Cloud Streets During KonTur

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Abstract

On four days during the KonTur experiment cloud streets were investigated. Results of measurements with the German aircraft FALCON from one day, 20 September 1981, are presented in this paper. The cloud streets seem to be forced dynamically due to an inflection point in the wind profile, since the air-sea temperature difference and thus the thermal forcing is small. The cloud streets are approximately oriented with the layer averaged wind. The depth of the layer is 1.2 km including a 400 m deep cloud layer. The average separation of the cloud streets is 3.7 km resulting in an aspect ratio of 3.1.

Four different scales of motion are involved: the mean flow, the cloud street circulation (wave length 3.7 km), convective scale motions (1 - 0.3 km) and turbulent motions (300-1 m). The cloud street circulation can be detected down to 100 m height (the lowest flight level) where the motion is nearly horizontal. The vertical transports of heat, moisture and momentum by the rolls have the opposite sign of the mean vertical gradient of these quantities. Convective scale transports in the cloud layer have the same sign as the mean gradient. Transports by turbulence dominate at low levels and decrease with height.

1. Introduction

Rolls in the atmospheric boundary layer can be forced either by thermal instability or by dynamic instability. The latter results from an inflection point in the vertical profile of the mean horizontal wind component perpendicular to the roll axis. Both instability mechanisms have been discussed in detail in the literature, see e.g. the review paper by Brown (1980). According to theory the horizontal wave length of the rolls is two to four times larger than their vertical depth. This ratio is called the aspect ratio. Apart from theoretical investigations atmospheric roll motions sometimes together with cloud streets have been observed by e.g. Woodcock (1942), Küttner (1959) and Hardy and Ottersten (1969). In these papers mainly the geometrical dimensions of the streets were determined. In addition, LeMone (1973 and 1976) estimated several terms in the budget of roll kinetic energy using measurements at towers and by aircraft. Nevertheless, our knowledge about the transports of energy and momentum associated with cloud streets is still small. The KonTur experiment which took place during September/October 1981 in the German Bight area of the North Sea was planned to improve this situation.

2. The Data

Cloud street observations during the KonTur experiment were performed using two aircraft. Both planes, the HERCULES C-130 of the Meteorological Research Flight in Farnborough, England and the FALCON 20 of the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt in Oberpfaffenhofen, Germany, were equipped with instruments to measure three wind components, temperature, moisture, liquid water content of clouds, short-wave and long-wave radiation (for details see the KonTur Field Phase Report). The flight pattern were rectangular, equilateral "L"s with legs

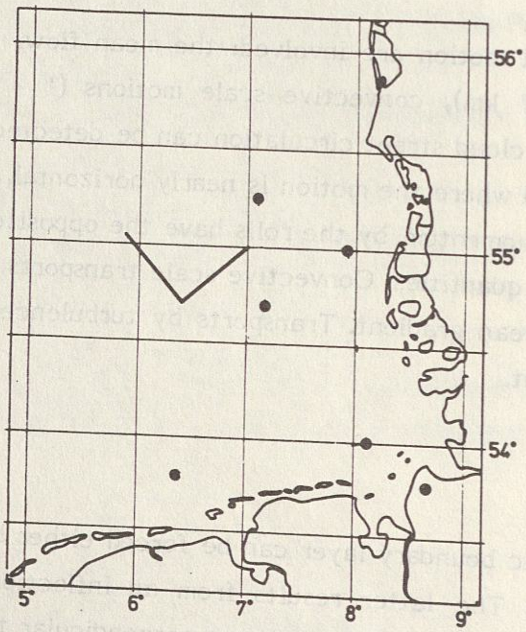

Fig. 1: Aircraft flight pattern (L-pattern) on 20 September 1981 and KonTur aerological stations (dots). The SW/NE leg of the L-patterns is about parallel to wind at 170 m.

about 25 nautical miles long and oriented parallel and perpendicular to the wind at 500 feet height. Such pattern were flown simultaneously by both aircraft at different levels in a coordinated manner. During a joint mission, the duration of which was limited by the smaller FALCON, about four L's were flown together resulting in measurements at eight levels. The levels were distributed between 100 feet above the sea surface and the top of the cloud street layer.

Cloud street observations could be performed on four days during the experiment, on 18, 20, 26 and 28 September 1981. In this paper the flight of 20 September 1981 is discussed. The presentation is based on the FALCON data.

