EMPIRICAL INVESTIGATION OF CLOUD STREETS OVER NORTHERN GERMANY BY USE OF ROUTINE AEROLOGICAL DATA

by Detlef Muller

Presented at the XX OSTIV Congress, Benalla, Australia (1987)

1. Introduction

Cloud streets are a quite frequently observed phenomenon in the atmosphere as has been revealed by satellite pictures during the last two decades. Cumulus clouds are organized in longitudinal bands, which may extend up to 500 km with a spacing of approximately 2-8 km. Generally, street spacing is between 2 and 4 times the height of the convection layer; observations over eastern Asia during cold air outbreaks gave an aspect ratio up to 18. Cloud streets are orientated roughly along the mean wind of the convection layer, and the phase speed in the transverse direction is usually small to the direction of the lower pressure. Under convective conditions and moderate wind speeds, cloud streets can be found over land as well as over the oceans. The organization of clouds into streets is explained by the existence of horizontal roll vortices in the atmospheric boundary layer (Figure 1). Near the surface, the vortices collect convective elements into their upward vertical velocity regions.

The formation of horizontal vortex rolls in the planetary boundary layer have been explained by two models: the first one based on a combination of thermal instability and shear (e.g., Kuettner, (1)), and the other one on the so called inflection point instability (e.g., Lilly, (2)).

The inflection point instability theory is based on laboratory experiments which simulate the boundary layer flow. Rotating water tank experiments revealing longitudinal instability waves in the neutral boundary layer were discussed by Faller (3). The existence of an inflection point in the velocity component perpendicular to the roll axis is due to influence of the Coriolis effect and friction in the atmospheric bound-

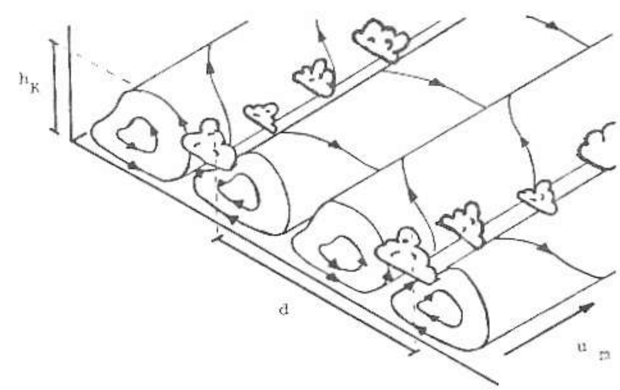


FIGURE 1. Typical secondary flow in the planetary boundary layer. U(m) marks the mean wind direction, h(k) the height of the convection layer and d the cloud street spacing. Near the surface, the vortices collect convective elements into their upward vertical regions.

ary layer resulting in a turning of the wind vector with height in the lowest kilometer. Examples of such wind profiles for a typical neutrally stratified boundary layer and a geostrophic wind of 10 m/s are given in Figure 2. The coordinate system is orientated with the u-component in the direction of the vortex axis and the v-component (shown in Figure 2) perpendicular to it. Profiles are shown for different orientation angles with the positive sign indicating the counterclockwise orientation of the roll axis relative to the geostrophic wind. The inflection points are marked by the line h (i B) in each profile.

In this paper, one presented some results of an investigation of cloud streets over northern Germany with the help of routine aerological radiosonde data. Because this area is rather flat, cloud streets are not very much effected by orographic structures. The results suggest that the inflection point instability may serve as a trigger for vortex roll development in the planetary boundary layer. The roll development in the planetary boundary layer. The roll development is enhanced and modified through the action of buoyancy for unstable stratification.

2. Data analysis

Using satellite pictures taken at about 6 and 14 UTC (Central European time), those days in 1982 and 1984 were selected when cloud streets could be detected over northern Germany. Routine observations were used for the analysis of the meteorological situation on days with cloud streets. The geographical distribution shows a distance of about 200 km between the station used for aerological analysis. By use of routine aerological soundings, it was possible to analyze data taken at about 5, 11 and 17 UTC before and after cloud streets could be observed.

