If the trade wind velocity is not too weak the general wind direction can again be estimated by a flying observer simply from looking down upon the cloudstreets. (Fig. 19.) In spite of the somewhat stable lapse rates in the upper sub-cloud layer[1] (MALKUS 1957) the tradewind cumuli must be considered as a convective phenomenon which accomplishes the distribution of heat from the ocean surface through the tradewind layer. Accordingly, the mean trajectories of the trades cross from low to high potential temperatures (RIEHL and MALKUS, 1957) in a similar manner as the polar outbreaks discussed earlier.

The vertical wind variation in the trades (Fig. 20) shows the same characteristics as in the extratropical cloudstreets, only on a more modest scale. The profile is negatively curved with a vertical shear gradient of the order of -5×10^{-8} (cm^{-1} sec^{-1}). "Winds decrease downwards and upwards from the cloud base" (RIEHL, 1954). Average level of cloud base and tradewind inversion are 900 mb and 800 mb respectively as indicated in Fig. 20. In contrast to the situation in higher latitudes, the inversion does not mark a discontinuity in wind speed and direction. The nature of this

[1] This sub-cloud layer is also found in convection over land (LUDLAM 1953) and is most pronounced in the surroundings of cumulus clouds, not directly under them (probably as a product of mixing between cloud air and environment). It does not keep glider pilots from climbing right into the cloud base.

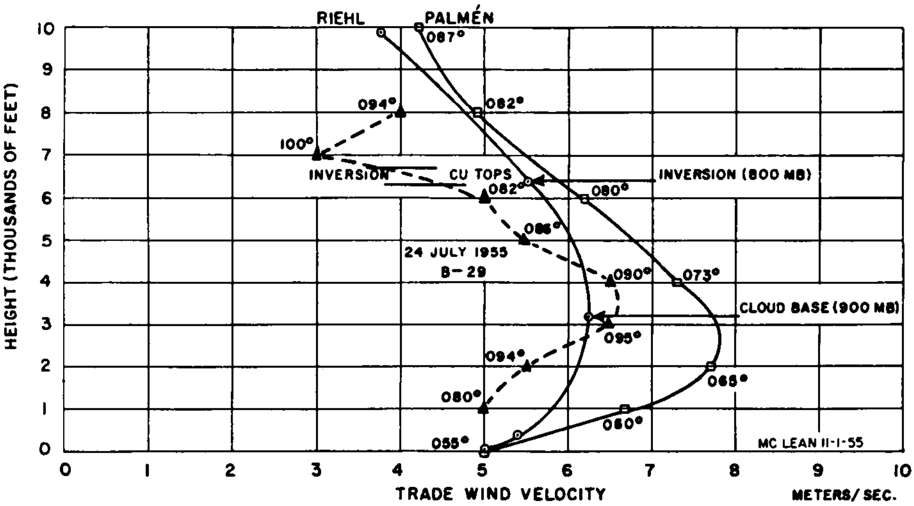


Fig. 20. Vertical profiles of tradewinds. Solid curves: Mean profiles after Riehl, 1954 (Pacific Ocean, July to October 1945) and Palmen, 1955 (along half of latitude circle 13° N, Pacific-Atlantic, Jan.—Feb. 1952). Dashed curve: Doppler radar measurement by B-29 research aircraft of wind profile connected with cloudstreet, Fig. 21, on 24 July 1955. Small numbers along curv.s denote wind direction (in degrees).

wind profile has been discussed by Riehl and Malkus (1957) who also noted the almost two-dimensional character of this type of heat driven flow with little vertical change in wind direction. From a viewpoint of balance of forces they postulate "a vertical wind profile with a curvature in the turbulent layer such that turbulence must act to retard the flow... this kind of profile is typical of the portions of the tradewind belts where the meridional temperature gradient is directed poleward. The geostrophic wind is strongest at the ground and decreases throughout the tradewind layer. On account of friction, however, the maximum wind is situated some distance above the ground... In the trade section (along a ground streamline) it is warmer at the downstream than at the upstream end. Since the pressure decreases from right to left across the section looking downstream, the isobars will rotate counterclockwise with height under the influence of the temperature field and thus assume more and more the direction of the surface wind." This is a very similar situation as the one governing the extratropical cloudstreets (Section 3). It appears that the uniformity of the flow direction and the developing negative shear of the geostrophic wind (resulting in the curvature of the actual wind profile) are general characteristics of heated flows. We will encounter a similar situation during the discussion of the squall lines.

In the summer of 1955, R. Rados and the writer had an opportunity to measure characteristic parameters of a tradewind cloudstreet during a flight over the subtropical Atlantic Ocean with a specially instrumented B-29 of the Air Force Cambridge Research Center assigned to Hurricane studies (Rados, 1955). The cloudstreet (Fig. 21) stretched about 25 miles east-westwards in the general wind direction and was arbitrarily selected out of a great number of similar streets, 300 miles northeast of Puerto Rico. Vertical wind and temperature profiles were measured by Doppler radar APN-82 and Vortex thermometer in the following way: First, the aircraft climbed slowly under and through the cloudstreet along its axis, subsequently it descended on a parallel course in clear air. The familiar wind characteristics may be recognized in Fig. 20. To compare furthermore the mean *vertical* motions beneath the cloud base and in the clear air between streets two "precision speed runs" were made at 1,000 feet height in the direction of the cloudstreet axis holding pressure altitude (and power) constant by means of the autopilot. This technique developed during the "Jet Stream-Mountain Wave Project" allows one to evaluate differential air speeds in terms of approximate ver-

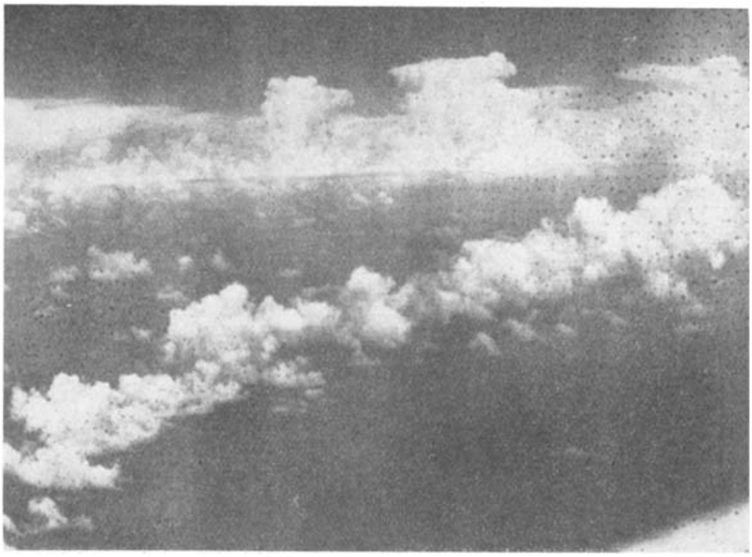


Fig. 21. Tradewind cloudstreet, about 300 miles northeast of Puerto Rico, probed by-B-29 research aircraft on 24 July 1955, see Fig. 20. Cloudbase: 2,000 ft, tops: 6,000 ft, length 25 miles. (Photo: J. Kuettner.)