3. Case Study of Cloud Streets on 20 September 1981

3.1. Mean Thermodynamic and Kinematic Structure

In the morning of 20 September 1981 a cold front passed from WSW to ENE over the German Bight. The aircraft measurements took place behind the front in the northwestern area of the German Bight between 12 and 14.30 GMT. Fig. 1 shows the location of the L-shaped flight pattern and the KonTur radiosonde network. The wind at 500 ft blew from 220-230° with a speed of about 17 ms^{-1}. The air temperature near the surface was between 15.5 and 16.5°C. The sea surface had temperatures between 14.5 and 16.0°C with the highest values at the NE part and the lowest at the NW part of the L-pattern. This indicates a nearly neutral density stratification near the sea surface. Therefore we suppose that the cloud streets have developed due to dynamic instability. This is supported by the wind profile (Figs. 2a, b) which was measured between 12.10 and 12.20 GMT during descent from transit level down to the operational area. Fig. 2b shows the wind components parallel and normal to the vertically averaged wind direction (226°) which was about the orientation of the cloud streets; observers in both aircraft give estimates of 224° to 235° for the orientation angle. The normal component (v_R) exhibits two extrema at 700 m and 1000 m, respectively, with an inflection point (i.e. a vorticity extremum) in between, at about 850 m.

The thermodynamic structure is presented on the right hand side of Fig. 2a. There is a mixed layer between the sea surface and 700 m. Cloud base is at about 850 m, the level of the inflection point and the speed maximum. The cloud layer is topped by an inversion at 1300 m which lowers to about 1100 m during the measuring period. The average depth of the convective layer (sea surface to cloud top) is about 1200 m.

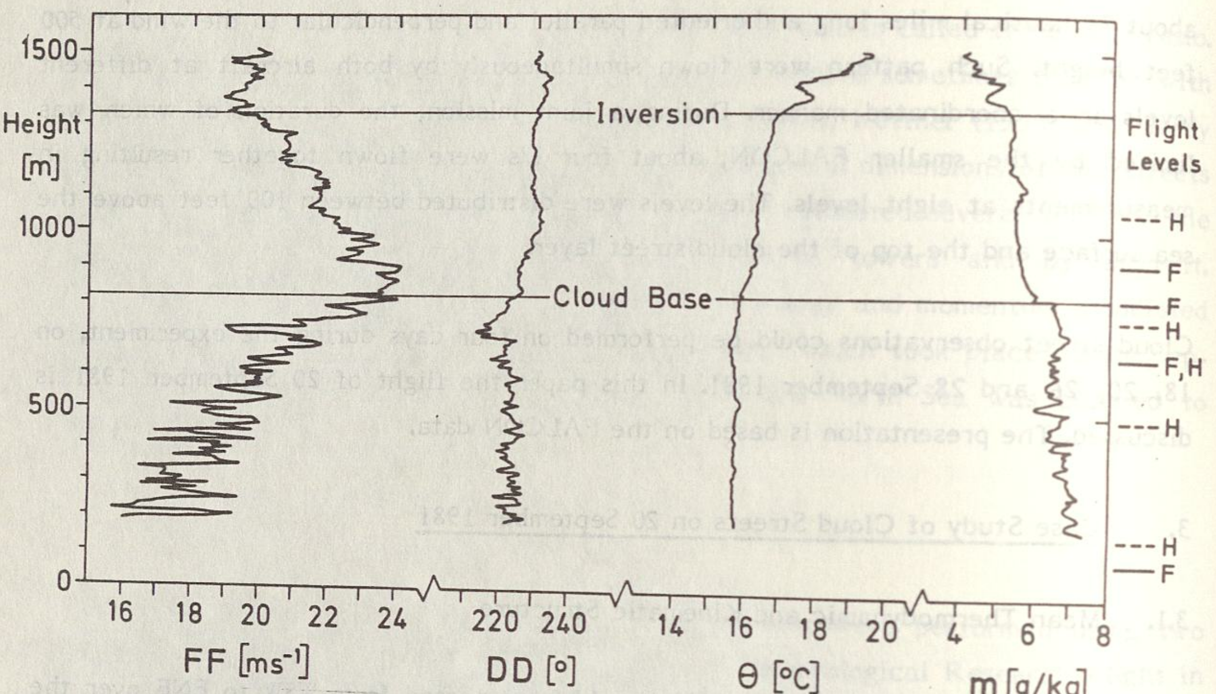

Fig. 2a: Profiles of wind speed (FF), wind direction (DD), potential temperature (Θ) and mixing ratio (m) measured by aircraft FALCON during descent from transit to area of L-pattern on 20 September 1981 between 12.10 - 12.20 GMT. The letters F and H indicate the flight levels of the FALCON and the HERCULES.