Using routine pilot balloon measurements for wind profile analysis, three problems have to be regarded:

a) There is a time-space between wind soundings and the time the satellite pictures were taken,

b) in areas where cloud streets had developed, the mean wind profile will be modified with time by the rolls, and

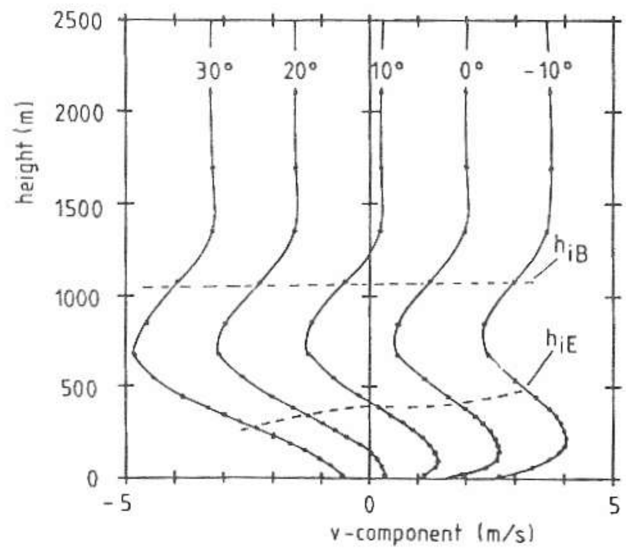


FIGURE 2. Mean cross-wind component v(h) for a typical atmospheric boundary layer for different orientation angles of possible vortex rolls. Inflection points due to Ekman layer shear flow marked by h(iE), those due to thermal wind marked h(iB).

c) the rolls modify the mean wind profile in different ways.

Because of the rather large areas effected by roll development, the error in time-space coordination was neglected here.

Figure 3 presents the mean wind profile of a neutral boundary layer modified with time by roll vortices simulated with the help of a numerical model of Raasch (Etling et al., (4)). At 2000 m the boundary layer is capped by an inversion. The plot demonstrates the profile smoothing with time by mixing.

