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RESEARCH ON THE PROPERTIES OF CLOUD SYSTEMS

by

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Summary.

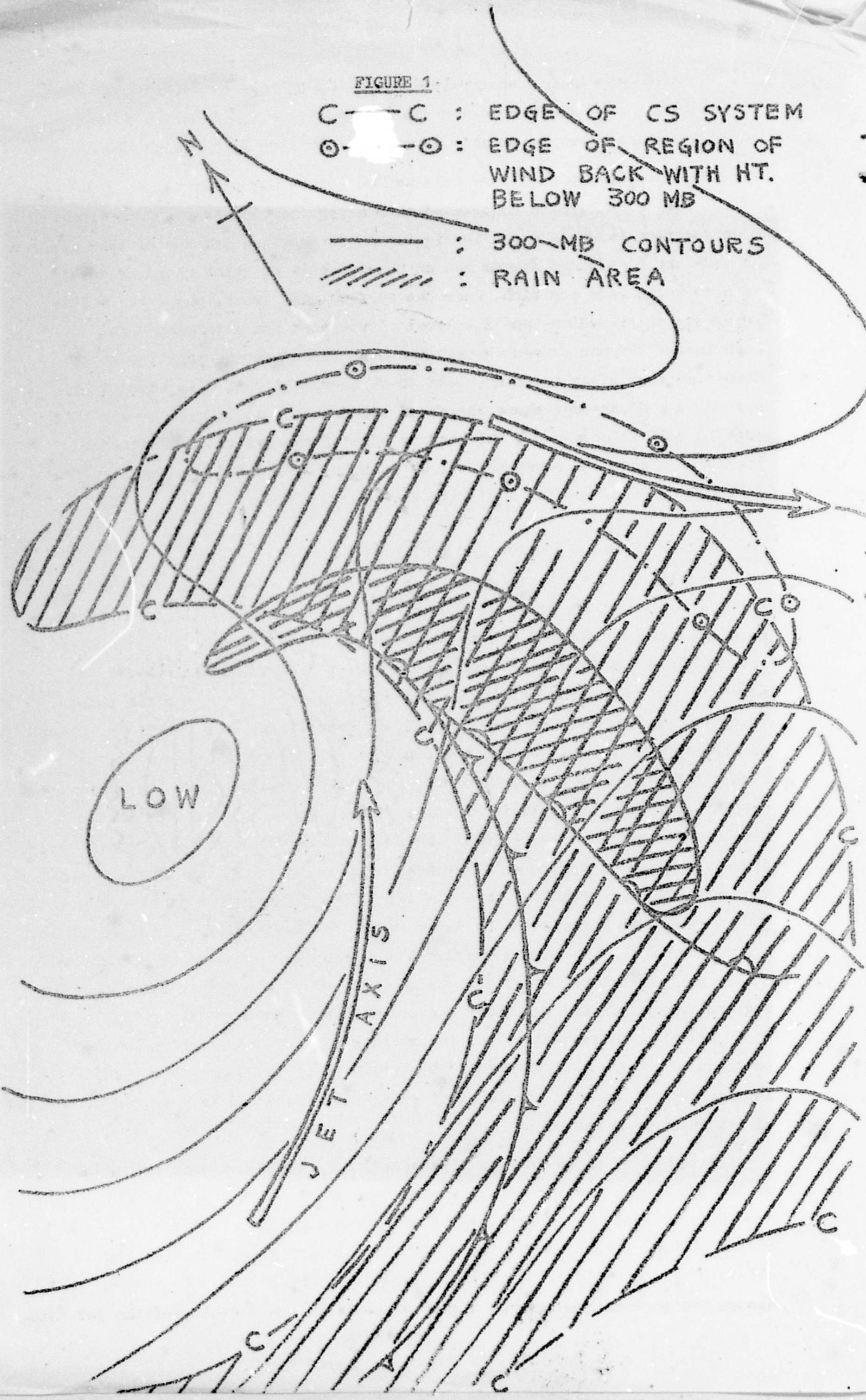
After consideration of the kind of pictorial reconnaissance possible from high-flying aircraft and other vehicles it was decided that the immediate application of such observations in forecasting weather and upper clouds would lie in delineating the extent of cloud systems and providing indirect information about the pattern of the wind flow in the high troposphere. The usefulness of the observations is likely to be greatest in the tropics, where conventional meteorological observations, particularly of the upper winds, are too sparse.

