On the occurrence of cloud streets over northern Germany

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SUMMARY

Cloud-street observations over northern Germany are analysed with respect to wind and temperature profiles obtained from routine radiosonde stations in the area. In nearly all cases the wind profiles on cloud-street days were characterized by an inflection point in the cross-wind component with unstable stratification of the boundary layer. The height of the inflection point was found to be related to the convection height on those days, which may suggest the importance of both inflection point and convective instability for explanation of cloud-street development.

1. INTRODUCTION

Cloud streets are a quite frequently observed phenomenon in the atmosphere, as has been revealed by satellite pictures during the last decade. Small cumulus clouds are organized in longitudinal bands which may extend up to 100 km with a spacing between the bands of approximately 2–6 km. The cloud streets are orientated more or less in the direction of the mean wind in the convection layer, and the phase velocity in the transverse direction is usually small (Kuettner 1971). Under slightly unstable stratification and moderate wind speeds cloud streets can be found over land as well as over the oceans. The organization of clouds into rows is explained by the existence of horizontal roll vortices in the atmospheric boundary layer, and the cloud streets are visualized above the upward parts of the roll system. The existence of such helical vortices has been confirmed by measurements in the boundary layer. A quite detailed study of roll vortices over land has been made by Le Mone (1973). The formation of cloud streets over the sea was investigated during the KonTur experiment over the North Sea area (Brümmer et al. 1982).

In a newly evolving discipline in physics, called synergetics (Haken 1978), the phenomenon of cloud streets is often quoted as an example of self-organizing structures. Although there is much visible evidence of cloud-street formation, not many observations exist with respect to related wind and temperature profiles which could give more insight into the physical mechanism of cloud-street development.

The formation of cloud streets by horizontal vortex rolls in the atmospheric boundary layer may be explained by a special dynamic instability (inflection point) interacting with an initially randomly distributed field of convective elements. In our investigation we will focus on the inflection point instability in the analysis of observational data. In contrast to the detailed case studies of Le Mone (1973), who used tower and aircraft measurements, the problem will be dealt with here by use of routine radiosonde soundings and in relation to the synoptic situation.

2. THEORETICAL ASPECTS OF CLOUD-STREET DEVELOPMENT

The formation of cloud streets is caused by horizontal vortex rolls in the atmospheric boundary layer. The roll development itself can be caused by three main instabilities: dynamic (inflection point), parallel (Coriolis) and thermal (convective) instability, which may act separately from a theoretical point of view (Shirer 1982), but can usually hardly be distinguished in real atmospheric flows.
Theoretically, the Ekman layer type of inflection point instability was investigated by Lilly (1966) and Brown (1970) for the case of constant eddy viscosity and has been extended to variable viscosity profiles by Etling and Wippermann (1975). The main results of these linear studies were that horizontal vortex rolls can form with wavelength approximately 2–3 times the boundary layer depth and an orientation deviating only slightly from the direction of the geostrophic wind. These results were confirmed by numerical simulation of the development of vortex rolls in the boundary layer by Mason and Sykes (1980). The existence of an inflection point in the velocity component perpendicular to the roll axis is due to the influence of the Coriolis effect and friction in the atmospheric boundary layer resulting in a turning of the wind vector with height in the lowest kilometre. Examples of such wind profiles for a typical neutrally stratified boundary layer and a geostrophic wind of 10 m s\(^{-1}\) are given in Fig. 1. The coordinate system is orientated with the \(u\) component in the direction of the vortex axis and the \(v\) component (shown in Fig. 1) perpendicular to it. Profiles are shown for different orientation angles \(\epsilon\) 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 \(h_{iE}\) in each profile.

![Diagram](image)

Figure 1. Mean cross-wind component \(v(z)\) for a typical atmospheric boundary layer for different orientation angles \(\epsilon\) of possible vortex rolls. Inflection points due to Ekman layer shear flow marked by \(h_{iE}\), those due to thermal wind marked \(h_{iB}\).