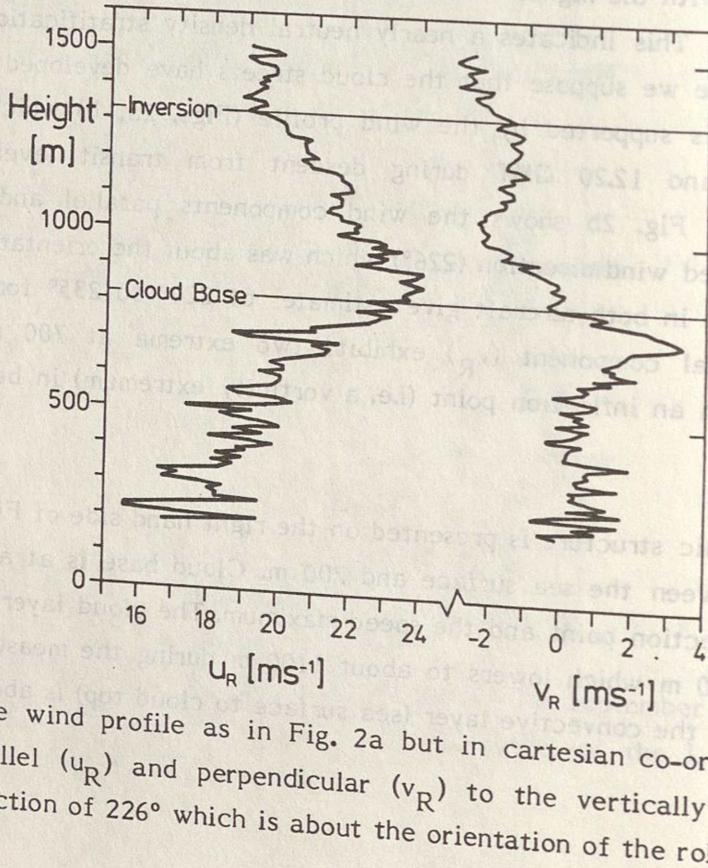

Fig. 2b: Same wind profile as in Fig. 2a but in cartesian co-ordinates oriented parallel (u_R) and perpendicular (v_R) to the vertically averaged wind direction of 226° which is about the orientation of the rolls.

3.2. Aspect Ratio

The wavelength of the cloud streets was determined from the records of shortwave radiation and moisture during the flight legs perpendicular to the 500 ft wind. Since variations of these parameters are largest in or near the cloud layer only those flight levels are taken into account. Fig. 3 shows the results from three successive flights at 830 and 930 m and 1000 m. As a function of relative time those periods when the radiation is smaller or humidity is larger than certain values are marked by bars. The two parameters give different results. Whenever the radiation trace signals a cloud overhead, the humidity is high; but there are some additional moisture maxima to which there is no corresponding radiation signal. The reason for this is not known. It could be that the radiometer does not sense a cloud street which is intercepted between individual clouds. Fig. 3 also shows the result of an eye observation from board of the HERCULES (personal communication) during a special flight at 1000 m perpendicular to the streets. In Table 1 the wavelengths and aspect ratios are summarized. Both radiation measurements and eye observation give an average wavelength of 3.7 km and an aspect ratio of 3.1, whereas humidity measurements suggest values of 2.6 km and 2.2, respectively. Both aspect ratios are within the theoretically derived limits.

Table 1: Wavelength and aspect ratio of cloud streets on 20 September 1981 based on measurements of shortwave radiation and mixing ratio and on eye observation.