tical velocities of the atmosphere. The mean air speed beneath the cloudstreet exceeded that on a parallel course outside the street by 4 knots. According to calibrations, this corresponds to a relative vertical motion of approximately 1 meter per second averaged over the whole length of the cloudstreet, the updrafts being beneath the cloudstreet while the downdrafts are outside in clear air. The 1,000 foot flight level war about half way between the ocean surface and the cloud base. On further runs across the street at 3,000 ft a similar technique indicated maximum local updrafts of the order of 4 meters per second inside portions of the cloud.

From this crude investigation it appears that the vertical circulation in and around this tradewind cloud street may have been of the type suggested by the seeding experiment mentioned earlier (AUF'M KAMPE et al, 1953), namely: "An updraft under the ridge, diverging horizontal flow near the top of the cloudline and downdrafts at some distance left and right of the cloud edges".

Tropical Cyclones

It is now generally known that spiral bands are an essential part of the hurricane circulation. (Fig. 22.) Probably the first practical evaluation and description of these spiral bands from radar data was given by H. WEXLER (1947). He reported that the spacing of the radar bands varies from 5 to 25 miles, averaging about 10 to 15 miles. These values have been confirmed in later observations. (Fig. 23 suggests a characteristic spacing of the order of 10 miles or a multiple thereof.) The depth of the layer affected by shower activity in the banded area can be estimated to be of the order of 5 miles giving a spacing-depth ratio between 2 and 3 (which is a familiar value). The length of the radar bands usually exceeds 50 miles, occasionally 200 miles. In between the precipitation bands multiple lower cumulus streets can be observed, see Fig. 24, which are rarely visible on the radar scope. According to verbal information by Mr. R. Simpson who took the picture, the cumulus cloudstreets in the lower-left of that figure extended through the wind maximum below 10,000 feet. The high, towering cumulo-nimbus line in the background illustrates the negative shear in high levels where the cloud tops lean backwards. (The picture is taken from the eye outwards.) WEXLER (1947) has already suggested that the radar bands form from tropical cloudstreets of this type. A confirmation may be found in the recent investigations by SENN, HISER and BOURRET (1957) who find: "The mean crossing angle of the radar rain bands with the isobars is the same as that of the wind flow at about 2,500 ft. This suggests strongly that it is the wind flow around the 2,500 foot level with

Fig. 22. Spiral bands of Hurricane Connie, 12 August 1955, as seen on 10 cm radar at Cape Hatteras. Range marks every 20 miles. (Courtesy: US Weather Bureau.)

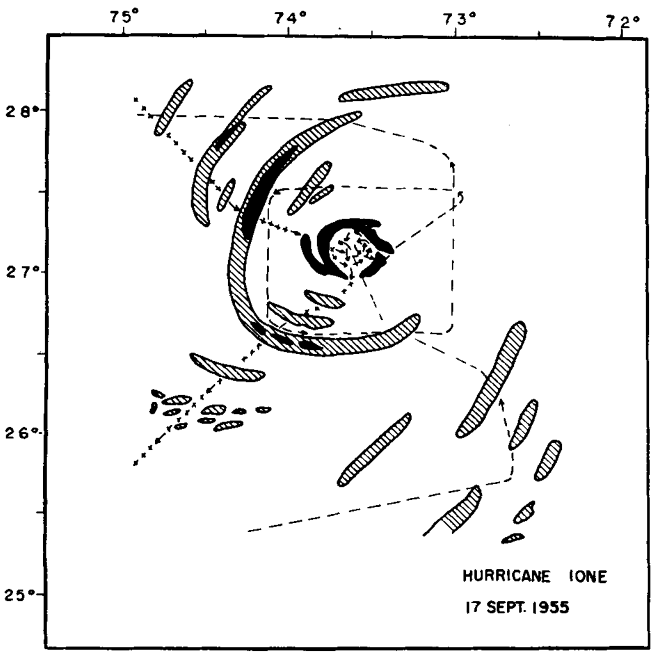


Fig. 23. Spiral bands of Hurricane Ione as observed by airborne radar of B-29 research aircraft on 17 September 1955. Dashed and crossed lines give path of two flight traverses. Hatched areas are observed radar echoes, solid areas are quasi-permanent echoes. Analysis by N. La Seur, 1957. (Reference system moved with hurricane center.)

