

Cirrus bands as related to meteorological parameters

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In selecting a flight path and altitude, the following questions—among others—are of interest:

- (1) Which is the wind direction;
- (2) where is there an ascending air motion, and where may turbulence occur?

None of these parameters are directly visible; also not visible are those atmospheric data upon which the criteria for the occurrence of clear air turbulence are being based—such as regions of strong vertical wind shear, or the areas of confluence of two jet streams (1).

So far, the information on these and additional data has to be deduced from the daily flight weather reports; these, however, may represent the actual conditions only to the extent that they still reflect—as to space and time—the actual meso- and small-scale details.

To which degree do cirrus bands represent (for their close environment) a visible sign of meteorological parameters? May we locate the latter in a "cloud-fixed" coordinate system, and with how much certainty?

In the lower troposphere, areas of ascending motion are known to prevail below—and parallel with—cumulus streets; they are also linked to a wind which nearly parallels the cumulus streets (2). It shall be explained later, why pronounced cumulus streets, as a rule, nearly parallel the wind, whereas pronounced cirrus bands in many cases lie cross the wind direction.

Our photogrammetrical studies, in dealing with these questions, were primarily aimed at finding the principles on which the meteorological interpretation of photographs taken by the *Tiros* and *Aeros* satellites should be based. These problems also contain the questions raised introductory. We shall discuss them in the following:

Cirrus bands as related to

- I. wind direction, and to
- II. vertical wind shear (thermal wind) and additional parameters, including turbulence and ascending air motion.

I. Let us first consider the acute angle a , between the orientation of pronounced bands and the wind direction at their level (equal to the motion direction of the bands). 45 different cases of cirrus bands yielded the following results:

- (1) At small wind velocities, all values of a are of equal probability. Hence, if we define the range of variation, Δa , by $0 \leq a \leq \Delta a$, this here means that $\Delta a = 90^\circ$.
- (2) Towards greater wind velocities, Δa steadily decreases. For cirrus bands at an altitude of about 10 km they travel e. g. at 80 m/sec, $\Delta a \approx 20^\circ$.

This statistics is well approximated by
$$\text{tg}(\Delta a) \times |u|^2 = 1500 \text{ m}^2 \text{sec}^{-2} \quad (1)$$
 for large- and meso-scale cirrus bands at $z \approx 10 \text{ km}$. ($|u|$ = wind veloc., [m/sec]).

Upon this result, for instance we may determine the probability \mathcal{P}_{20° that a would not surmount 20° . It merely depends on a long-term mean of the high-level wind velocity of an area under consideration. We obtain e. g., $\mathcal{P}_{20^\circ} \approx 0.7$ for the northeastern U.S.A.; while $\mathcal{P}_{20^\circ} \approx 0.3$ for Central Europe—the long-term mean of the high-level wind velocity here being considerably less than over the northeastern U.S.A.

Investigations of many satellite pictures have revealed an apparent second meaning of Δa : Let us consider an uncertainty a' which limits the determination of the orientation of a cloud under consideration. With very pronounced bands, a'_{pr} is close to zero; while for almost circular cloud forms, or for a very "disordered" array of clouds, a' tends to close to 90° , i. e. an orientation cannot be determined, in other: it does not exist (a' , alike a , is also defined as an acute angle). At small wind velocities, both pronounced bands and circular or "disordered" shapes (3) (a'_{circ} may be encountered. Hence, here $\Delta a' = a'_{circ} - a'_{pr}$). At great wind velocities, however, circular and other cloud forms lacking a somewhat certain orientation would not occur; only bands of a more or less clearly defined orientation will be present, hence limiting the range of variation of a' , $\Delta a'$, to the order of 10° . Although the clear definition of a' still presents some difficulty, $\Delta a'$ —according to the results hitherto obtained—appears to obey relation (1) if a' is substituted for Δa .

The meaning of relation (1) may be demonstrated by a *Tiros* photograph, for instance, of 4th April 1964 (Fig. 53 z: While (at 700 mb) the wind parallels the cumulus streets where the former blows with 70 knots, the wind lies nearly cross the cumulus bands where it has only 25 knots.

The hitherto described results imply that in attempting to deduce the wind direction from a cloud pattern we must take into account an uncertainty which is rather great if the wind velocity in the area under consideration is small. This fact provokes the question: The isopleths of which parameters do

(1) Accdg. to E. R. Reiter.
(2) Accdg. to J. P. Kuettner.

(3) J. H. Conover has denoted these as "random masses".

parallel pronounced bands exactly (and without any exception, i. e. regardless of the wind vector). This leads us to (the above introduced) problem.

II. At the beginning of our stereo-photogrammetrical evaluations it became evident that cirrus bands lie normal to waves (undulatus) which occur at nearly the same level. Further research revealed that vertical wind shear would parallel the bands, and would lie normal with respect to the waves. The details, as derived from pronounced cases of cirrus band occurrence, may be summarized as follows:

Regardless of the wind direction, pronounced large-scale cirrus bands originate close to the upper boundary of a layer of the following properties: It is a layer of maximum vertical wind shear and—as a rule—increased thermal stability; it is in most of the cases identical with a high-level air masses boundary or a front; it is inclined with respect to the horizontal by about 1%. In all of the cases, this layer implicates a strong horizontal temperature gradient, which causes the strong vertical shear, to which cirrus bands orient parallel. In order to produce meso- or large-scale cirrus bands, the vertical thickness of this layer of strong shear must be > 1 km.