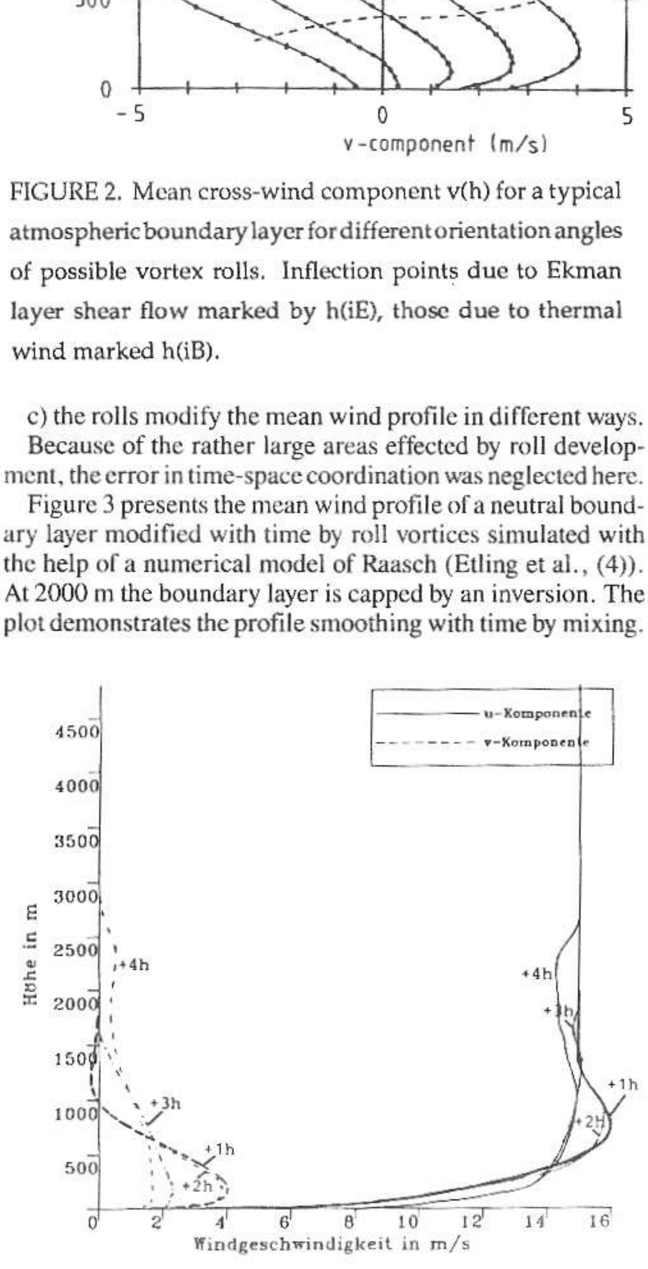


FIGURE 3. Change of a wind profile with time caused by vortex rolls. (Numerical simulation of a neutral atmospheric boundary layer capped by an inversion at a height of 2000m. S. Raasch, Inst.f.Meteor.u.Klimatol.,Universitaet Hannover).

To examine the profiles taken at midday, the profiles were compared with aerological measurements taken in the evening and before cumulus clouds occurred. Besides this profiles were compared with profiles taken outside the areas with cloud street observation. If there is a maximum or minimum vertical wind speed near the middle of the convection layer, there is little modification of the mean wind profile.

3. Main result

Over all, 25 days with cloud street observations over northern Germany could be analyzed. For all cases with wind speed faster than 3 m/s the wind profiles show well-marked inflection points in those areas where cloud streets were observed.

There are two main reasons for such inflection points under convective conditions:

1. Ekman shear flow, and
2. Baroclinic shear flow. Here the turning of the wind is due to the change of the geostropic wind with height.

Either of these may dominate or both may contribute equally.

According to Brown (15), the height of the inflection point, h(i), should be related to the depth of the convection layer, h(c), by

$$h(i)/h(c) <= 0.7 \quad (1)$$

for optimal development. This was tested against all the cases of observations of cloud streets at noon and for which radiosonde observations, together with wind measurements were available. Since some of the radiosonde stations were in areas with cumulus clouds not organized in streets at the same time, the condition for the non-occurence of cloud streets can also be discussed.

In Figure 4, the relative height of the inflection point h(i)/h(c) has been plotted against the shear at this point in v. This plot shows that the relative height of h(i) was in a range of

$$0.25 < h(i)/h(c) < 0.75 \quad (2)$$

This agrees well with the criterion of Brown. The minimum wind shear for obtaining cloud streets was

$$(dv/dz)_{h(i)} = 5*10^{-3} sec^{-1} \quad (3)$$

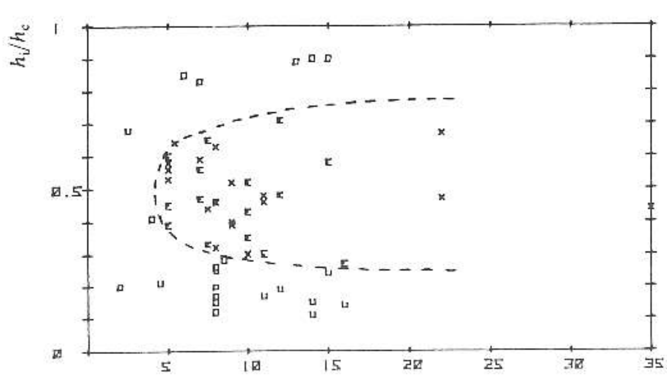


FIGURE 4. The dependence of the wind shear of the v-component at the height of the inflection point normalized by the depth of the convective layer, for cases with cloud streets (X,E) and random cumulus clouds (O,U) (daytime soundings).

at h(i)/h(c)=0.5. Larger or smaller heights were connected with greater shear. All wind profiles with an inflection point outside the areas of cloud streets are grouped well outside that part of the diagram which is enclosed by the dashed line.