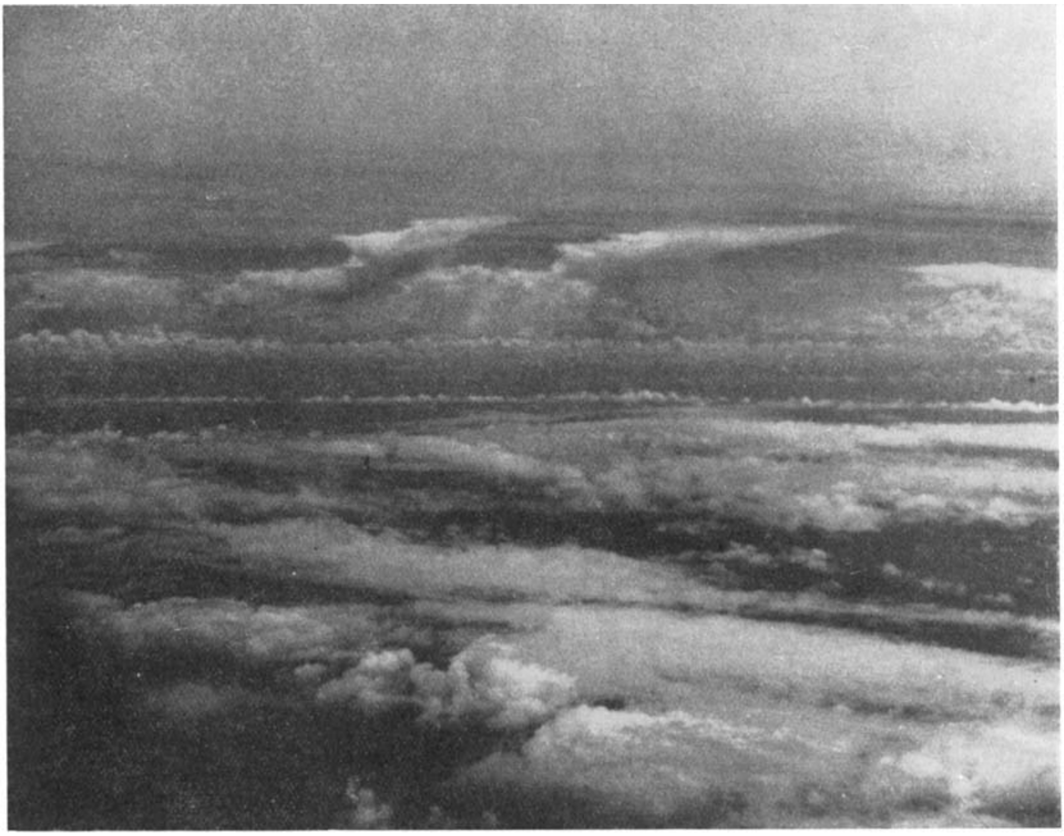


Fig. 24. Cloudstreets surrounding hurricane as viewed radially outwards from center. Note cumulo-nimbus band in background with tops falling backwards. Cloud systems are circulating from right to left. (Photo: R. Simpson.)

its associated intense convective activity which is responsible for both the generation and the shape of the spiral bands."

In the later stages of hurricanes which have moved into higher latitudes the variation of wind direction with height complicates the picture, but the orientation of the bands still agrees with the direction of the winds near the surface. (KESSLER and ATLAS, 1956.)

Very few vertical wind soundings are available from the neighborhood of the mature hurricane center, although recent horizontal soundings by aircraft have supplied a rather complete picture of the circulation at a given pressure level (RADOS 1955, LA SEUR 1957). Until data from the National Hurricane Project become available conclusions will have to be based upon present evidence. Fig. 25 shows wind soundings in close proximity to a Pacific Typhoon near Guam (RIEHL 1954) and an Atlantic Hurricane near Bermuda (JORDAN 1954). Apparently the hurricane profile is an enlarged image of the wind profile in the extratropical cloudstreets, the shear gradient being, again, of the order of $-10^{-7}\ cm^{-1}\ sec^{-1}$ (or slightly more) but the wind maximum occurring at a somewhat higher level, close to 10,000 feet.

The Hurricane Eye

Some radar bands spiral directly into the rain wall around the hurricane eye (Fig. 22; RIEHL 1954, Fig. 11.24). At the risk of stretching the point one may venture to suggest that the rain wall itself is "the ultimate convection band" whose diameter is given by the spacing between bands (2 or 3 times its height). As

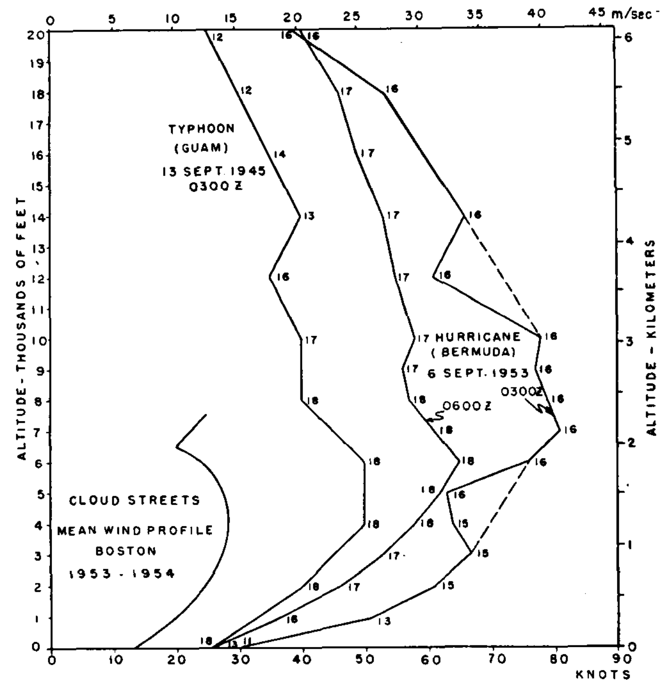


Fig. 25. Vertical wind profiles (Us Air Force) near center of Pacific typhoon and Atlantic Hurricane. Numbers along curves give wind directions in tenths of degrees. For comparison, mean wind profile of extratropical cloudstreets is shown in lower left. Note: curvature values are in all cases of similar order (10^{-7} cm^{-1} sec^{-1}).

the rain wall extends in the vertical to as much as 7 or 8 miles, a typical diameter of the eye of 20 miles would be in accord with expectations. Following this line of thought the eye itself would represent the downward leg in the vertical circulation. As "the pressure gradient-force decreases upward... air particles moving upward... will be accelerated outward" (RIEHL 1954) and there should be a systematic outward displacement of precipitation falling from the tilted band. Air descending in the center branch of the circulation will quickly evaporate the remainder of the liquid water entrained from the cloud wall, and subsequently, will follow the dry rather than the moist adiabate. Downdraft and humidity observations along the inner cloud wall by LA SEUR (1957) support this assumption.[1]

The situation, if true, has a striking similarity with the classical *foehn* (FICKER and DE RUDDER 1943). Here, precipitation also falls outside the descending branch of the circulation, namely, on the upwind side of the mountain range. In both cases, hot and dry air is produced throughout a large portion of the atmosphere with excellent visibility and very low hydrostatic pressure ("lee-low") and in both cases the horizontal pressure gradient between the precipitation and the "foehn area" reaches excessive values.

7. Some Related Phenomena

At this time it may be permissible to extend the speculation started in the last section to circulations of the atmosphere which contain some of the characteristics of band convection, although, at first glance they would appear to be of an entirely different nature. The two phenomena to be considered are the squall lines and the "polar bands".