Studies have been made of the properties of high cloud systems, and in particular of the warm-front cirrus system. It has been confirmed that there is a general evaporation of cloud along the advancing edge of this system as the high level winds flow through it, but there must be meso-scale disturbances, probably orographic, which in places restore ice-supersaturation and permit the development of cirrus fall-streaks (uncinus). The fall-streaks indicate wind shears which were dominated by ageostrophic components of the wind, and it has been confirmed by careful analysis of wind observations on selected occasions that these do exist and that contrary to present thought the wind usually backs with height near warm-front cirrus, in spite of the advection of warm air.

The general disposition of high cloud seems well indicated by the sign of the advection of vorticity along the 300 mb streamlines, and the wave-length and amplitude of the long waves of the upper troposphere are probably well indicated by the pattern of high cloud systems seen from very high levels. Quantitative relations are being sought. The direction of the upper flow is also indicated by the orientation of cirrus bands, but with a closeness which varies from one part of a cirrostratus system to another, since the bands sometimes follow the wind flow exactly, and at others are aligned along the direction of the wind shear, by a mechanism of cloud re-generation in an up-shear direction. Observation of the orientation of fall-streaks is likely to indicate regions of accelerated flow and hence the location of jet stream wind speed maxima.

High level photographic reconnaissance of cloud systems over Europe and the Mediterranean has been begun, and the study of the relation between cirrus systems and the high tropospheric flow is being extended into a large region in the tropics.

FIGURE 1


C — C : EDGE OF CS SYSTEM
⊙ — ⊙ : EDGE OF REGION OF WIND BACK WITH HT. BELOW 300 MB
—— : 300-MB CONTOURS
////// : RAIN AREA
N
LOW
JET AXIS
C

Studies have been concentrated on systems of high cloud, with the aim of eventually concluding how from their disposition and internal detail alone information may be obtained about the air flow in the high troposphere.

Detailed analysis of some selected occasions has prompted the model of the high cloud system associated with a typical high-troposphere trough-ridge pattern which is shown in Fig.1. An interesting feature of this diagram is that the high cloud system has an up-wind edge at which cloud is formed, in almost the same position, near the surface cold front, where the multi-layer system of medium- and low-level clouds also has a forming-edge. At high levels the air passes through the high cloud system, arriving at the down-wind edge after an interval of 18-24 hours, so that this edge of the system is a decay-edge where the cloud evaporates. As is well known, this edge is well in advance of the leading edge of the system of medium- and low-level clouds, an asymmetry which probably is produced by a smaller fractional fall-out of condensed water at high levels.

The occurrence and distribution of high cloud.

In general the distribution of the high cloud seems to be indicated satisfactorily by the pattern of vorticity advection along the streamlines, as suggested by Riehl and others (1). French and Johanessen (2) and James (3) found that extensive cirrus layers were almost always associated with the advection of cyclonic vorticity at the 300 mb level. In the systems which have been examined in the present study it seemed that even simply the change of curvature along the streamlines could be related to the occurrence of high cloud, which tended to form near the position where the curvature changed from cyclonic to anticyclonic and vice versa. These associations have a simple interpretation in terms of the sign of the horizontal divergence, and hence the sign of the probable vertical motion, at the 300 mb level. They may break down on occasions when the level of non-divergence is near the 300 mb level, as perhaps in the early stages of the genesis of high cloud systems and in low latitudes, rather than considerably below the 300 mb level, as is usual in the well-developed multi-layer cloud systems of extra-tropical regions, and also when the upper winds do not flow quickly through the upper flow patterns. Nevertheless the investigation of the association of the patterns of cirrus systems and of the vorticity in the high-troposphere wind is regarded as the most promising of practical reward and is now being conducted on a quantitative basis.

In the model shown in Fig.1 the upper troughs and cyclones are regions of no high cloud, and the cirrus systems are found in the upper ridge, separating a SW'ly jet-stream at the rear from a NW'ly jet stream in advance of the system. The leading edge of the cirrus system extends from the left entrance of the NW'ly jet-stream approximately through the jet maximum and across the streamlines towards higher pressure in the vicinity of the jet axis.

and along most of its length lies at an angle of some 20-40° to the direction of the wind flow. The forward and rear edges of the cirrus system are more nearly parallel to the jet axes, since these have orientations approaching those of the warm and cold fronts, sidling across the contours from low to high pressure in advance of the cloud system and from high to low pressure in its rear.

Forms of warm front cirrus and related wind structure.