These observations agree well with the results of linear analysis of inflection point instability in a neutral layer published by Brummer et al. (6) (Figure 5). The calculations that the critical Reynolds numbers Re increases with decreasing distance of the inflection point from the boundaries of the roll layer. The asymmetry in the curve was caused by the asymmetrical boundary conditions (rigid bottom and stress-free top). But there is not only good agreement with theoretical results: For example, three of four reanalyzed wind profiles published by Kuettner (1) fulfill the criterions described above. Figure 6 shows the wind profiles up to the top of the convection layer plotted in components (see Section 2). One typical appearance of wind profiles taken in regions with cloud streets can be pointed out in this figure: In nearly all cases the height of the inflection point in v at v=Om/s is near the height of a wind speed maximum.

In 1986 Miura (7) published wind profiles taken in regions with cloud streets over the eastern Asia oceans. Figure 7 shows velocity components of the wind parallel (u) and perpendicular (v) to the mean wind which was obtained by averaging winds from the surface to the inversion base. These profiles are classified into three stages of evolution of cloud bands: an upstream class (1), a middle class (2) and a downstream class (3). Nearly all wind profiles show inflection points in v at about half the height of the boundary layer capped by an inversion.

4. Case study, 26.06.1984

Picture 1 shows a NOAA satellite picture of the 26th of June, 1984, 7 UTC. Cloud streets can be seen in the northern parts of northern Germany around Kiel. On picture 2 taken at 14 UTC no cloud streets could be observed.

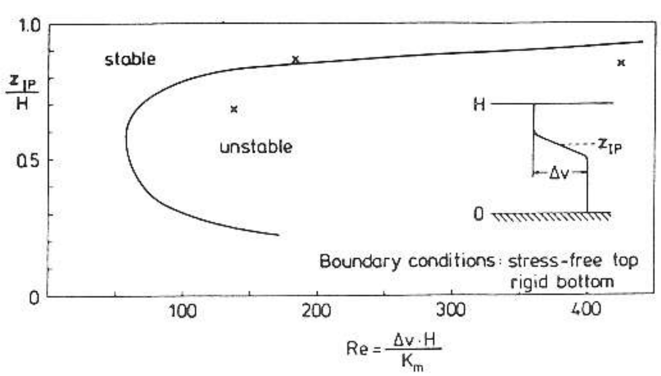


FIGURE 5. Reynolds number Re versus normalized height z(ip)/H of the inflection point. The solid curve separates stable from unstable (with respect to infinitesimal perturbations) cross-roll wind profiles which are sketched in the inserted figure. Diffusion coefficient k(m) is constant with height and the stratification is neutral. Crosses represent three KonTur days: 18, 20 and 26 September, 1981. (Bruemmer, et. al., (19)).

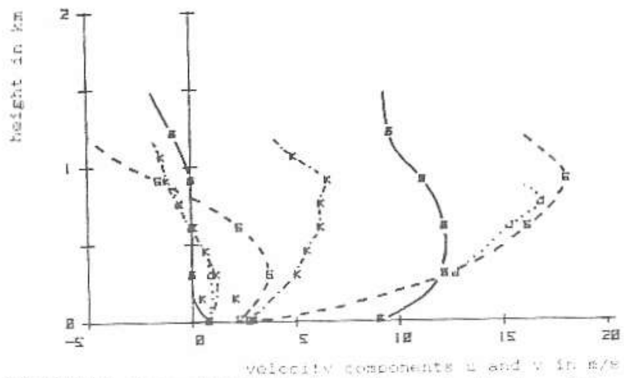


FIGURE 6. Reanalysed wind profiles up to the top of the convective layer published by Kuettner (l). Three of the four profiles taken in regions with cloud streets fulfill the inflections-point criterions described in chapter 3. B: Barbardos, 28-06-1969, K: Cape Kennedy, 31-01-1961, G: Green Bay, 30-08-1964, J: Jacksonville, 04-04-1968.