Squall Lines

Recently it has become known that most squall lines are connected with a low-level jet (PORTER et al 1955, STAFF MEMBERS SELS CENTER USWB 1956, BAIRD 1956). The fact that intense convective activity organizes itself in a line parallel to the low-level flow and that the jet, by definition, possesses a curvature of the wind profile is of significance in connection

[1] MALKUS (1958) in a paper published after completion of this manuscript deals more rigorously with this problem.

with our earlier discussions. The flow usually appears in the 850 mb map as a band in the horizontal plane. PORTER et al (1955) found it at this level in 75 % of 171 cases studied, while BAIRD (1956) did so in all of his 12 cases. Interest in this jet has generally centered around its ability to transport moisture from the gulf coast northward in a 'tongue'. If viewed in a vertical plane the jet characteristic of the wind profile is even more striking. The flow generally peaks below 5,000 ft and the curvature reaches values in excess of 10^{-7} cm^{-1} sec^{-1}, occasionally approaching the enormous value of 10^{-6} (corresponding to a change of wind shear of 100 m/sec per km^2).

Recently this type of vertical wind profile has attracted wider attention in the problem of the atmospheric boundary layer (BLACKADAR 1957, LETTAU and DAVIDSON 1957). It has been interpreted as an inertial oscillation induced when the frictional constraint imposed by daytime mixing is released at nighttime, an effect most pronounced if the geostrophic wind is a maximum at the ground. We have seen earlier that the latter is a characteristic of heated flows. The geography of the South Central U.S. favors the entrance of tradewind air from the Gulf of Mexico. This air carries its (band favoring) properties along (see Sec. 6, viz. high moisture content, curved wind profile, tradewind inversion). The low-level geostrophic wind maximum may then be expected during the time of maximumheating, i.e. in the afternoon, while the peak wind of the inertia oscillation is reached in the early morning hours. Full development of squall lines and tornado activities generally occurs in between these hours, that is, in the late evening (TEPPER 1954).

An example which is exceptionally well documented by synoptic radar data (LIGDA 1956) is presented in Fig. 26. At the time selected (2100 CST) a squall line of almost 1,000 miles length reached its full strength with the severest weather concentrated in its north center section. To give an idea of the nature of the three-dimensional wind field the figure shows the vertical wind profiles folded over onto the horizontal plane with the axis of rotation pointing into the direction of the low-level jet.

The solid black arrows in Fig. 26 giving speed and direction at the lowest maximum-wind-level, indicate that the orientation of the squall line parallels roughly the direction of the low-level jet. The vertical wind profiles show the strong curvatures connected with this type of flow. In the horizontal plane, the low-level jet seems to be most pronounced along the leading edge of the squall line and just ahead of it. In drawing an analogy to the cloudstreets discussed earlier we may suspect that here, too, the convective activity organizes itself in a line parallel to the wind, in accordance with the curvature of its vertical profile.[1]

Of course, there is enough indication that other factors, such as the horizontal deformation field of the low-level jet stream, the moisture distribution, etc., contribute to the formation of a squall line, but inspection of numerous squall line cases reveals that the features displayed in the example of Fig. 26 are typical enough to be generalized.

Polar Bands and the Jet Stream

It has been known for a few years that characteristic cirrus clouds develop in the jet stream (SCHAEFER 1953). Prominent among the forms seen are bands and lenticular clouds. Methods have been described for using these clouds as a navigational tool on transatlantic flights (FROST 1953, 1954). The cirrus bands which run in the direction of the maximum wind (Fig. 27, 28) are probably identical with the "polar bands" widely discussed in the early cloud literature. It appears (TYCOS 1927) that Alexander von Humboldt first described these clouds which seem to radiate from one point at the horizon, stretch across the entire sky and converge at the opposite side of the horizon, actually covering more than 400 visible miles. Humboldt believed that they formed under the influence of the geomagnetic field pointing toward the magnetic poles and, therefore, called them "polar bands". At the end of the century CLAYTON (1896), in some monumental nephanalysis work, studied 1,392 cases of these bands and found significantly "that at all velocities the majority of bands lies in the general direction of their motion and but few at right angles to it; but the proportion

[1] It should be noted that a secondary wind maximum exists near the 10,000 ft level. There are also indications of inversions (I) or shallow stable layers (S) developing in the late evening near the ground, particularly in the rear of the squall line.