Frequently the leading clouds of the advancing cirrus system, seen as the decay-edge approaches, are formless and tenuous streaks which gradually fuse and thicken into a diffuse cirrostratus or altostratus. About equally often the cirrus uncinus are among the clouds first seen. Bergeron (4) distinguishes between a leading zone of cirrus uncinus and the 'real' frontal cirrostratus, saying of the cirrus (p.528) : ' the individual elements of these clouds are constantly dissolving, but they are replenished from the horizon so that the cloud amount continues to increase '.

Undoubtedly details can be found which are in the course of dissolution, but cirrus uncinus are to be regarded as young clouds, unlikely to be much more than an hour or two old (5); their occurrence is in general an indication of the presence of a process of cloud formation, not one of cloud decay. Moreover, the growth of a substantial fall-streak implies the presence of layers of air, extending over 1 km or more below the formation level, in which there is a state of supersaturation with respect to ice (6,7) which permits the continued growth and fall of the cirrus crystals. Equally, the development of long fall-streaks over periods of up to an hour or two demands a process of crystal-formation which shall persist for such periods in localised regions near the tops of the fall-streaks. The only such process which has been suggested also requires the presence of a considerable supersaturation with respect to ice in the clear air into which the fall-streak crystals descend (8). In spite of this evidence the leading edge of the cirrus system must be regarded as a decay-edge, beyond which the clear air should generally be in a state of sub-saturation with respect to ice.

This apparent contradiction can only be resolved by supposing that in the vicinity of the decay-edge disturbances of smaller scale than are shown on synoptic charts locally restore vertical motion and the renewal of cloud formation. These disturbances may be a characteristic of the air-stream, associated with the 'streakiness' of the jet structure or internal waves of the kind which produce billow clouds moving with the wind, or they may be introduced into the airstream by the hills or mountains over which it passes. Disturbances of this latter kind often produce shallow wave clouds in the medium levels before the advancing cirrostratus has thickened into an altostratus. Such clouds are very localised and do not suggest that the air which has risen above some ground obstacle returns only slowly to its original level, thus maintaining the high humidity over a great distance downwind in the manner which seems to be required for persistent fall-streak regeneration. On the other hand the formation of streamers of ice-cloud , whose length may reach hundreds of kilometres, from persistent cold wave-clouds produced over even small hills has already been described (9, 10, 11). Such clouds are typically found on the flanks of major cirrus systems, especially on the northern fringes of systems associated with quasi-stationary cold fronts, and also within the warm air mass on the southern fringes of frontal systems. Frequently such clouds are responsible for the appearance of a remarkably sharply defined edge to the cirrus system. Their recognition is important, for their edges lie strictly along the air flow, unlike the edges of other cirrus systems. Because of their great extension down-wind I have called them 'great hill-wave clouds' to distinguish them from ordinary hill- and lee-wave clouds. Probably they reach their greatest development when air moving near a high cloud system would not have received a sufficient vertical displacement to produce cloud (at near-saturation over liquid water) in the absence of the orographic disturbance, but yet which is brought to a state of ice supersaturation over a very long path. Sometimes, however, droplet clouds are observed at lower levels which are similar, though not of such great horizontal extent, and these certainly imply that the air displaced upwards near a hill only slowly returns to its original level.

Concerning the mechanism of fall-streak regeneration, it has been shown that an isobaric condensation which reduces a state of saturation over liquid water to a state of ice saturation releases sufficient heat to allow a dry-adiabatic ascent of the warmed air through a distance which depends upon the prevailing temperature and lapse-rate, and which at high temperatures (-10 to -20°C) and moderate lapse-rates (6.5 to 7.5°C/km) is sufficient to restore the state of saturation with respect to liquid water (12). If this is to occur at lower temperatures the lapse rate must be greater: it must exceed 8.4°C/km at -30°C, 9.2°C/km at -40°C and 9.7°C/km at -50°C. These values are not altered if it is considered that crystal formation begins at some vapour pressure intermediate between those representing saturation with respect to ice and with respect to liquid water. Their implication is that the temperature at the tops of cirrus fall-streaks is rarely likely to be much above -40°C (when ice nuclei are likely to be very rare) nor much below -40°C (unless the lapse rate is very great, approximating to the dry adiabatic). A limited number of observations seem to support this conclusion: of 18 occasions when this temperature was estimated, on 16 it lay between -37 and -50°, and only twice outside this range (consequently it is probably permissible to convert nephoscope observations of the motion of cirrus uncinus tops into estimates of the upper wind at the -45°C level; the speeds are unlikely to be in error by more than 10%). Therefore given the occurrence of the meso-scale disturbances discussed above, it is entirely reasonable to expect a narrow zone of fall-streak cirrus to occur along the decay-edge of the cirrostratus system.