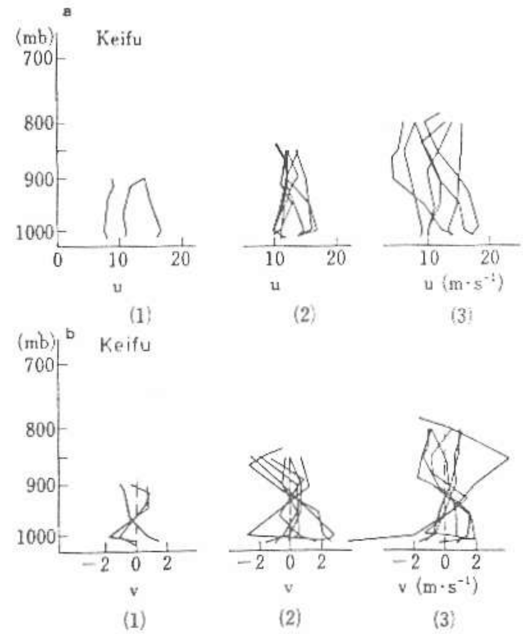
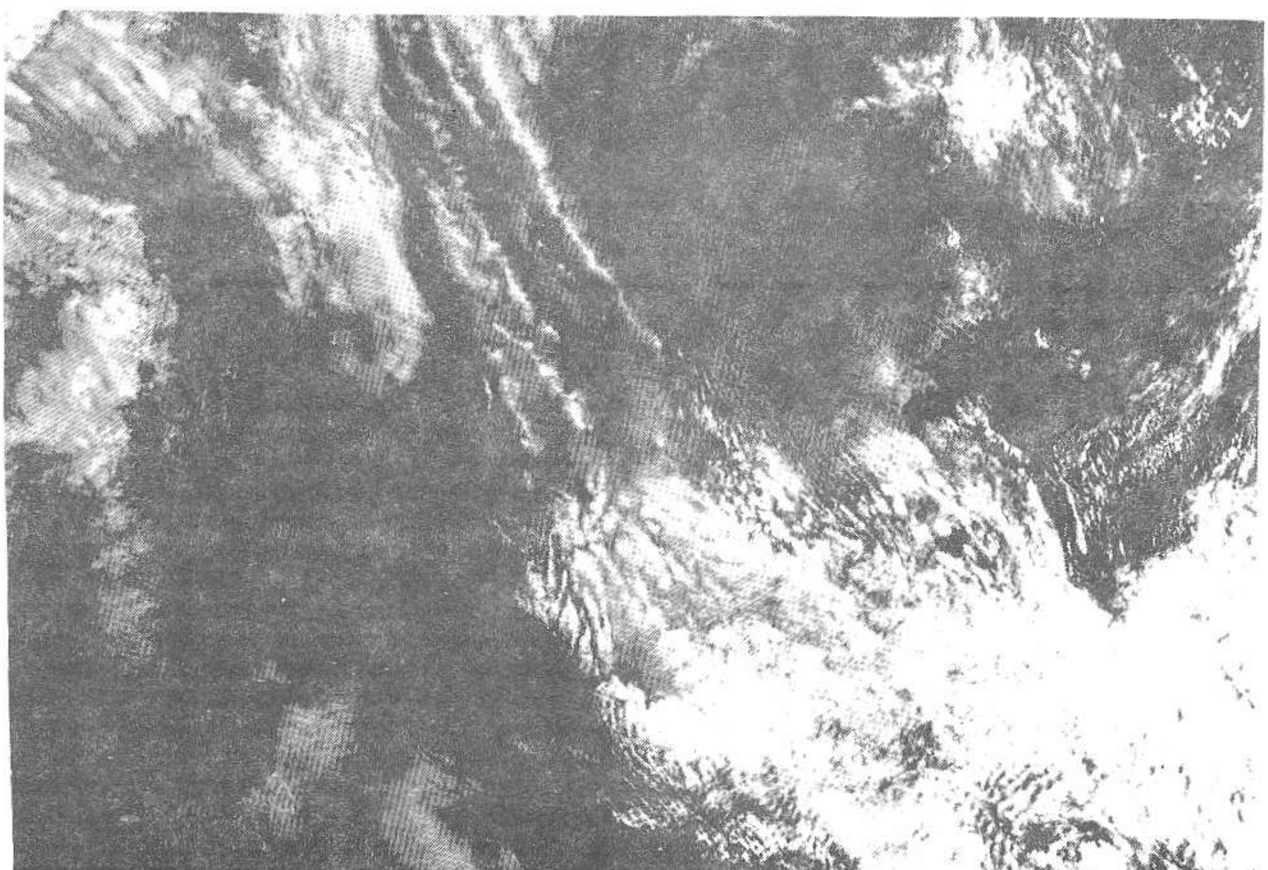


FIGURE 7. Wind profiles taken in regions with cloud streets over the eastern Asia oceans. Velocity components of the wind parallel (u) and perpendicular (v) to the mean wind which was obtained by averaging winds from the surface to the inversion base.