Another possibility of creating inflection points even without a boundary layer flow is provided by the turning of the geostrophic wind by cold or warm air advection in the lower atmosphere. Brown (1980) has shown that an inflection point instability can develop even for cases of pure turning shear flows. Those inflection points caused by thermal wind are shown in the upper part of Fig. 1 and marked by \(h_{iB}\). In this case the orientation angle \(\epsilon\) is defined with respect to the surface geostrophic wind. Some cases of strong
turning wind shear in the boundary layer where cloud streets were observed seem to be
due to thermal wind in the KonTur experiment or in other areas over the sea (Walter
and Overland 1984). In the following analysis we will distinguish between these two types
of inflection points.

The inflection point instability described so far can develop for neutral or even
slightly stable stratification. However, observations of cloud streets show that they occur
mainly under unstable stratification, often bounded by an inversion layer above. This
may suggest that cloud streets are of purely convective origin, i.e. driven by buoyancy.
It is well known that in a parallel shear flow over heated surfaces convection is organized
into rolls with axes parallel to the mean wind. If the wind component perpendicular
to the cloud street axis is neglected, a shear flow parallel to the roll vortices can always be
found in the atmospheric boundary layer. This led Kuettnner (1971) to his thermal theory
of cloud-street development. In a moderately unstable boundary layer there will always
be a turning wind profile exhibiting an inflection point. Thus it is possible that dynamic
and convective instability occur simultaneously, leading to vortex roll development and
cloud-street formation. This combined effect in a stratified Ekman boundary layer has
been investigated by, among others, Brown (1972) by means of linear perturbation
analysis. He found that for moderate unstable stratification the inflection point mode
was significantly enhanced by thermal convection, but the size and the orientation of the
vortex rolls did not differ very much from the case of pure dynamic instability. Mason
and Sykes (1982) extended their nonlinear numerical study to the convective case for an
unstable atmospheric boundary layer capped by an inversion. They found the thermal
instability mode to be dominant with an orientation of the vortex rolls more in agreement
with the observations.

Whether the inflection point mode or the convective mode is the more responsible
for cloud-street formation is still a matter for discussion. Here the argument is put forward
that the inflection point instability may serve as a trigger for vortex roll development in
the boundary layer which is enhanced and modified through the action of buoyancy for
unstable stratification. Hence this paper will focus on the existence of inflection point
wind profiles in situations where cloud streets were observed. From the analysis of
observations it became clear that a composite evaluation of the data was best possible
for inflection points caused by boundary layer (Ekman layer) shear flow, as denoted by
$h_{IE}$ in Fig. 1. Hence the inflection point $h_{I}$ is used in the calculations. For convenience
we denote the height of the inflection points by $h_{I}$ instead of $h_{IE}$, if not otherwise noted,
throughout the paper.

As can be seen from Fig. 1, the profile of the wind component perpendicular to the
roll axis, and hence the location of the inflection point, depends on the orientation angle
with respect to the direction of the geostrophic wind. But since there are neither good
estimates of the geostrophic wind nor of the cloud-street orientation, those wind profiles
were chosen where the cross-wind component at the inflection point height $h_{I}$ vanishes,
i.e. $v(h_{I}) = 0$. This can be done easily by turning the observed wind profiles in a roll
coordinate system until the required inflection point is obtained, as in Fig. 1. This choice
of a wind profile is not altogether arbitrary but has a physical background. From linear
theory it is known that the phase velocity of the vortex rolls corresponds to the wind
speed at the inflection point, i.e. $c_{r} = v(h_{I})$. By choosing $v(h_{I}) = 0$ one just obtains standing
vortex rolls. This condition differs only slightly from observed and simulated phase speeds
of cloud streets which are in the order of 1 m s$^{-1}$. In addition this choice of wind profiles
makes it possible to analyse all observed wind profiles in the same way, as will be
described later.

