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An observational study of convective cloud streets

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ABSTRACT

Satellite pictures and radiosonde information are used to study occasions of cloud streets over the British Isles. Their average aspect ratio and alignment are investigated and the most favourable synoptic pattern for their occurrence identified. In common with the work of Kuettner (1971), a curved wind profile is found to favour streets, but his explanation of its origin, that of a decreasing geostrophic wind with height, is not confirmed.

1. Introduction

It has long been recognized that the motions of the atmosphere occur on a whole spectrum of sizes from the global to the turbulence scale, but it was not until the advent of meteorological satellites that the full extent of cloud patterns on the medium scale—the mesoscale—became apparent. Satellite imagery is ideally suited for studies of mesoscale phenomena (say from 5 to 100 km)—a scale too large to be easily studied from a fixed point and too small to be adequately resolved by data from the conventional synoptic network.

Cloud streets are a familiar mesoscale phenomenon. Viewed from the ground they appear as lines of cumulus or stratocumulus, sometimes composed of discreet elements and at other times forming almost unbroken lines. When viewed from satellites these cloud streets are sometimes seen to cover very large areas, perhaps many thousands of square kilometres. Fig. 1 shows a striking example of cloud streets over south-east England: here the lines appear to consist of discreet cumulus clouds and extend to over 100 km in length. It is noteworthy that topography has rather little influence on this phenomenon: on this occasion the streets extend from the English Channel coast to north of the Thames Valley over a variety of land types and with the ground rising to about 300 m over the central part of the area. Despite this, the mesoscale circulations normally associated with such topography do not disrupt the continuity of the lines.

This study aims at determining the conditions under which cloud streets occur, their diameter-depth ratio and their orientation with respect to winds in the boundary layer. The results are compared with the findings of other investigators.

2. Previous investigations

Kuettner (1959, 1971) carried out observational and theoretical studies of cloud bands. Using data from a variety of sources, including special observations taken during the BOMEX project, he found that the length of these lines varied from 20 to 500 km, with spacings of between 2 and 8 km. He measured the ratio of width to depth, called the aspect ratio, and found it to be between 2 and 4. The occurrence of lines appeared to be associated with vigorous cold air outbreaks with the cold centre to the right of the flow direction leading to a decrease of the geostrophic wind with height and a curved wind profile—one in which the direction changed little with height, but in which the speed reached a maximum somewhere within the convective layer. He found an average profile curvature on these occasions of 10^{-5} m^{-1} s^{-1} and attributed this to a frictional wind increase with height in the lower part of the boundary layer and a thermal wind decrease in the upper part. According to the mechanism discussed by Kuettner the curved profile leads to baratropic instability and a circulation pattern sufficient to organize the convection into streets. He found that the cloud streets

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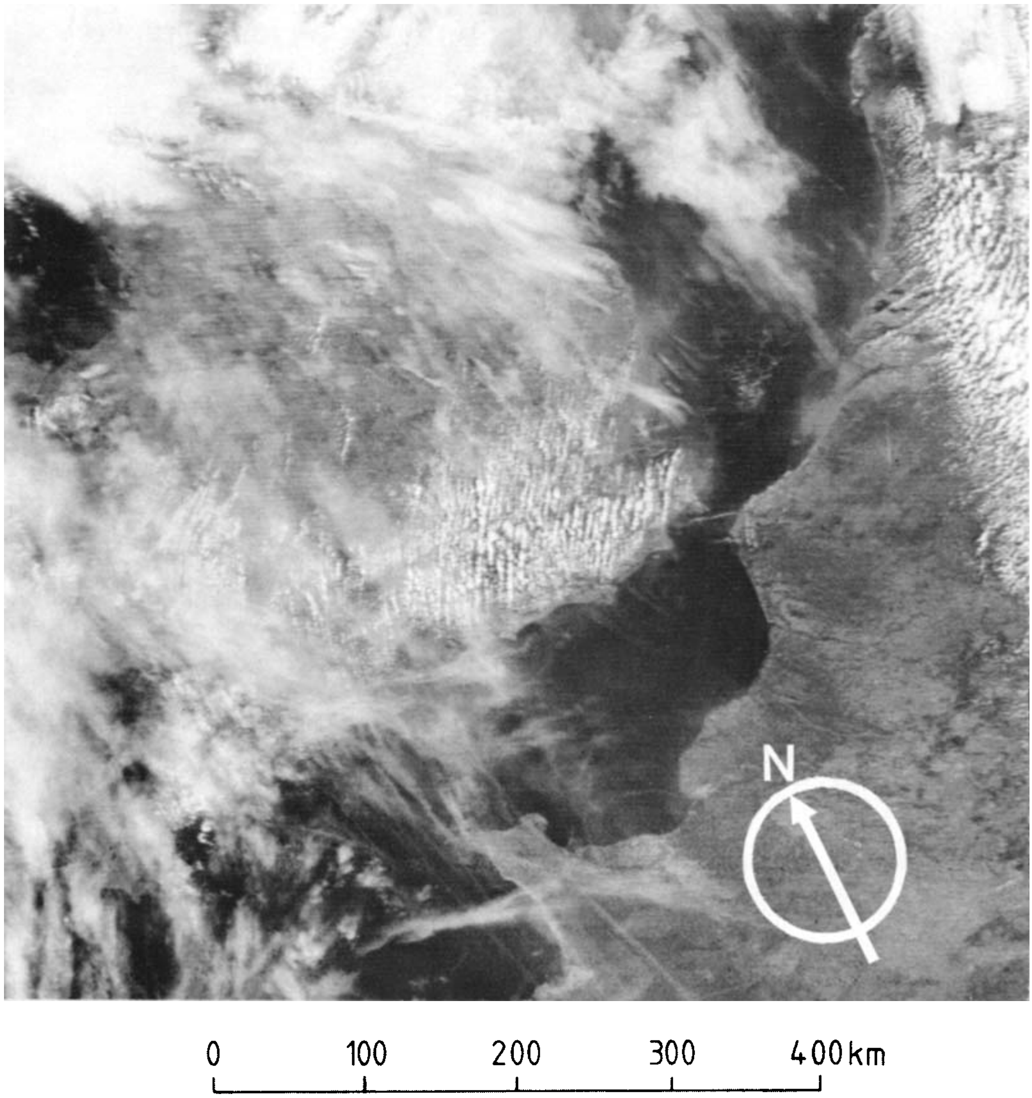