The surface weather map at 12 UTC (Figure 8) shows northern Germany lying in the rear of a cold front with not much curved isobars. There was a wind speed of about 10 m/s above the friction layer. Balloon measurements of wind components at 7 UTC show the inflection point and minimum



PICTURE 1. Satellite picture taken by NOAA 6 on 26-06-1984, 7 UTC.

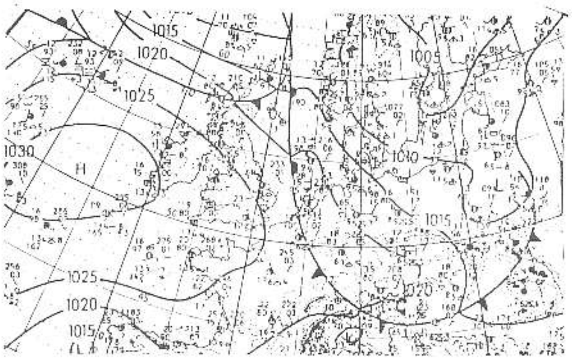


FIGURE 8. Surface weather map, middle of Europe, 26-06-1984, 12 UTC.

wind speed close to half the height of the convection layer. Cloud streets could be observed. At 13 UTC the inflection point occurred at a lower height of the convection layer. There were no cloud streets.

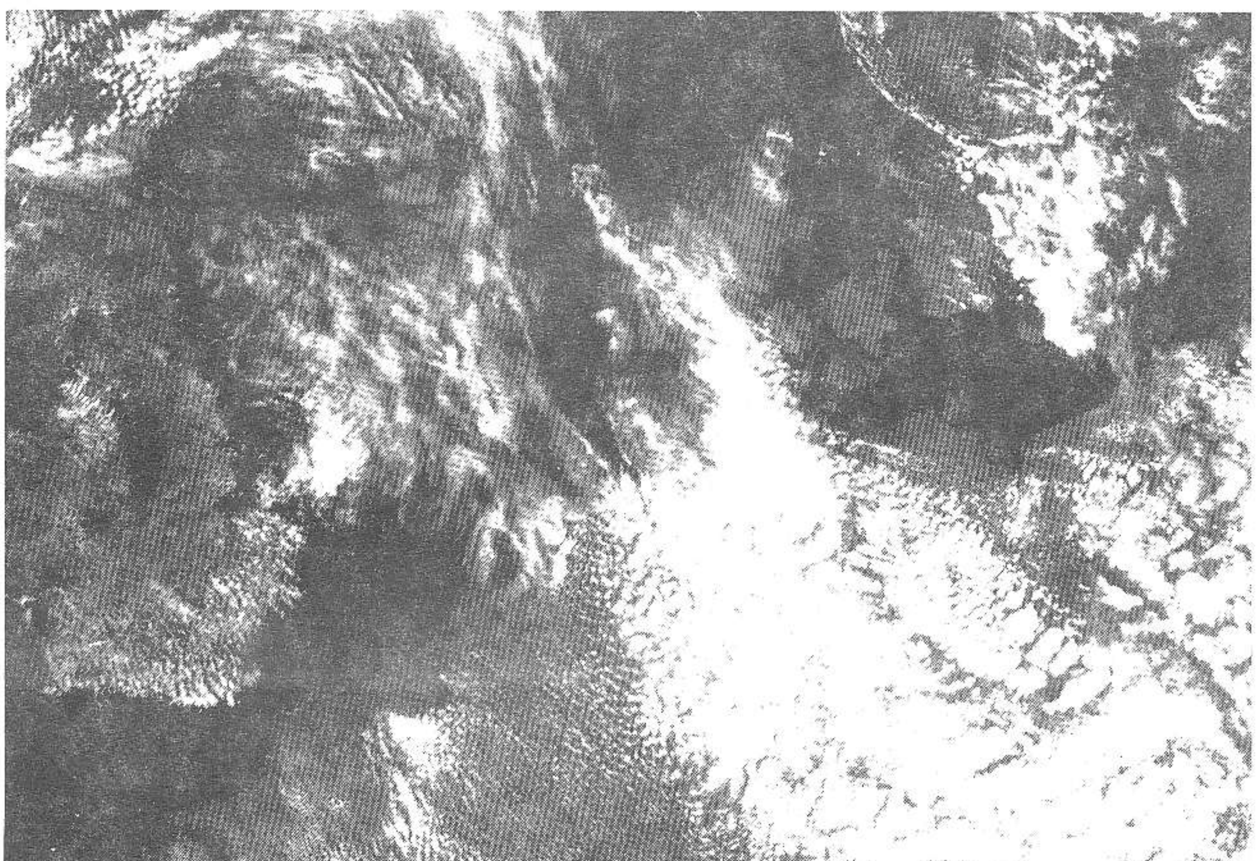
5. Forecasting cloud streets caused by inflection point instability