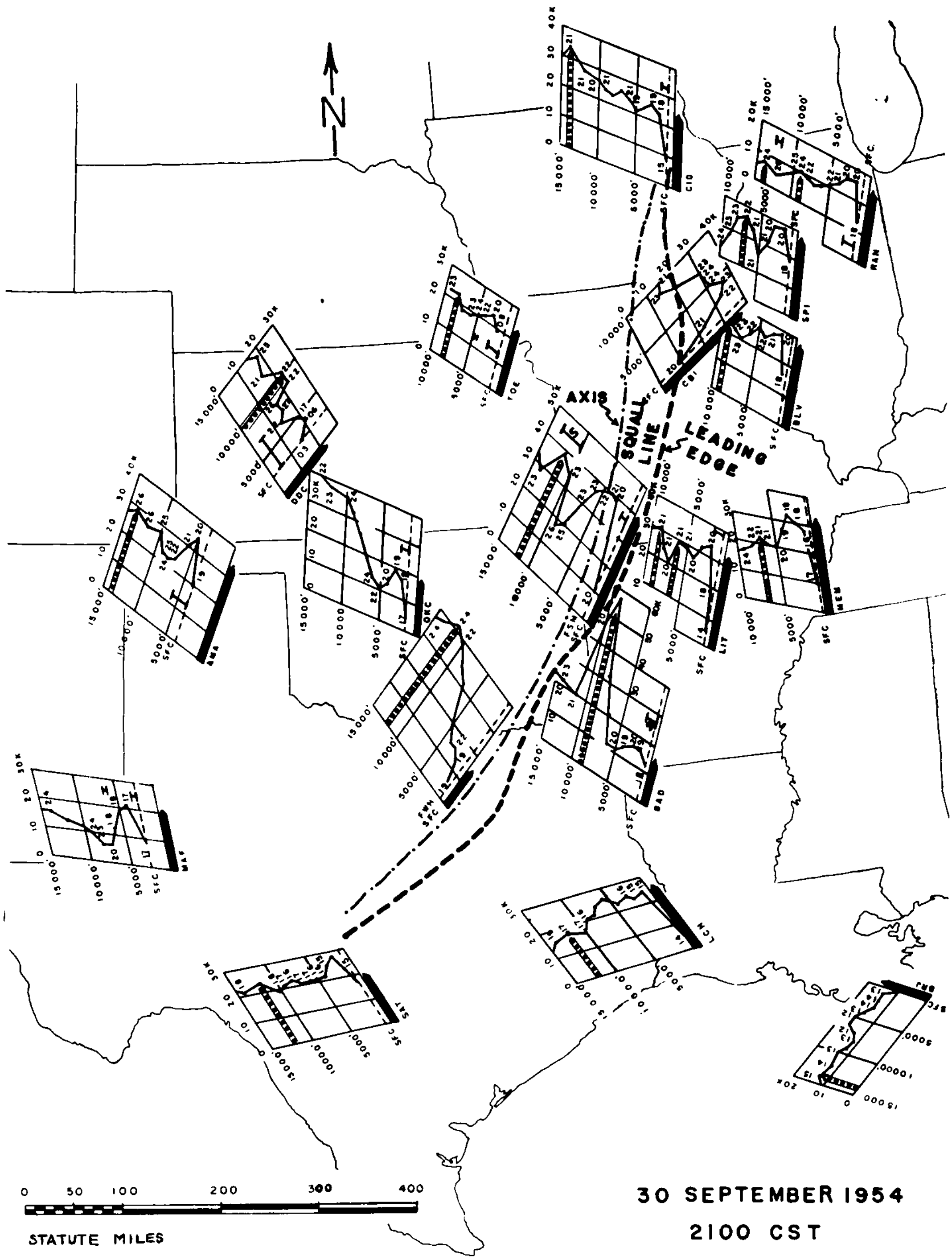


Fig. 26. Aerological analysis of squall line about 1,000 miles in length, over Central USA on 30 September 1954. Position of squall line according to radar analysis (LIGDA 1956). Vertical wind profiles folded over into horizontal plane give wind velocity (knots) vs. height (feet). Small numbers along curves give wind direction in tenths of degrees. For further explanations, see text. Note: orientation of line follows approximately low level jet (black arrows).

Fig. 27. Typical jet stream cirrus, 18 Dec. 1956, looking southeast from Blue Hill Observatory. (Photo: Conover.) Westerly jet stream overhead. Note: Northern edge of cirrus shield and cirrus bands paralleling jet core on its right side (looking downwind).

of the bands which move in the direction of their length increases rapidly with the velocity". Between 1889 and 1894 nearly 80 % of the rapidly moving bands (more than 100 knots) "varied less than 23° from the direction of motion". He also concluded "that cirrus bands have the greatest mean velocity when moving longitudinally, and the least when extending at right angles to their direction of motion".

He cites earlier studies by Ley in England "which give a much higher velocity for the bands than for ordinary cirrus". This and the following discussion suggest that the type of cloud, now generally called "cirrus radiatus" indicates the existence of a jet stream overhead.

New information on these clouds has been obtained in "Project Jet Stream" (McLean 1957) and "Project Cloud Photo" of the Blue Hill Observatory (Conover 1958). Tentative

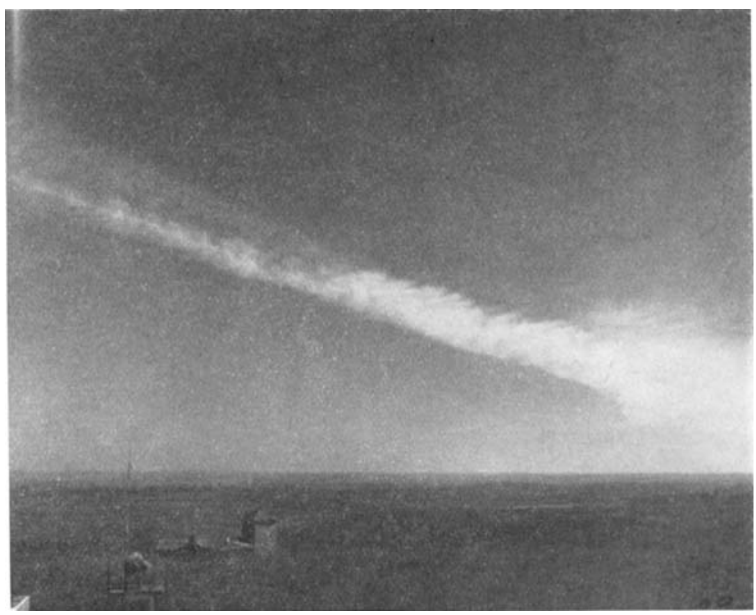


Fig. 28. Cirrus band in close proximity of and parallel to jet stream core of 180 knots over Boston, 3 April 1957, as seen from Blue Hill Observatory, looking northeast. (Photo: Conover). For upper winds, see Fig. 30.

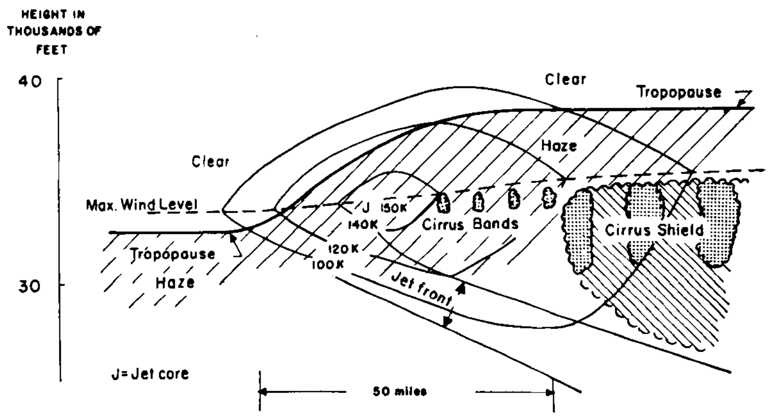


Fig. 29. Schematic cross section through "tropopause break" and high clouds near jet stream core. Note that "break" is continuous on the mesoscale as observed from high flying aircraft.

assessment of this knowledge may be summarized as follows:

In a typical westerly jet stream the cloudiness consists of a cirrus shield extending to the south of the core and frequently subdivided in a band-like fashion. The striking feature is the sharp cut-off on its northern edge, parallelling the jet stream core over distances of many hundreds of miles. The space between this straight edge and the core just north of it may be as small as a few miles or as wide as 30 miles. It is either clear or filled with cirrus bands extending over distances of the order of hundreds of miles in wind direction and spaced several miles apart. The core itself and the area north of it is generally free of clouds. Occasionally there may be just one long cirrus band parallelling the jet core over tremendous distances. On the record breaking coast-to-coast flight of the Jet Stream Project's B-47 (25 January 1957) the northern edge of the cirrus bands parallelled the zone of maximum wind (as measured by Doppler-radar) more than 1,000 miles over the Western Plains of the U.S.A. Capt. Frost (1953) of BOAC describes how he followed with his transatlantic stratocruiser an individual cirrus band over a distance of 1,700 miles closely delineating the jet stream core of about 150 knots. Obviously the polar bands are not dependent on the terrain below.