	Wavelength (km)	Aspect Ratio
Shortwave Radiation: 830 m	4.0	3.3
930 m	3.5	2.9
Average	3.75	3.1
Mixing Ratio: 830 m	2.6	2.2
930 m	2.6	2.2
Average	2.6	2.2
Eye Observation (HERCULES)	3.9	3.25

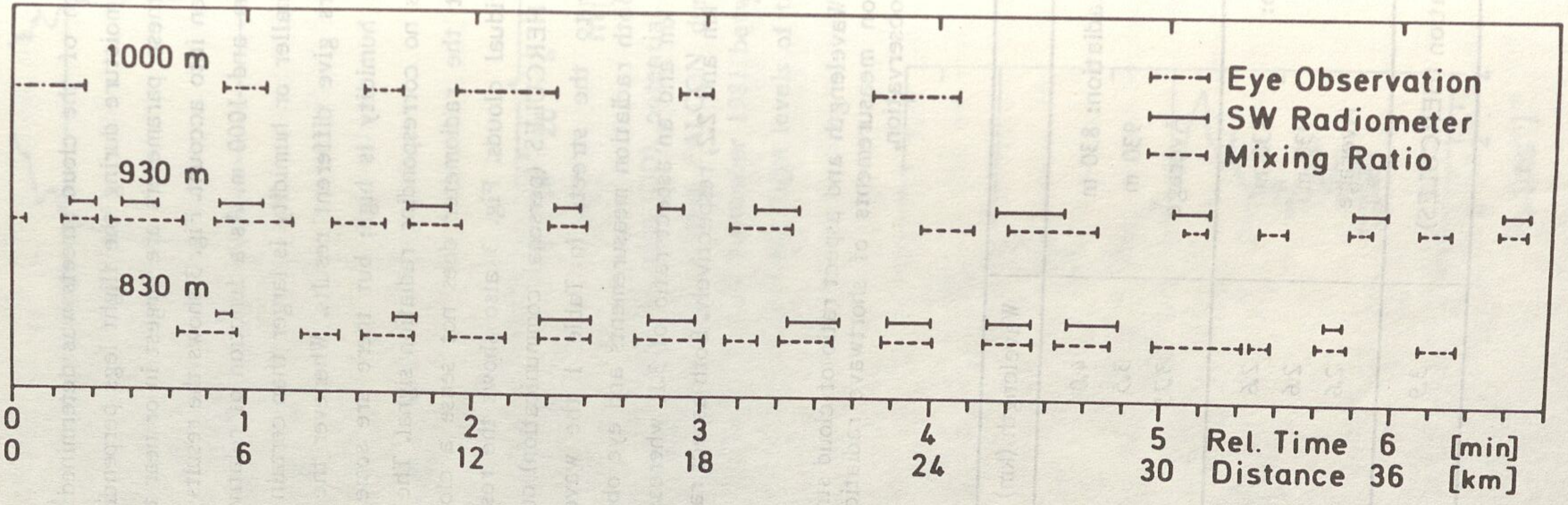

Fig. 3: Temporal and spatial distribution of cloud street sections observed during three different flights perpendicular to cloud streets. Cloud street sections are defined as time intervals with shortwave radiation below and mixing ratio above certain threshold values or are observed by eye.

3.3. Variances and Co-variances in the Cloud Street Field

In Fig. 4 an example of time series of temperature (T), mixing ratio (m), vertical wind (w) and downward shortwave radiation is presented for a flight leg perpendicular to the streets at 830 m (near cloud base). A cloud street is marked by the minimum in the radiation curve. The following relations can be seen from the figure: On the average there is a cool, moist upward velocity in the cloud street area and a dry, warm downward velocity between the cloud rows. Variations with a shorter than the cloud street scale, but with a larger than the turbulence scale are superimposed. This can be seen most clearly in the time series of vertical motion; within the mean upward area of the cloud street there are updrafts as well as downdrafts, probably connected with individual clouds. This scale is referred to as the convective scale.

Different variances are measured for flights parallel and perpendicular to the wind at 500 ft. This is shown in Fig. 5 by means of the variance spectra of mixing ratio. The variances are small for all flights along the wind. For the flights across the wind they are considerably larger and a maximum emerges between 2.2 and 4 km wavelength (taking into account the aircraft speed of 100 m/s) increasing with height and representing the cloud streets. Such differences between across-wind and along-wind legs appear also in the spectra of other quantities such as temperature.