As a result of the investigation, it was possible to create rules to forecast cloud streets caused by inflection point instability: As pointed out by Muller et al. (8) for conditions with strong geostrophic wind speeds ($u(g) > 10$ m/s) and not too large thermal stability, the shear at the inflection point at $v(i) = 0$ m/s and its height may be used to forecast the possibility of the occurrence of cloud streets by using night time soundings. The height of the day time convection layer has to be forecast with the help of the nocturnal temperatures.

Unfortunately, there are often no detailed analysed wind profiles. Therefore, I looked for a more simple rule to forecast cloud streets. A simple method of forecasting cloud streets caused by Ekman shear flow is based on the following consideration: To estimate the height of the inflection point at midday we can assume that this height scale with the Ekman layer scale height, $H=\varkappa u_*/f$, where $\varkappa$ being the von Karman constant, u_* the friction velocity and f the Coriolis parameter. Therefore, the height of the inflection point $h(i)=a(\varkappa u_*/f)$, where a is a constant to be determined. To simplify the input parameters, the assumption is made that the upper wind speed u(h) is close to the geostrophic wind speed u(g) and that a linearized form of the resistance law of the planetary boundary layer $u_*=0.037u(g)+0.043$ could be used. This relation fits the resistance law by Wippermann (9) well for $f=1.16*10^{-4}sec^{-1}$, $Z(0)=0.3m$ and wind speeds between 5 and 25 m/s. Thus, finally, together with the assumption $u(h)=u(g)$, the relation

$$h(i)=a(128u(h)+149) \qquad (4)$$

follows, where h(i) is in meters and u(h) is in meters per second. Figure 9 shows the dependence of the height of the inflection point in relation to the wind speed at that height for soundings during night. Cases with near neutral stratifiction


PICTURE 2. Satellite picture taken by NOAA on 26-08-1984, 14 UTC.

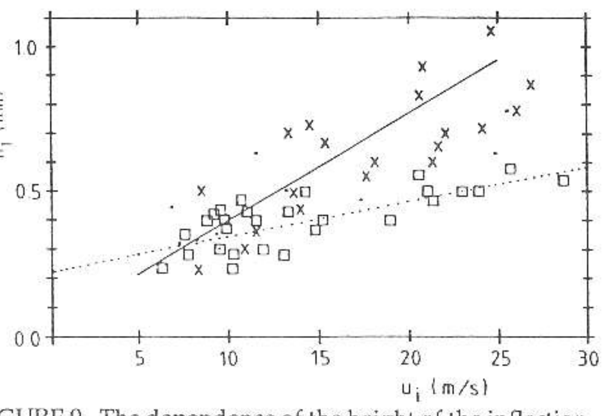


FIGURE 9. The dependence of the height of the inflection point in relation to the wind speed at that height for soundings during night in and out of areas where cloud streets occurred during the following day (X: cases with near neutral stratification; straight line, according to equ. (4); O: stable stratification; dotted line: linear fit to stable stratified cases; dots: unknown stratification).

are marked by 'x'. The straight line is given by relation (4) with the constant a=0.28. It fits the observations very well.