Besides the height of the inflection point, the convection height $h_{c}$, defined as the
maximum height of convective motions (cloud top) as derived from aerological soundings, was also considered as a possible parameter in cloud-street development. In this respect it is interesting to note that Brown (1972), in his linear analysis, also investigated the influence of a variable convection height \( h_c \) in an unstably stratified Ekman layer. Starting with a convection height below the inflection point height, he found that the growth rate of unstable perturbations grew with increasing convection height until this height was greater than the inflection point height, with \( h_I/h_c \sim 0.7 \). Increasing the convection height

<table>
<thead>
<tr>
<th>Data type</th>
<th>Data source</th>
<th>Specification</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite pictures</td>
<td>I</td>
<td>NOAA 6 and 7 VHRR VIS and IR pictures</td>
<td>1982 completely</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>NOAA 6 and 7 AVHRR enlarged pictures</td>
<td>Days with cloud streets in 1982</td>
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<tr>
<td></td>
<td>II</td>
<td>NOAA 7, AVHRR enlarged pictures, VIS range</td>
<td>Selected days with cloud streets</td>
</tr>
<tr>
<td>Temperature, dewpoint, weather</td>
<td>III</td>
<td>Station reports, surface charts, 500 hPa charts</td>
<td>Days with cloud streets</td>
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<tr>
<td></td>
<td>I</td>
<td>Surface and 500 hPa charts</td>
<td>Days with cloud streets</td>
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<td>IV</td>
<td>Synoptic messages</td>
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<tr>
<td>Radiosoundings of temperature and dew-point up to 4.5 km</td>
<td>III</td>
<td>Radiosoundings 0 and 12 h</td>
<td>Days with cloud streets</td>
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<td>IV</td>
<td>Radiosoundings 0 and 12 h</td>
<td>Days with cloud streets</td>
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<td></td>
<td>VI</td>
<td>Radiosoundings 12 h</td>
<td>Days with cloud streets</td>
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<td></td>
<td>VII</td>
<td>Radiosoundings 6 and 12 h</td>
<td>Mondays to Fridays with cloud streets</td>
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<td>VIII</td>
<td>Radiosoundings 6 and 18 h</td>
<td>Selected days with cloud streets</td>
</tr>
<tr>
<td>Pilot balloon wind measurements up to 4.5 km</td>
<td>IX</td>
<td>Original sounding data 0, 6, 12, 18 h</td>
<td>Days with cloud streets</td>
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<td>IV</td>
<td>Significant points 0, 6, 12, 18 h</td>
<td>Days with cloud streets</td>
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<td></td>
<td>VI</td>
<td>Original sounding data evaluation 12 h</td>
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<td>VII</td>
<td>Original sounding data evaluation 6, 12 h</td>
<td>Mondays to Fridays with cloud streets</td>
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<td>VII</td>
<td>Original sounding data 6, 12, 18 h</td>
<td>Selected days with cloud streets</td>
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Data sources

I Institut für Meteorologie der Freien Universität Berlin, Berliner Wetterbericht
II Deutsche Forschungs-und Versuchsanstalt für Luft- und Raumfahrt, Angewandte Datentechnik
III Deutscher Wetterdienst, Offenbach, Europäischer Wetterbericht
IV Koninglik Nederlands Meteorologic Institute, De Bilt
V Institut für Meteorologie der Freien Universität Berlin, Meteorologische Satellitenforschung
VI Institut für Meteorologie der Freien Universität Berlin, Aerologie
VII Erprobungsstelle 91, Meppen, Abt. 224
VIII Geophysikalische Meßstation Bergen-Hohne, Emden, Fritzlar, Kiel
IX Wetterämter Essen, Hannover, Schleswig Aeroniogie
TABLE 2. DAYS ANALYSED AND STATIONS USED FOR EACH ANALYSIS