Flights across the jet stream reveal that the cirrus bands form in the area of the tropopause "break" (ENDLICH and MCLEAN, 1957). The structure of this "break" is most interesting and by no means discontinuous as the name may imply. If viewed from an aircraft flying in the jet stream core, the "break" looks as follows (see Fig. 29):

To the north of the jet stream at the height of the core, skies are very clear, corresponding to the polar stratosphere. The haze layer marking the lower side of the tropopause can be seen (visually) to rise rapidly but continuously from north to south through the core area over a distance of about 30 miles. On the south side the haze tops the cirrus by several thousand feet depicting a transition layer which is sandwiched between the cirrus deck and the subtropical stratosphere. (This transition layer may be connected with the somewhat diffuse tropopause generally found on temperature soundings near the jet stream core; Type B tropopause, ENDLICH, SOLOT, and THUR 1955.) Between the core and the edge of the cirrus shield to the south the cirrus bands are found. Recent observations of "Project Jet Stream" reveal that a wide zone of dynamic instability spreads south of the jet stream core which may be responsible for the development of the cirrus shield. (ENDLICH, KUETTNER, MCLEAN, and RADOS 1958.) Imbedded in this cloud mass are layers of convective instability.

Turbulence encountered almost invariably in jet stream cirrus is indicative of unstable zones developing in the upper troposphere just to the south of the jet stream core. The level of maximum wind falls in this layer only on the southern side of the core while on the northern side it continues into the stratosphere. The whole phenomenon is perceptable only on the meso-scale.

Fig. 28 (3 April 1957) gives a photo of a jet

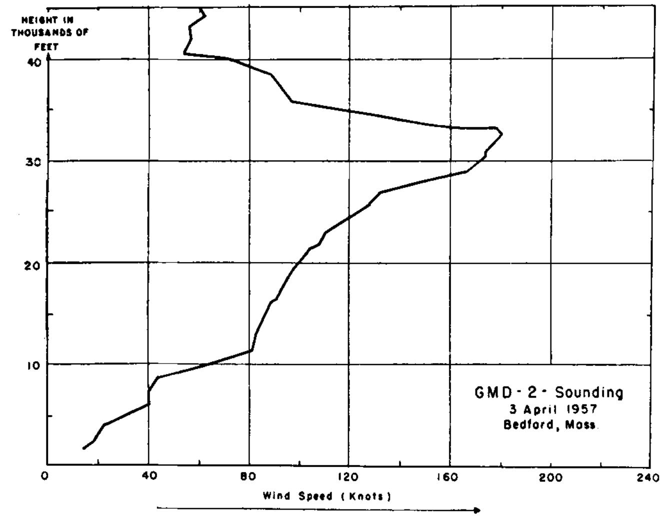


Fig. 30. Vertical wind sounding through jet stream of 3 April 1957 over Boston (see Fig. 28). GM D-2 test sounding. (Courtesy: Mr. R. Leviton, Air Force Cambridge Research Center.)

stream cirrus band taken from the Blue Hill Observatory near Boston (courtesy of Mr. John Conover) about one hour before the GMD-2 rawin sounding of Fig. 30 was taken at Bedford, Mass., 20 miles away (courtesy of Mr. Leviton). The supplementary temperature sounding made at the same time, revealing a superadiabatic lapse rate below the tropopause is not considered reliable. (The height of the tropopause was indicated above the peak wind.) Within the 5,000 ft thick layer directly below the maximum wind of 180 knots the shear gradient reaches $3 \times 10^{-7}(\text{cm}^{-1}\ \text{sec}^{-1})$.

A similar value is given in the jet stream case of Fig. 31 (8 March 1954). Here the Jet Stream Project's B-47 reported cirrus streaks between 33 and 34 thousand feet close to and slightly south of the jet stream core which was located at 34,000 ft with 116 knots. Temperatures and winds were recorded by vortex thermometer and Doppler radar at the levels of 30, 34 and 36 thousand feet. Since all jet streams display

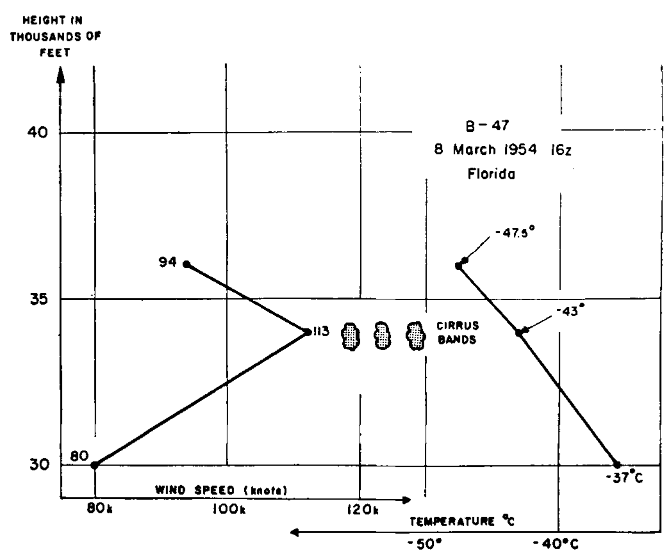


Fig. 31. Cloud observations as related to wind and temperature measurements at three different levels (30, 34 and 36 thousand feet) by B-47 aircraft of "Project Jet Stream". Florida, 8 March 1954.

Fig. 32. Cirrus bands forming in the lee of Sierra Nevada, California, and trailing downwind under jet stream conditions during afternoon of 24 April 1955. (Photo: B. Woodward.)

spectacular values of vertical shear the vertical *variations* of this shear are always remarkable and exceed considerably the value of 10^{-7} (cm^{-1} sec^{-1}) encountered in our other studies on cloudstreets.

According to the criteria found earlier the optimal location for a possible developmen of convective bands would be directly south of the core, where the wind maximum lies in the upper troposphere thus locating the maximum curvature of the wind profile in the layer of maximum vertical temperature lapse rate.