With the assumption that the convection layer has to have a maximum height of three times the inflection point height to cause cloud streets, the relation for the maximum height of the convection layer is

$$h(c)=108u(h)+125 \quad (5)$$

where h(c) is in meters and u(h) is in meters per second. To create rules for forecasting cloud streets caused by baroclinic shear flow is very difficult, because of the large change in the wind profile in a few hours. Here lists or schematic weather maps with typical weather conditions when cloud streets occurred are a praticable way for forecasting.

Figure 10 shows a composite surface chart with typical synoptic situations of the observed days with cloud streets:

Cloud streets could be observed

a) in the rear of a cold front or occlusions with nearly straight surface isobars and straight contours in 850 and 700 hPa height fields. The wind speed in the Ekman layer has to be larger than 10 m/s. The inflection point is caused by Ekman shear flow.

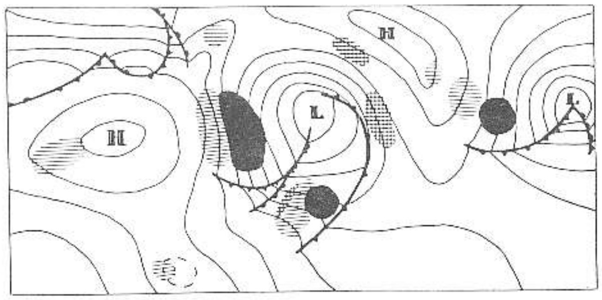


FIGURE 10. Schematic weather map showing areas where cloud streets maybe expected. In black areas, shear is Ekman shear; lined areas: baroclinic shear; cross hatched: combined shear.

b) in the rear of a cold front or between cyclones with small anticyclonic curvature of the isobars. The inflection point of these cases is caused by baroclinic shear flow, which is seen in a change of wind direction towards the higher pressure with increasing height within the PBL.

c) in areas showing a high pressure ridge with strongly curved isobars. The wind speed within the PBL may be less than 5 m/s; the inflection point is caused by baroclinic shear flow.

d) in areas ahead of a cold or warm front with small angles between the isobars and the front when the geostrophic wind changes little with height. The wind speed within the PBL is generally larger than 10 m/s and the wind direction changes towards the left near the ground when the front is approaching, thus enforcing the inflection in the wind profile.

Acknowledgement

I wish to thank Prof. Dr. R. Roth, Institut für Meteorologie und Klimatologie, Universität Hannover, for permission to work on cloud streets to take my diploma and my doctor's degree.

References

(1) Kuettner, J. 1971 Cloud bands in the earth's atmosphere: Observations and theory. Tellus, 23,404-425.

(2) Lilly, D.K. 1966 On the stability of Ekman boundary flow. J. Atmos.Sci., 23,481-494.

(3) Faller, A.J. 1965 Large eddies in the atmospheric boundary layer and their possible role in the formation of cloud rows. J.Atmos.Sci., 23,176-184.

(4) Etling, D. and S. Raasch Numerical simulation of vortex roll development during cold air outbreaks. Dynamic Atmos. Oceans, accepted f.publication.

(5) Brown, R.A. 1972 The inflection point instability problem for stratified rotating boundary layers. J.Atmos. Sci., 29, 850-859.

(6) Brummer, B., S. Baken and H. Hinzpeter 1985 KonTur: Observations of cloud streets and open cellular structures. Dynamics Atmos. Oceans, 9,281-296.

(7) Miura, Y. 1986 Aspect Ratios of Longitudinal Rolls and Convection Cells Observed During Cold Air Outbreaks. J.Atmos.Sci., 43,26-39.

(8) Muller, D., Ch. Kottmeier, D. Etling and R. Roth 1985 On the occurrence of cloud streets over northern Germany. Quart. J.R.Met.Soc., 111,761-772.

(9) Wippermann, F.K. 1973 The planetary boundary layer of the atmosphere. Ann.Meteor., No. 7, Deutscher Wetterdienst, Offenbach a.M.