Fig. 1. NOAA5 satellite picture, 0952 GMT, 16 April 1977; linearized visible image. The cloud streets cover much of southern England in anticyclonic flow around a high centred over N.E. France. Picture received at Dundee University, Electronics Laboratory.

were aligned quite closely along the direction of the surface wind.

These findings were in contrast to those of Plank (1966) who studied convection using photo-reconnaissance data from flights over Florida. He concluded that there were no consistent differences between the wind profiles on occasions of patterned and non-patterned convection, and although the average alignment of streets was only slightly to the left of the wind at cloud base that on more than 30% of occasions the deviation was greater than 30°.

Le Mone (1973) determined the characteristic structure and dynamics of cloud streets using tower and aircraft data. She found aspect ratios and orientations to be in broad agreement with the results of Kuettner and that roll structure resembled that predicted by theoretical models invoking instability due to the presence of an inflection point in the wind profile in the plane normal to the roll axis, as is present in an Ekman layer (Brown, 1972).

Nicholls (1978) described aircraft measurements of boundary layer parameters on an occasion of cloud streets over the sea. He showed that such motions strongly influence the transport of water vapour and momentum above the surface layer.

3. Present studies

The data used in this study were enlarged visible and infrared VHRR photographs for the months of March and April 1977 from the American NOAA5 satellite, and midday upper-air ascents and 06 GMT pilot balloon wind observations from British Isles land stations. Scrutiny of twelve months of satellite photographs showed these two months to have the highest frequency of occurrence of cloud streets over the British Isles, twenty-one cases being identified.

3.1. *Aspect ratio*

For the determination of the spacing-depth ratio of cloud streets we require the depth of the convective layer and the average spacing between streets. Since no direct measurements of cloud tops were available, the depth of convection was inferred from radiosonde soundings. Perhaps the most reliable method for estimating the level of the top of a convective layer is to identify this with the level at which the saturation wet-bulb potential temperature has a minimum value—i.e. the level at which the lapse-rate changes from greater to less than the wet-adiabatic. In almost all of the cases studied here this coincided with a level at which there was a distinct fall in humidity with increasing height, supporting the estimation. The spacing of streets was measured directly from satellite photographs taken during the late morning and an average value obtained over the area covered. The depth of convection was estimated from the nearest available radiosonde sounding or an average taken in the event of more than one station lying within the area of cloud streets. Fig. 2 shows values of spacing and depth for the twenty-one cases considered. The results show considerable scatter but there is clearly an increase in spacing as the

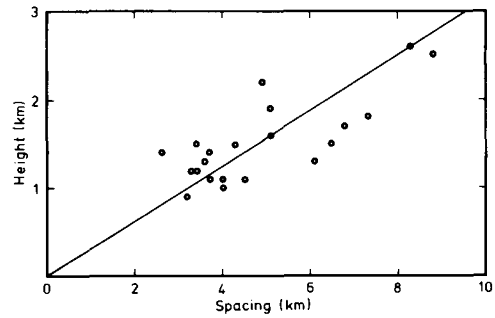

Fig. 2. The relationship between the spacing of cloud streets and the height of the top of the convective layer. The solid line represents the average aspect ratio of the 21 cases.

depth increases. The average aspect ratio is 3.2 to 1, close to the vaue found by Kuettner.