<table>
<thead>
<tr>
<th>Date (1983)</th>
<th>Stations in areas</th>
<th>With cloud streets</th>
<th>Without cloud streets</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 Jan.</td>
<td>E, H</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>7 Jan.</td>
<td>E</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>31 Jan.</td>
<td>H, B</td>
<td>E, S</td>
<td></td>
</tr>
<tr>
<td>5 Mar.</td>
<td>S</td>
<td>E, H</td>
<td></td>
</tr>
<tr>
<td>11 Mar.</td>
<td>S, BH, K</td>
<td>E, H, M</td>
<td></td>
</tr>
<tr>
<td>14 Apr.</td>
<td>S, B</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>22 Apr.</td>
<td>M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 Apr.</td>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 Apr.</td>
<td>S, E, H</td>
<td>E, H, BH, K</td>
<td></td>
</tr>
<tr>
<td>11 May</td>
<td>S</td>
<td>E, H, BH, K</td>
<td></td>
</tr>
<tr>
<td>2 Aug.</td>
<td>H, BH</td>
<td>E, S, M, K</td>
<td></td>
</tr>
<tr>
<td>20 Aug.</td>
<td>E</td>
<td>H, S</td>
<td></td>
</tr>
<tr>
<td>23 Sep.</td>
<td>M</td>
<td>E, S</td>
<td></td>
</tr>
<tr>
<td>27 Sep.</td>
<td>E, S</td>
<td></td>
<td></td>
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<td>E, H</td>
<td>S</td>
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<td>28 Oct.</td>
<td>E, S</td>
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<td>20 Nov.</td>
<td>E, H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 Nov.</td>
<td>E, H, S</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

E: Essen; H: Hannover; S: Schleswig; B: Berlin; M: Meppen; BH: Bergen-Hohne; EM: Emden; K: Kiel

beyond this threshold did not affect the perturbation growth rates, hence a maximum growth rate was found for \( h_i/h_c \approx 0.7 \). The physical interpretation of this linear analysis would suggest that for cloud-street development favourable conditions would occur when the inflection point is located at a height less than about half the convection height.

3. DATA ANALYSES

Using satellite pictures, those days in 1982 were selected when cloud streets could be detected over northern Germany. This area, north of the hills of the Weserbergland and the Sauerland, is rather flat. Its highest point is the Wilseder Berg (162 m) south of Hamburg. Therefore cloud streets are not very much affected by orographic structures.

Routine observations (Table 1) were used for the analysis of the meteorological situation on days with cloud streets. The days analysed are presented in Table 2, which also shows which of the stations were situated, at noon, in areas with cloud streets. The geographical distribution and areal extent of the stations used for this analysis are presented in Fig. 2. However, these data could not be used in the same form as they are distributed for weather forecast purposes. The original observations had to be reanalysed. Thus, for instance, for those stations where the balloon launching point is not very close to the balloon tracking radar, the programme for the wind calculation was rewritten to take account of this.

For each balloon ascent the time series of radar wind measurements was used up to a balloon height of 4 km. Most profiles showed a large scatter due to turbulence. In order to obtain estimates of smooth profiles for time steps of 1 min, roughly 300 m, mean values were calculated. Using these values a smooth wind profile was reconstructed by interpolation by eye for both components, \( u \) and \( v \). This started at the height of \( z = 0 \) with \( u, v = 0 \) and using the known wind speed at 10 m.
Figure 2. Distribution of stations for the analysis of cloud streets in northern Germany.
Then for each of these wind profiles the system of coordinates was transformed in such a way that at the height where $d^2 v/dz^2$ changed sign the $v$ component itself became zero. This height was defined as the height of the inflection point $h_i$. All the results are presented in this individual system of coordinates. Typical errors were estimated using the characteristics of the radar instruments. These errors are $\Delta h_i = \pm 25$ m; $u = \pm 1$ m s$^{-1}$; $v = \pm 0.5$ m s$^{-1}$; for the height of the inflection point and the wind speed components.

4. Results

For all cases with $u(h_i) > 3$ m s$^{-1}$ the wind profiles show well-marked inflection points in those areas where cloud streets were observed or—in the case of nighttime wind profiles—where cloud streets were observed in the following day after convection started. There are two main reasons for such inflection points under convective conditions: (1) Ekman shear flow; (2) baroclinic shear flow (turning of the wind due to the change of the geostrophic wind with height). Either of these may dominate or both may contribute equally.

For the cases dominated by Ekman shear flow it is possible to construct a composite showing the nocturnal wind profile for those areas where cloud streets happened to occur during the following day. This composite is given in Fig. 3 for the $u$ and $v$ components which were normalized with the wind speed at the height of the inflection point itself.