How far does the cloud street circulation extend down? To answer this question the variance spectra of temperature, mixing ratio and the three wind components u, v, w (East/North coordinate system) for legs at four levels perpendicular to the wind at 500 ft are displayed in Fig. 6. The temperature spectra, similar to those of mixing ratio, show negligible variances at 100 m height. In the cloud street frequency range (2-5 10^{-2} Hz corresponding to 5-2 km wavelength) this is also true for the vertical wind component. However, for both horizontal wind components at this level there appears a (secondary) variance maximum in the spectral range of the cloud streets indicating a cloud street circulation at least down to this level. The primary variance maximum for all three wind components at 100 m height occurs in a broad spectral range between 50 and 300 m wavelength which can be associated with turbulence. The variances in this spectral interval decrease with height. Taken together these features suggest a downward extension of the roll circulation to a least 100 m height but with nearly horizontal flow and without thermal forcing there.

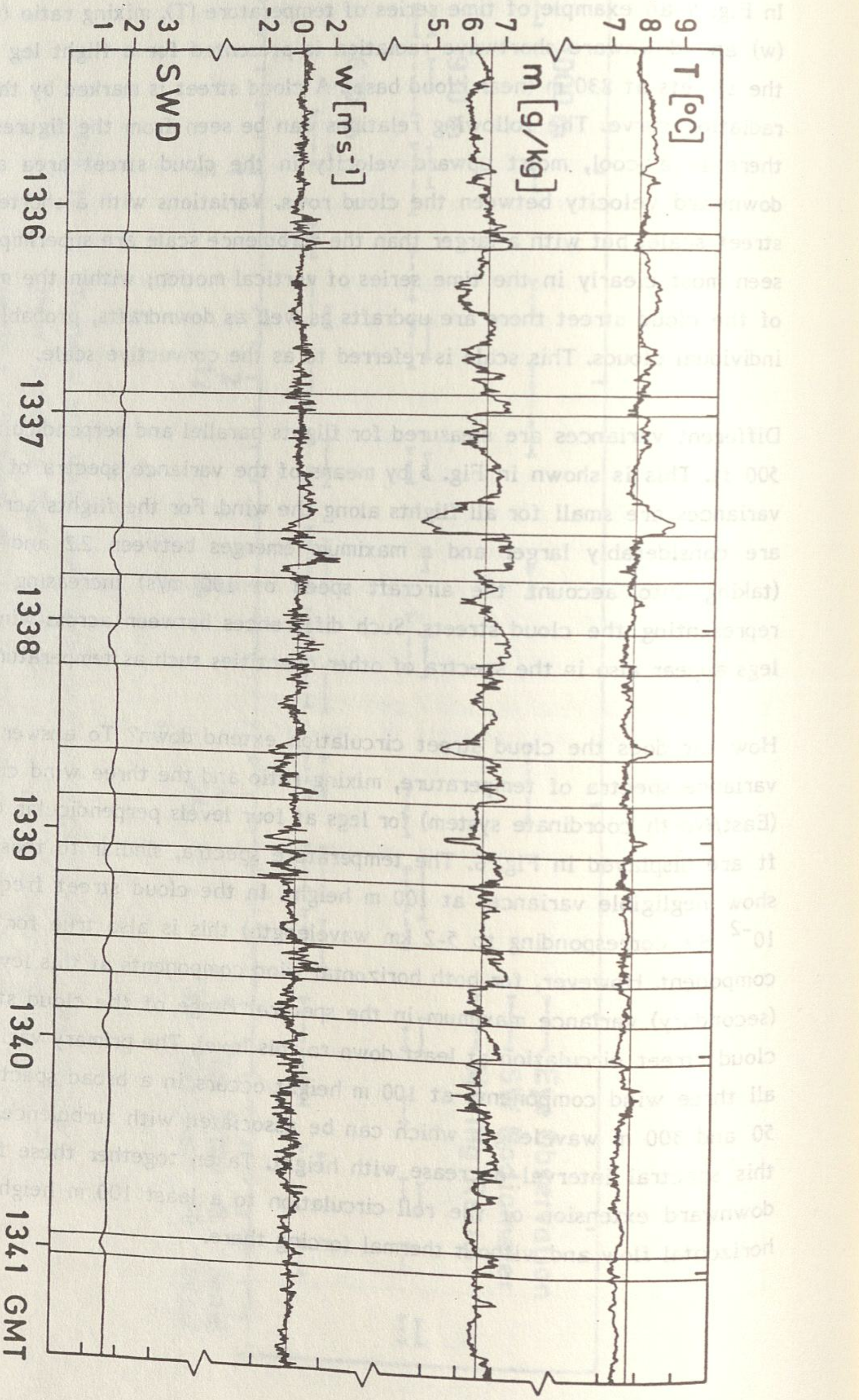

Fig. 4: Time series of temperature (T), mixing ratio (m), vertical velocity (w) and shortwave downward radiative flux (SWD, uncalibrated) during flight nearly perpendicular to cloud streets near cloud base at 830 m on 20 September 1981 between 13.35 and 13.41 GMT. Time intervals of visible cloud streets are bounded by thin vertical lines.