Preferred but not exclusive places of cirrus band development are *mountain ranges* crossed by a jet stream. The cirrus bands shown in Fig. 32 formed in the lee of the Sierra Nevada under a combined jet stream and mountain wave condition. The point of origin of the bands (which run, again, parallel to the jet stream) is located just downwind of the mountain crest. It is known that this is not only the area of maximal updraft but also of maximal streamline divergence in the vertical plane which tends to steepen the vertical temperature lapse rate thus favoring cloud convection. (The bottom streamline falls several thousand feet along the contour of the mountain slope, while the tropopause streamline is lifted upwards as much; HOLMBOE and KLIEFORTH 1957.) It has been observed during the "Sierra Wave Project" that a strong jet stream tends to break up the wave cloud (which runs parallel to the mountain range) into bands oriented normal to the mountain range. These bands may trail over hundreds of miles downstream.

The idea that the jet stream clouds at the cirrus level constitute "helical vortices" of Bánard type convective cells has been advanced by CLEM (1955) and SCHAEFER (1957). The similarity between the aerological condition of these cirrus-bands and the low-level cloudstreets discussed earlier are striking enough to justify such analogy although the term "helical" may be somewhat misleading. (There is no evidence that individual air parcels describe several complete circulations.) In addition, observations by Pan American transatlantic flights and by Project Jet Stream's B-29 and B-47 show that the indicated airspeed deviates systematically during level flight in the jet stream by amounts corresponding to vertical motions of the order of one meter per second (ENDLICH, KUETTNER, MCLEAN, and RADOS 1958). These motions seem to be organized in bands along the jet stream axis. The existence of such circulations is of particular interest in the problem of high level turbulence and for the art of high altitude soaring (KUETTNER 1955).

8. Preliminary Note on the Underlying Mechanism

The observations presented in the foregoing sections indicate that most cloud bands line up in the flow direction and originate in convective layers. The characteristic wind profile in the vertical has a jet-like curvature. Not the shear but the *shear gradient* is the striking feature.

This suggests that inertia forces enter the problem, similar in type to those responsible for the Tollmien-Schlichting waves in the boundary layer or the Rossby waves in the westerlies.

In part II, to be published separately, the theory of this type of organized convection will be discussed. Here only a preliminary note on the mechanism thought to be operative in the convection bands shall be given.

As in any normal convection, unstable density gradients due to heating from below or cooling from above create buoyancy forces. In the vertical circulations set up by these

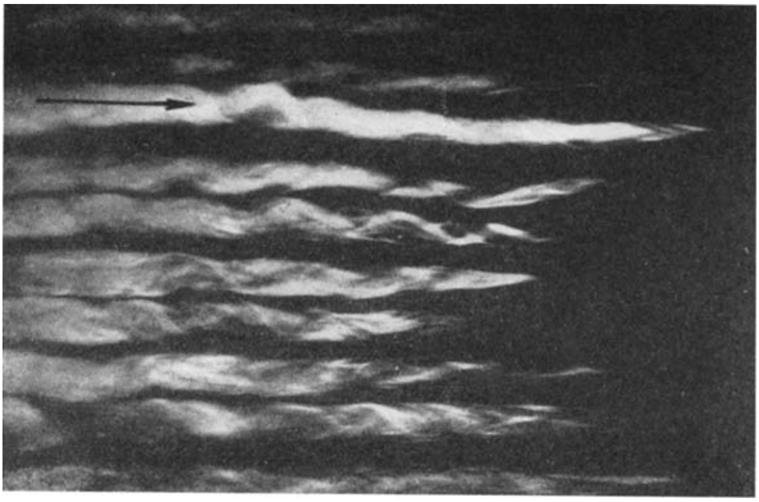


Fig. 33. Convection bands forming in air layer moving from left to right and heated from below (Avsec, 1939 Fig. 43). In this laboratory experiment tobacco smoke is injected at left and progresses towards right in longitudinal rolls.

forces adjacent parcels will rise and fall. If, as in our case, the heated layer is moving horizontally and its velocity as well as its vertical shear (vorticity) is changing with height[1], the rising and falling parcels will carry their vorticity (shear) along. In this way vorticity differences will arise between horizontally adjacent parcels. These differential vorticities exert restoring forces (inertia forces) which tend to return the parcels to their original levels (LIN 1955). Hence, the curved velocity profile acts similarly to a *stable* density stratification and tends to counteract the circulation set up by the existing *unstable* density stratification. This counteraction will be most pronounced in the plane in which the curvature is a maximum, i.e. in vertical planes *along* the flow direction. Convective circulations in these planes will be inhibited. In contrast, cross-sections *perpendicular* to the flow do not show any curvature and circulations normal to the flow do not meet such opposing forces.

It is clear, then, that convective circulations will tend to restrict themselves to planes normal to the flow forming uniform lines with axis parallel to the flow direction. Thus, the curved velocity profile may be said to exert a "lineating effect" on convection. This calls for "longitudinal rolls" of the type observed in our cloud studies and in many laboratory experiments with heated boundary layer flow (BÉNARD 1900, 1927, TERADA 1928, MAL 1931, AVSEC 1939). See Fig. 33.

[1] Without changing the sign of the curvature.

One may derive this effect quite rigorously in terms of the amplification constant σ of the convective motion. If exponential growth with time t of the type exp (σt) is permitted, the small perturbation theory[1] to be presented later in more detail leads to the following approximate expression

$$\sigma = \left[\frac{g\beta(l^2+m^2)}{d^2} - \left(\frac{l\overline{u''}}{2d^2}\right)^2\right]^{\frac{1}{2}} - \nu d^2 \qquad (1)$$

where σ = time constant
d^2 = $l^2+m^2+n^2$ with l, m, n = wavenumbers in x, y, z direction (z vertical)
g = gravity
β = $\overline{\varrho'/\varrho}$ with ϱ = density
u = horizontal velocity (in x-direction) of basic flow
$\overline{(\,)'}$ = mean value of partial derivative with respect to z
$\overline{(\,)''}$ = mean value of second derivative with respect to z
ν = eddy viscosity

The first term in the bracket is the gravity (buoyancy) term, the second the vorticity (inertia) term containing the mean curvature

[1] Developed for the case that the Prandtl number equals unity and that the medium is incompressible.

$\overline{u''}$ of the wind profile and the last term is the viscosity term. Maximal amplification σ demands that the wavenumber l vanish, thus eliminating the stabilizing effect of the vorticity term. Now, $l=0$ means an infinite wavelength in the flow direction. This calls for convection rolls parallel to the wind. With the second term in the bracket removed, our problem reduces to the classical form of the three-dimensional theory of cellular convection (RAYLEIGH 1916), the only difference being that the well known uncertainty of this theory regarding the ratio of cell sides (i.e. of the wavenumbers l and m) has now been eliminated. The observed values of spacing between the centers of adjacent cloudstreets (2 to 3 times the layer height) agree with the theoretical optimum[1] and with laboratory experiments. (JEFFREYS 1926, AVSEC 1939).