It would be interesting to see if they are ever present in cloud systems over the ocean, in regions at least several hundred miles removed from hills and mountains. From some detailed observations of a cirrostratus system made in Sweden it was possible to deduce that the fall-streaks were not more than 3 hours old, and had all formed (in a NW'ly flow) after the air stream had reached the Scandinavian mountains. The conditions were favourable for the occurrence of wave motions over these mountains (wind component across the chain increasing with height). The occasions on which the fall-streaks do not occur at the decay-edge may arise when the air stream has a significantly different structure in which orographic waves are not produced. Further study of this possibility will be undertaken. Arrangements made to obtain observational data during the winter of 1957-58 were frustrated by abnormally long spells of unfavourable weather.

Wind shears shown by warm front cirrus.

The orientation of the fall-streaks of the cirrus uncinus along the decay-edge of the warm-front cirrostratus system conflicts with classical ideas about the wind flow in this region. If the winds are approximately geostrophic, the advection of warm air is accompanied by winds which veer with height (Fig.2).

FIGURE 2

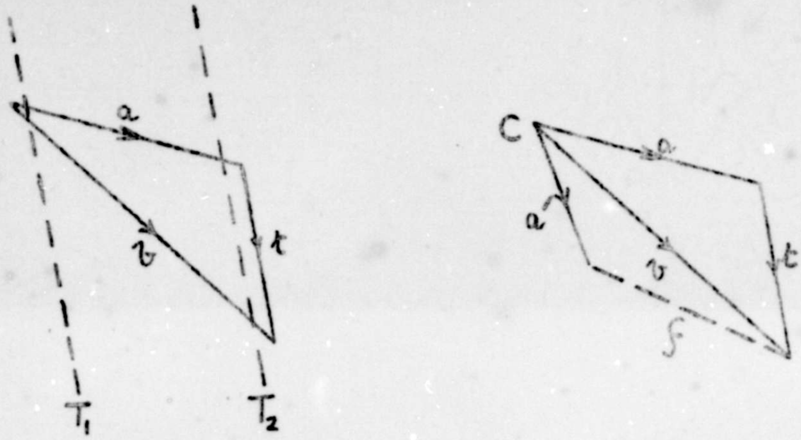


Fig. 2. (a) if the vector 'a' represents the wind at the base of a layer in which the mean isotherms are T_1, T_2 ($T_1 > T_2$, corresponding to advection of warm air), then the thermal wind t is veered from the wind a,

(b) if in the circumstances represented by diagram (a) a crystal-generating region C moves with the wind b at the top of the layer, the falling crystals lag behind and trail in the direction of the thermal wind t, to the right of the approaching cloud. Commonly, however, the trail f is observed to lie to the left, indicating an upper wind b' backed from the lower-level wind a'.

Usually, if not invariably, the fall-streaks are observed to trail into the high cloud system, often at such an angle that, although the edge of the system lies some 30° to the right of the wind flow, they lie to the left of the motion of the tops of the fall-streaks, indicating a wind which backs with height (Fig.2b)

Careful analysis of a series of double-theodolite balloon ascents, which were available for an occasion when cirrus observations were also made, confirmed the existence of these anomalous shears at the appropriate levels. The changes in velocity from one level to another which produce these shears are rather small, and they cannot be obtained with satisfactory accuracy if, as in usual practice, the observed winds are reported as average winds over layers about 4000 feet thick, and particularly when the wind directions are rounded off to the nearest ten degrees.

A study was made of the change of wind direction with height on soundings, over the British Isles, which entered NW'ly jet streams in the years 1949-1950, when the directions were reported to the nearest degree, with the results shown in the following table :

SOUNDINGS OVER BRITISH IS. IN NW'LY JET STREAMS, 1949-50

$(ddd)_m$ = direction of wind at level of strongest wind
$(ddd)_x$ = " " " " levels 50,100 or 150 mb lower.

Type and number of soundings	Mean value of $(ddd)_m - (ddd)_x$: x = 50 mb	x = 100 mb	x = 150 mb
All soundings (81)	1.0	2.6	4.8
Soundings with wind back in highest layer (32)	-2.7	-0.4	1.5
Soundings with wind veer in highest layer (49)	3.4	4.5	7.1

The preceding Table shows that in a substantial fraction of all the soundings the wind backed with height in the layer extending 100 mb below the level of the wind maximum. The small magnitude of this change and the widespread habit of reporting the wind direction only to the nearest ten degrees are probably responsible for preventing its earlier recognition as a common feature. An attempt was made to find if the soundings showing these anomalous shears were consistently made in a particular part of the jet stream by inspection of the published 300 mb charts and ascribing to them a position relative to the jet maximum (left, centre, right, entrance, exit). No preferential position was found, and it was concluded that if there is one the published contour charts were not drawn sufficiently accurately to reveal it.