![Normalized wind profiles for nighttime soundings in areas where cloud streets were observed during the following day. Height is normalized by use of the height of the inflection point. The system of coordinates is explained in the text.](image)

The same composite in the form of a hodograph is given in Fig. 4. From this hodograph an orientation of the vortex rolls can be expected between the direction of the surface wind and the wind at the top of the boundary layer (approximately the geostrophic wind). This implies an orientation angle $\epsilon$ of approximately 10° to the left of the geostrophic wind, which is in agreement with observations of cloud-street orientation.
Figure 4. As Fig. 3, but the composite hodograph is shown. The angle $\alpha$ between the surface stress and the wind vector at the inflection point is $17^\circ$, while the greatest angle $\beta$ between the surface stress and the wind vector in the PBL is $27^\circ$.

No composites were constructed for those cases where the inflection of the wind profile is mainly due to the change of the geostrophic wind with height, because these cases are difficult to normalize.

According to Brown (1972), the height of the inflection point, $h_i$, should be related to the depth of the convective layer, $h_c$, by

$$h_i/h_c \leq 0.7$$  \hspace{1cm} (1)

for optimal roll development. This was tested against 18 observations of cloud streets at noon and for which radiosonde observations together with wind measurements were available. Since some of the radiosondes were in areas which were covered by cumulus clouds not organized in streets at the same time, the condition for the non-occurrence of cloud streets can also be discussed.

Figure 5. Number of cases with specified relation between the height of the inflection point and the depth of the convective layer; and the reason for the inflection point (E: Ekman shear; B: baroclinicity of the thermal wind; E + B: combined reasons) for daytime soundings.
In Fig. 5 the number of observations for different values of \( h_i/h_c \) together with the cause of the wind shear at the height of the inflection point is given. In Fig. 6 the same cases together with wind profiles measured in those areas where cumulus clouds were not organized in streets are analysed from the point of view of the wind shear at the height of the inflection point. We see that the relative height of the inflection point has to be within the range

\[
0.25 < \frac{h_i}{h_c} < 0.75
\] (2)

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

\[
\left( \frac{\partial v}{\partial z} \right)_{z=h_i} = 5 \times 10^{-3} \text{s}^{-1}
\]

and this only causes cloud streets if \( \frac{h_i}{h_c} = 0.5 \). If the wind shear is larger, the relative height \( \frac{h_i}{h_c} \) may be larger or smaller than 0.5. All wind profiles outside areas of cloud streets also show inflection points. However, these are grouped well outside that part of the diagram which is enclosed by the dashed line.

This result may also be presented by an empirical formula, stating that cloud streets only develop if the conditions

\[
\left( \frac{\partial v}{\partial z} \right)_{z=h_i} \geq 1.7 \times (10 \frac{h_i}{h_c} - 5)^2 \times 10^{-3} \text{s}^{-1}
\] (3a)

and

\[
0.25 < \frac{h_i}{h_c} < 0.75
\] (3b)

are satisfied. For conditions with strong geostrophic wind speeds \( (u_g > 10 \text{ m s}^{-1}) \) these criteria may be used to forecast the possibility of the occurrence of cloud streets by using nighttime soundings to estimate the height of the inflection point and the magnitude of the wind shear at this height. This holds only for those nights when the wind profile is not influenced too much by thermal stability. This may be due either to nighttime cloud cover or to high wind speeds. The depth of the daytime convective layer has to be forecast by conventional methods using nighttime temperature soundings.

Figure 6. 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 (\( \times \)) and random cumulus clouds (\( \square \)) (daytime soundings).
To estimate the height of the inflection point $h_i$ at midday it is assumed that this height scales with the Ekman layer scale-height, $H = \kappa u_*/f$, and that therefore $h_i = a(\kappa u_*/f)$, where $a$ is a constant to be determined empirically, $\kappa$ being the von Kármán constant, $u_*$ the friction velocity and $f$ the Coriolis parameter. Neither the friction velocity nor the geostrophic wind speed is known for the cases analysed. Therefore the further assumption is made that the wind speed at the height of the inflection point, $u_i$, is close to the geostrophic wind $u_g$ and that a linearized form of the resistance law of the planetary boundary layer $u_g = 0.037u_g + 0.043$ could be used, which fits the resistance law by Wippermann (1973) well for $f = 1.16 \times 10^{-4} \text{s}^{-1}$, $z_0 = 0.3 \text{m}$ and wind speeds between 5 and $25 \text{m} \text{s}^{-1}$. Thus, finally, together with the assumption $u_g = u_i$ the relation

$$h_i = a(128u_i + 149) \tag{4}$$

follows, where $h_i$ is in metres and $u_i$ is in metres per second.