This dynamical interpretation appears more attractive than purely kinematical considerations such as the deformation of pre-existing convective cells in shear flows.

The *required curvature* of the wind profile can also be estimated: Band convection will be excited only if, in normal (symmetrical) convection, the vorticity forces arising from the curvature would be strong enough to counteract the buoyancy forces to such a degree that the convective growth rate were significantly reduced. In atmospheric convection the typical growth time is of the order of thousand seconds, i.e. the combined buoyancy and viscosity terms of equation (1) call for an amplification constant σ of the order of 10^{-3} (sec^{-1}). If the order of magnitude of the vorticity term is comparable to σ i.e. if

$$O(l\overline{u''}/2\,d^2) \approx O(\sigma) \qquad (2)$$

three dimensional (symmetrical) convection would be suppressed. In this case marginal stability requires optimum cell dimensions (RAYLEIGH 1916) such that $l/2d^2 \approx H/6\pi$, where H is the height of the convective layer (about 2 km in our observations). Using this expression in (2) the necessary shear gradient

$$|\overline{u''}| \approx 6\pi\sigma/H \approx 10^{-7}\ (\text{cm}^{-1}\ \text{sec}^{-1}) \qquad (3)$$

in good agreement with the observed curvatures of the vertical windprofiles.

[1] Depending on the boundary conditions the theoretical values range from 2.00 to 2.83.

9. Synoptic Cloud Analysis

Our study indicates that the banded structure of the atmosphere is more common than has been generally realized. Especially in the cumulus and cirrus level cloud bands oriented in the direction of the flow are quite frequent. If these cloud types can be identified from above the flow direction of considerable portions of the atmosphere may be estimated if viewed from high levels such as a *satellite* orbit (WIDGER and TOUART 1957, GLASER 1958). Some practice based on a more systematic study of the interrelation between cloud structure and synoptic weather (BROOKS 1951) may lead to the development of techniques permitting the construction of diagnostic weather maps from panoramic cloud photos taken over vast areas such as the Pacific Ocean from which synoptic observations are lacking.

A very crude estimate leads the writer to believe that at least 30 % of the cloud coverage existing over the world has a structure suitable for this kind of synoptic analysis.

Initial efforts based on a network of "whole-sky" time lapse cameras are now in progress at the Harvard Blue Hill Observatory (CONOVER 1958). Already now the cloud bands discussed in this paper can be expected to depict outbreaks of polar air, tropical circulations and the position of fully developed jet streams. Synoptic cloud analysis may very well develop to a diagnostic and prognostic tool as significant as synoptic radar analysis (LIGDA 1956).

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Appendix

Excerpt from flight report by Dr. ERNST STEINHOFF on the first glider flight in cloud-streets (30 July 1935).

"I was approximately 20 miles to the south-east of the city of Bayreuth soaring cross-country from Western Germany eastward towards Czechoslovakia using thermals and cumulus updrafts in a strong WNW flow. Suddenly my climb indicator, in a very smooth flight, registered 400 to 600 feet per minute so that I approached the base of a cloud in status nascendi very fast. I decided to go into this cloud since the turbulence did not amount to much and to stay there for a while circling inside the cloud. After about 10 minutes, I left the cloud towards the east to continue my flight.

"I saw that there was one cloud further south of me much larger than the one I had just left. I could see this not only by the cloud itself but also from the shadows on the ground. Therefore I decided to head south (crosswind) to this cloud and try to get underneath its base. As soon as I came closer to this cloud the intensity of the down drafts increased rapidly and I lost all the altitude which I had gained in the preceding cloud, and much more. I must have been 1,500 feet below the base of the cloud when I reached the north rim and the air became extremely turbulent. In spite of this, I decided to go through this down-draft field in the hope that I would find reverse currents soon. This was not the case until I was almost to the south rim when I hit ascending air, again extremely smooth. The climbing rates were between 200 and 400 feet per minute. It took me less than 10 minutes to reach the base of this cloud.

"This time I paid more attention to the clouds south and east of me and could observe the next cloud to be even larger than the one underneath which I was just flying and to stretch in its major extension from WNW to ESE. The shadow of this cloud was very accentuated on the ground and I could observe that the next cloud, almost invisible to me, extended even twice as far as the cloud directly south of me. The third one, seen by the shadow, seemed to extend from horizon to horizon, so I decided that if the same pattern of air circulation were present in the clouds south of me I should try to reach the third one. The distances between the clouds were in the order of magnitude of 2 to 5 miles, the altitude above sea level between 1.5 and 2 miles. Each cloud was covering approximately half of shaded and half of the bright sunlit surface beneath it, so I felt that the direction of wind and elevation of sun must have something to do with this cloud pattern. I flew eastward around the next cloud and tried to reach the second next. The same pattern was repeated. First I met increased downdraft, as reported before; then, I met a terrible turbulence with increasingly strong downdraft until just beyond the center of the cloud; then, after a short brief turbulence, I reached the area of smooth ascending air again.

"Again I had lost approximately 3,000 feet just in crossing over from one cloud to the other, I repeated my ascent to the cloud base again and took off for the next cloud which stretched from horizon to horizon. I now could see a number of cloud rows south of me leaving about as wide a shadow on the ground as the sunlit area in between... This time I did not circle any more but pointed my nose towards 135° and kept on climbing. With increasing climbing rate I increased my speed until I reached the cloud base. I flew close to the south rim of it, finally with a speed of 200 kilometers per hour and no climbing rate indicated any more. I must have flown approximately 30 minutes at that speed when these clouds discontinued. With wind velocities up to 120 km/h at 12,000 feet, I must have covered 160—180 km in 30 minutes.

"No one of the southern clouds extended further east than the one I was flying beneath. I was close to 13,000 feet altitude when I left this cloud. Within the next 10 to 15 miles there was no cloud ahead of me. The air was smooth... When I was nearly 1,000 feet above the ground I flew straight over some wheat and barley fields and searched again for thermals. Whenever I found one, I sacrificed some of my paper sheets to mark the thermal. A number of pieces of paper which were lifted up faster than the other pieces pretty well outlined the flow pattern of the thermal. This was repeated three times. When I did this the last time, I saw an airfield below me with the white letters 'BRNO'."

NOTE: The flight ended in Brünn, Czechoslovakia, where Steinhoff met three more pilots who had used cloudstreets to cover this 500 km distance, far beyond the world distance record of that time.

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