3.2. *Alignment*

Fig. 3 shows the relationship between the direction of alignment of the cloud streets and the mean direction of the wind in the convective layer. In all cases the alignment of streets was within 25° of the mean wind direction and three-quarters of cases were within 10°. In some cases there is a

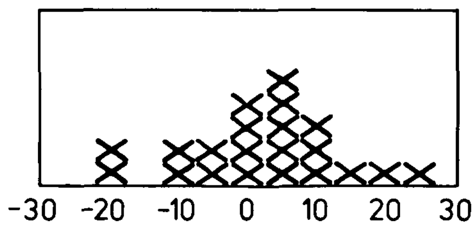

Fig. 3. The orientation of cloud streets with respect to the mean wind direction in the convective layer, in degrees (21 cases). A positive difference indicates a street orientation rotated in a clockwise sense to the mean wind direction.

difference of 2 hours between the times of the satellite photograph and the radiosonde measurements and it seems likely that concurrent observations would show an even closer agreement. Thus the alignment of cloud streets is an excellent indication of the mean boundary layer wind direction, though experience is needed in distinguishing streets from wave clouds.

3.3. *Synoptic pattern*

In an attempt to identify the synoptic pattern most likely to lead to the formation of cloud streets the synoptic situations associated with the cases studied were classified: firstly in terms of isobar curvature on the midday surface chart and secondly in terms of position with respect to the dominant weather system over the area.

Of the twenty-one cases thirteen showed anticyclonic isobar curvature, five had straight isobars and the remaining three displayed cyclonic curvature. However, a more detailed analysis of the pressure pattern over the area covered by the cloud streets on the three 'cyclonic' occasions showed the isobars to be straight or even slightly anticyclonic. Thus there is a strong indication that anticyclonic flow is one of the conditions conducive to convection in the form of cloud streets.

The prevalence of anticyclonic flow on occasions of cloud streets may reflect the fact that they tend to form only when convection is relatively shallow: the average depth of the convective layer on the twenty-one occasions studied here was 1.5 km and in no case did the depth exceed 2.6 km. Further evidence in this direction is found from satellite pictures of cold air outbreaks over the North Atlantic. As cold air flows off the ice sheet over relatively warm ocean, well-defined cloud streets commonly form; but these break up into convective cells further downstream. The spacing of the streets in the neighbourhood of this transition is typically about 5 to 10 km, and with an aspect ratio of 3 to 1 this implies a convective layer depth of about 1.5 to 3 km.

The most common synoptic pattern amongst the cases studied was the eastern flank of an anticyclone: ten of the twenty-one cases were in this category. Of the remainder seven cases occurred in a ridge, four of these immediately behind a cold front: three cases occurred on the southern flank of a low; and one case on the north-western flank of a high.

3.4. *Mean wind profiles*

This part of the study was confined to the nine occasions when cloud streets were particularly well-defined. For each day the wind speeds at 12 GMT (radiosonde) and 06 GMT (pibal), resolved along the direction of the cloud streets, were plotted as a function of height, normalised with respect to the depth of convection as determined by the method described in section 3.1. This normalization was carried out for winds at both times but using the convective depth determined from the 12 GMT

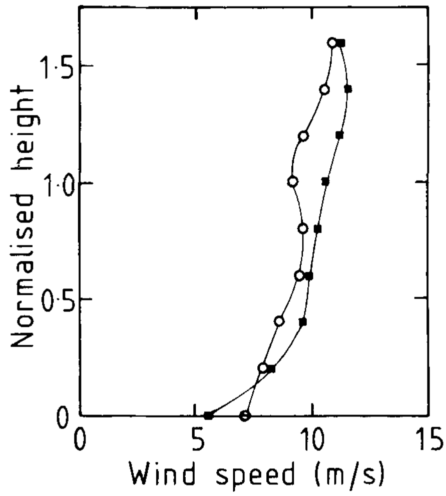

Fig. 4. The mean wind speed resolved along the direction of orientation of the cloud streets as a function of normalized height at 06 GMT (■) and 12 GMT (O) (9 cases).

sounding. At this time of year sunrise is at about 06 GMT, so convection had not begun at the earlier time. All nine occasions were combined to form average profiles for the two times: these are shown in Fig. 4. Only one wind profile per day is included in these averages—on occasions when cloud streets covered an area including several radiosonde stations a mean was compiled before inclusion in the average for the nine days.

The profile for 12 GMT shows a wind speed maximum within the convective layer at a normalized height of 0.8. Six of the nine individual profiles showed a wind speed maximum, at heights between 0.6 and 1.0. This low-level wind maximum is in agreement with Kuettner's findings, but the reason put forward is not supported by the present study. The profile here shows an increase of wind speed above the convective layer implying that if an "opposing" thermal wind is responsible for the low-level wind maximum, then it does not extend above the boundary layer top. (The thermal structure of cloud street occasions will be discussed in more detail in the next section.)