If such an air masses boundary parallels the jet stream, then the former is identical with a jet stream front (4).

Let us comprehend these and additional results in answering the following questions:

- (1) Where do cirrus bands lie with respect to the layer of maximum vertical shear?

Nearly always cirrus bands lie at the upper boundary of the high-level layer of strong shear—i. e. in a region of greatly reduced vertical shear. They are oriented parallel to the shear which prevails in the strong shear layer below.

- (2) Where, in a “band-fixed” coordinate system, should turbulence be encountered?

The “turbulence” criteria of L. F. Richardson and E. R. Reiter—although being much different in principle—both meet in the statement that bumpiness should occur in areas of strong shear. With the result described above, we should indirectly conclude that turbulence as caused by shear is apparently strong in a layer enclosed between the base and 1 or 2 km below the base of pronounced cirrus bands. At band tops, turbulence should be reduced perceptibly (5).

The studies of pronounced cirrus bands have further revealed the following: Along the entire length of a pronounced cirrus band, its shape and its relative motion (within a band-fixed system) are the same in principle: There are thin bands of small relative motion, their shape and appearance hence changing very slowly. Others are composed of cells with “wings” diverging towards their edges; (many bands of this type can be seen in an excellent silent movie colour film, produced by J. H. Conover, in 1956); other bands, in turn, display swift changes of their shape—also, more or less, throughout their whole length.

(4) Nomenclature accdg. to R. Endlich and G. S. McLean.

(5) The Reiter-type “turbulence” probably prevails below bands; while close to band tops—with both shear and thermal stability reduced—the Richardson-type of turbulence may prevail.

These observations suggest that the isopleths of those parameters, which determine the appearance of the band, are also oriented parallel to the latter.

From direct measurements, we found that pronounced cirrus bands always parallel the

- (1) isotherms (lines of equal temperature on a $p = \text{const.}$ level); also
- (2) lines of equal amount of vertical wind shear (which is parallel with the shear direction); also
- (3) isonephs (lines of equal amount of cloud cover); and
- (4) isohumids.

Upon further, indirect observations and conclusions, there is strong evidence that also the

- (5) lines of equal thermal stability, as well as the
- (6) lines of equal mean turbulence, and
- (7) lines of equal mean vertical velocity

parallel pronounced cirrus bands—regardless of the wind direction. If we comprehend these parameters as the “meteorological state”, we may say: The isopleths of the meteorological state parallel pronounced cirrus bands (at their level).

The isopleths of *these* parameters have in common that they are invariant with respect to the Galilei-transformation. (The wind vector itself, or the isotachs of the wind, are not Galilei-invariant; therefore, a statement which would assume bands to parallel the wind direction is not capable of generalization.)

As to the vertical motion, we have seen that—with a great probability—the isopleths of the amount of vertical motion also parallel cirrus bands. Beforehand, however, we have to distinguish

- (a) ascending air motion below the band axis, from
- (b) mean ascending velocity, averaged over the distance of at least two neighboured bands.

Both (a) and (b) appear to be comparatively great for bands which display swift changes of their appearance.

Measurements performed by J. H. Conover and J. H. Reuss both revealed that the edges of most of the bands diverge from the band axes at an average of 1 m/sec. With additional assumptions pertaining to the “helical” relative motion within and below bands, one may estimate the diverging motion to be linked with an ascending air motion below the band axis of little more than 0.1 m/sec. For the average over meso-to-large scale areas of band occurrence, calculations by K. Wege yielded only $- 2$ cm/sec.

These data yet bear much uncertainty; more accurate values could probably be obtained by precise photogrammetrical measurements of the flight paths of high altitude sailplanes, soaring just below cirrus bands.

We have to post up some remarks on the amount of vertical shear within the layer of maximum shear. Large- and meso-scale cirrus bands would generate, when vertical wind

shear, as averaged over a thickness of about 1.5 km, is $7 \times 10^{-3} \leq |s| \leq 30 \times 10^{-3} \text{ sec}^{-1}$ —strong shear producing the more pronounced bands. Since vertical shear strongly decreases above this layer, this implies the existence of a Kuettner-profile of the relative wind (this profile of the relative wind u_{rel} —hence parallel with the vertical wind shear—is enclosed between the lower boundary of the strong shear layer and a level not far above band tops). In all of the cirrus band cases so far investigated, the relative wind profile as expressed in terms of $\partial^2 u_{rel}/\partial z^2$ was, on the average, close to the value postulated by J. P. Kuettner, $1 \times 10^{-7} \text{ m}^{-1} \text{ sec}^{-1}$. If the relative wind is nearly parallel with the wind direction, the profile of the relative wind can be substituted by the wind profile $\partial^2 u/\partial z^2$.

The above mentioned range of amounts of vertical shear also seems to be a pre-condition for the formation of cumulus streets. This would explain why they most often lie nearly

parallel to the wind direction: It suggests itself that the necessary amount of S—as averaged over a layer between surface and cloud level—can as a rule only be attained if this shear nearly parallels the wind blowing at cloud level.

At cirrus level, a strong shear which parallels the wind direction will add a considerable amount to the wind velocity. This—at least in part—explains the results of J.H. Conover, J. P. Kuettner and V. J. Schaefer, according to which cirrus bands close to a jet stream always lie nearly parallel to it. Considerations of this kind also explain the statistics we described in the introduction.

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