Figure 7 shows that this agrees well with the observations and the best-fit value for the constant $a$ is 0.28.

Equation (4) holds for nocturnal wind profiles observed under near neutral stratification. Cases where the thermal stratification was stable are also depicted in Fig. 7. If the wind speed at the inflection point is less than $5 \text{ m} \text{s}^{-1}$ then the Ekman shear flow can organize only very shallow convection in the form of cloud streets.

The analysis of the height of the inflection point in relation to the wind shear in areas with cloud streets is based on routine wind soundings at 11 UTC while most of the satellite pictures were taken at about 1330 UTC. Because of the rather large areas affected by roll development the error in time-space coordination is neglected here. However, another source of error still remains: within those areas where rolls had developed the wind profile itself is affected by those rolls. This was also discussed by Brown (1970), but there is no possibility of overcoming this problem. If conditions are suitable for roll development there will be rolls and therefore there may be just no chance to observe the undisturbed wind profile. Only roll development with and without convective enhancement may be studied over land. But for the case without convection the additional information from satellites is missed. So the analysis here is based on the disturbed wind.

![Figure 7](image-url)  
Figure 7. 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 (×: cases with near neutral stratification; straight line, according to Eq. (4); □: stable stratification; dotted line, linear fit to stable stratified cases; dots: unknown stratification).
profiles and therefore reflects the situation which one would meet if one makes randomly spaced measurements in areas with convection organized in rolls.

The only way to analyse the original undisturbed wind profiles in relation to disturbed wind profiles after the roll development is to use a numerical model. Such model results will also give some further hints regarding the path of pilot balloons in relation to a system of well-developed rolls. Studies on these problems are currently being performed and results will soon be published.

5. Synoptic Situation

Synoptic situations for the occurrence of cloud streets may be divided into four groups:

(1) Areas in the rear of cold fronts or occlusions with nearly straight surface isobars and straight contours in the 850 and 700 mb height fields. The wind speed in the Ekman layer has to be larger than 10 m s\(^{-1}\). The inflection point is caused by Ekman shear flow. Since the thermal stratification also favours convection these are the cases in which cloud streets were detected most often (9 cases).

(2) Areas 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 left with increasing height within the PBL (3 cases).

(3) Areas showing a high pressure ridge with strongly curved isobars. The wind speed within the PBL may be less than 5 m s\(^{-1}\); the inflection point is caused by baroclinic shear flow (2 cases).

(4) 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\(^{-1}\) and the wind direction changes towards the left near the ground when the front is approaching, thus enforcing the inflection in the wind profile (2 cases).

These situations are depicted in a schematic weather map in Fig. 8. Similar synoptic conditions over the British Isles were found by Weston (1982). In addition to his study, the synoptic situations have been discussed here with regard to their ability to cause inflection points.

6. Conclusion

Analysis of routine radiosonde observations revealed that wind profiles showing an inflection point can be found on those days when cloud streets were observed. Areas where clouds are organized in streets can be distinguished from areas with random cloudiness by: (i) the wind shear at the height of the inflection point; and (ii) the ratio between the inflection point height and convective layer height. In areas with cloud streets the height of the inflection point was approximately half the height of the convection layer. This suggests that inflection point and convective instabilities operate together when conditions are most favourable for the occurrence of cloud streets. This conclusion agrees with theoretical studies on vortex roll development in boundary layer shear flows.

More detailed information on the problem of cloud-street development can be obtained from field observations like the KonTur experiment or from numerical modelling of boundary layer vortex rolls.
Figure 8. Schematic weather map showing areas where cloud streets may be expected. In black areas, shear is Ekman shear; lined areas, baroclinic shear; cross hatched, combined shear.

REFERENCES


Haken H. 1978 *Synergetics*. Springer Verlag, Berlin