Careful construction of contour and cross-section analyses of selected occasions, for which the radar winds were recomputed over 1-minute instead of the usual 3-minute intervals, suggested that the anomalous shears are usually found in the region in which strong acceleration into the NW'ly jet occurs at high levels, as indicated in the model shown in Figure 1. In a typical case the acceleration of the wind at high levels is such that at the 300 mb level the wind id directed across the contours towards low pressure at an angle of about 15°. On the other hand lower down, near the 450 mb level, the wind speeds and acceleration are so much less that the wind blows practically along the contours. The __thermal__ wind in the layer 400-300 mb is __veered__ by about 10° from the 400 mb wind, but because of the strong cross-contour flow at the 300 mb level the wind there is backed by a few degrees from the 400 mb wind. It is this backing which is consistentl indicated by the orientation of the cirrus fall-streaks at the fringe of the advancing cirrostratus system.

The domination of the observed wind shear by the ageostrophic wind components leads to the incorrect estimation of vertical velocities by the well-known method which separates advected temperature changes from the local changes actually observed in successive soundings by using the thermal wind relation. Since the cirrus fall-streaks have dimensions which may reach 1 mile across their length and 20 miles along it, their recognition from very high altitudes might be used to reveal the regions of accelerating motion and hence the location of the wind speed maxima in the jet stream. The general disposition of the extra-tropical jet streams and the wave-lengths of the large-scale upper troposphere flow disturbances and their rate of movement would probably be readily determinable from successive very high-level views of the pattern of the cirrus systems. The investigation of the relation between these systems and the upper troposphere flow will be continued with particular attention to the early stages of cyclogenesis and cyclone deepening, and to the lower cloud systems which might interfere with the recognition of cirrus from very high levels.

Cirrus in the tropics and sub-tropics.

Since it is to be expected that the reconnaissance of cloud systems from very high levels will be important principally in low latitudes where the conventional observations are of poor quality, unrepresentative of large-scale weather, or too sparse, it is important to extend the study of cloud systems to include those which occur in the tropics.

Advantage was taken during March 1958 of an opportunity to observe cirrus systems from a mountain observatory in the Canary Islands (latitude 28° N). A preliminary appraisal suggests that some cirrus systems found to extend over large areas of North Africa might be related to orographic disturbances in the air-flow. Many banded systems of cirrus were observed to form in the vicinity of the Canaries and extend hundreds of miles or more down-wind. Unlike similar cirrus bands which have been observed over England, which extend in the direction of the wind at their level, these cloud bands lay along the direction of the wind shear, at an angle of 30° or more to the wind at the cirrus level. It was found that the up-wind end of a cirrus band may extend up-shear by the formation of fresh cloud at a rate of 35 knots. The mechanism by which these bands form and extend is being investigated. It seems that the orientation of high cloud bands, at first thought a clear indication of the wind flow at cloud level, may diverge by 30° or more from the true wind direction, and it will be important to determine what produces this orientation and to identify the circumstances in which it is different from the wind direction.

High-level aircraft photographic reconnaissance of cloud systems over Europe and the Mediterranean has been begun, and arrangements have been made to obtain other observations by which the investigation of the relation between high cloud systems and the upper troposphere flow patterns is being extended into a large region in the tropics and sub-tropics.

REFERENCES.

1)	Riehl, H., Norquest, K.S. and A.L.Sugg.	1952	J. Met., 9, p. 291
2)	French J.E. and Johannessen, K.R.	1953	Proc. Toronto Met. Conference, p. 160
3)	James, D.G.	1957	Met. Mag., 86, p. 1
4)	Bergeron, T., Godske, C.L., Bjerknes, J, and R.C. Bundgaard.	1957	Dynamic meteorology and weather forecasting.
5)	Ludlam. F.H.	1951	Compendium of Meteorology, p. 19?
6)	--------	1938	Quart. J.R. Met. Soc., 74, p. 39
7,8)	--------	1956	ibid, 82, p. 257
9)	--------	1952	ibid, 78, p, 554
10)	--------	1952	Weather, 7, p. 300
11)	--------	1955	Discovery, p. 112

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