If, as Kuettner suggests, the shape of the wind profile lies at the heart of the formation of cloud streets, then a curved profile should exist before the onset of convection. The mean profile for 06 GMT does not show a wind speed maximum but six of the nine individual profiles did display a maximum, though over a range of heights from 0.2 to 1.0. Thus this part of the analysis is inconclusive: although a wind speed maximum in the boundary layer occurs on the majority of days of convective cloud streets, there are occasions when no such maximum can be identified.

3.5. *Thermal patterns*

Kuettner listed cold advection as one of the necessary conditions for cloud street formation. This finding is borne out by the present study. Using midday radiosonde ascents from British Isles stations it was found that in all nine cases of well-defined streets there was cold advection within the convective layer with an average magnitude of 0.15 °C hr^{-1}, leading to a backing of the geostrophic wind with height. However, this value is about that expected solely from warming of the boundary layer by the sensible heat flux from the ground, leading to a downstream temperature increase. Indeed, an average sensible heat flux of only 60 Wm^{-2} would account for the observed cold advection. Thus, although all nine occasions of cloud streets studied here exhibited cold advection, it appears to be a result of the convection rather than a contributory cause.

Kuettner found that the temperature gradient *across* the flow on cloud street occasions was such that the geostrophic wind component along the streets decreased with height: that is, cold air lay to the right of the flow direction. For the nine occasions of well-defined cloud streets identified in the present study, the thermal wind in the convective layer was determined using midday data. Results showed that only one of the nine occasions had a geostrophic wind component along the streets which significantly decreased with height, most showing an appreciable *increase* with height. Thus the curvature of the wind profile cannot be attributed to the thermal field.

4. The significance of convective streets for flux measurements

Many techniques have been employed for the measurement of fluxes of sensible and latent heat at various levels in the boundary layer and intercomparisons have been made between the different methods. Ground-based instruments may be used to estimate fluxes by the flux-profile method (e.g. Wood, 1977) or by eddy correlation techniques (Haugen et al., 1975). The first of these methods is used close to the surface where gradients of temperature and humidity are large, while the second is limited to the height of tower-mounted probes, say 100 m or so. Balloon-borne turbulence sensors have successfully measured fluxes to greater heights (Readings and Butler, 1972), while Milford et al. (1979) effectively used an instrumented powered glider as a turbulence sensor enabling heat and moisture fluxes to be determined at several heights. Cattle and Weston (1975) used a budget technique to indirectly deduce fluxes as a function of height.

Observational programmes aimed at comparing fluxes measured by different techniques have been carried out by several workers. Some investigators (Lenschow and Johnson, 1968; Milford, 1973) found reasonable agreement between budget and eddy correlation methods but Moores et al. (1979) in a comprehensive intercomparison showed discrepancies between methods which varied from occasion to occasion. It has been suggested that some of these differences are due to fluxes carried on scales larger than about a kilometre. Eddy correlation methods from fixed sites are particularly suspect when a significant part of the heat transfer is on large scales; and even fluxes measured by a relatively slow-moving glider are liable to underestimate fluxes on such occasions.

Le Mone (1973) and Nicholls (1978) showed the importance of fluxes on relatively large scales. Le Mone found that between a third and a half of the vertical sensible heat flux was carried by roll convection at heights of about 100 m, the proportion increasing with height. In view of the frequent occurrence of convective streets, usually on space scales of about 6 km, the presence of such motions must be carefully considered in any interpretation of flux measurements within the boundary layer.

5. Summary and conclusions

Cloud streets over the British Isles appear to be most frequent in spring. In common with other workers aspect ratios were found to be about 3 to 1 and streets were aligned quite closely along the direction of the mean wind in the boundary layer. Most occasions of cloud streets occur when the flow is anticyclonic, with the eastern flank of a high or a ridge behind a cold front being particularly favourable synoptic patterns. A curved wind profile was present in the majority of cases, but in general this curvature could not be explained in terms of a decreasing geostrophic wind with height. Cold advection was present in all the cases studied, with a magnitude of about 0.15 °C hr^{-1}.

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НАБЛЮДЕНИЯ КОНВЕКТИВНЫХ ОБЛАЧНЫХ ДОРОЖЕК

Для наблюдения случаев облачных дорожек над Британскими островами используются спутниковые фотографии и информация с радиозондов. Исследуется их среднее отношение вертикального масштаба к поперечному и удлинение и определены наиболее благоприятные синоптические ситуации для их образования. Найдено в согласии с Кютнером, что благоприятным для дорожек является криволинейный профиль ветра, но его объяснение их происхожения, связанное с уменьшением геострофического ветра с высотой, не подтверждается.