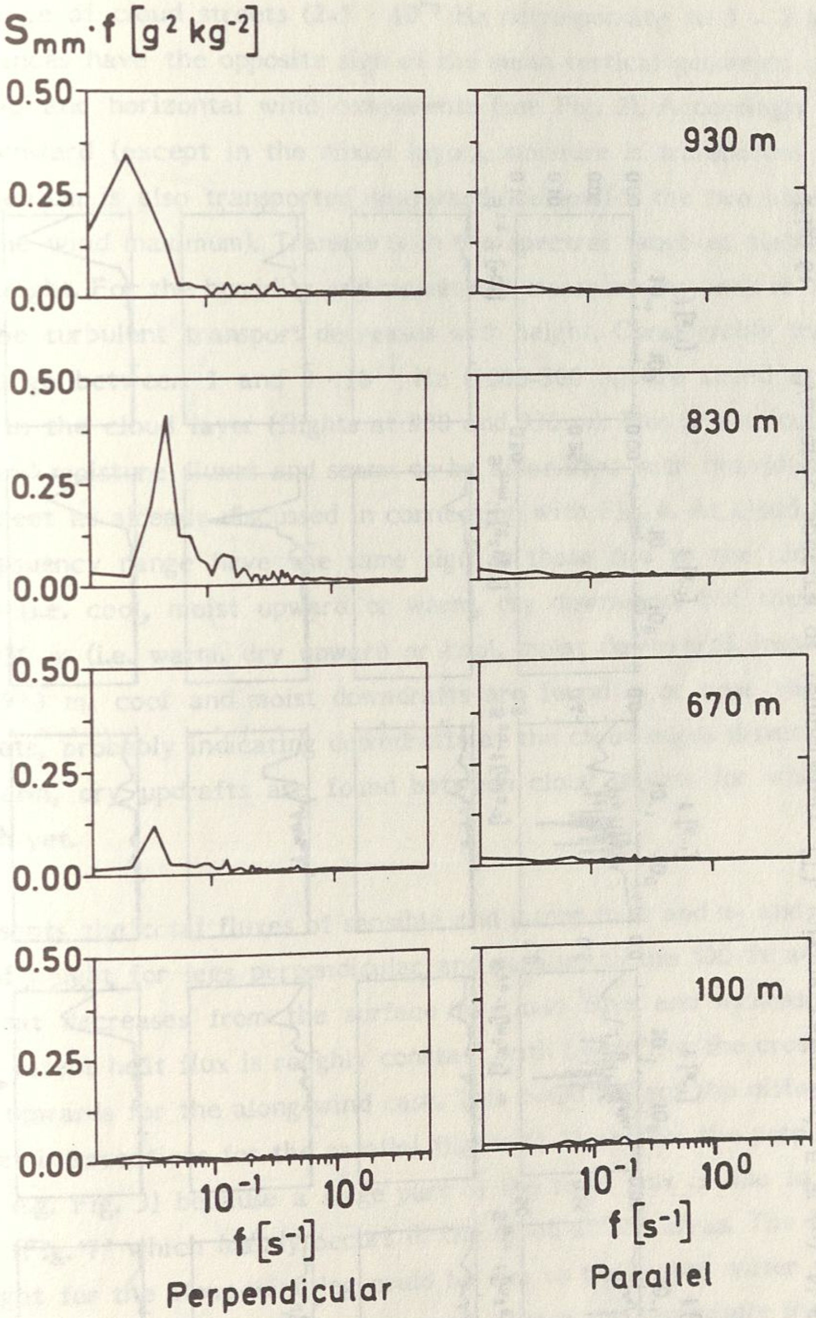

Fig. 5: Variance spectra of mixing ratio for flight legs at four levels perpendicular (left column) and parallel (right column) to wind at 170 m. The scales are the same for all spectra.

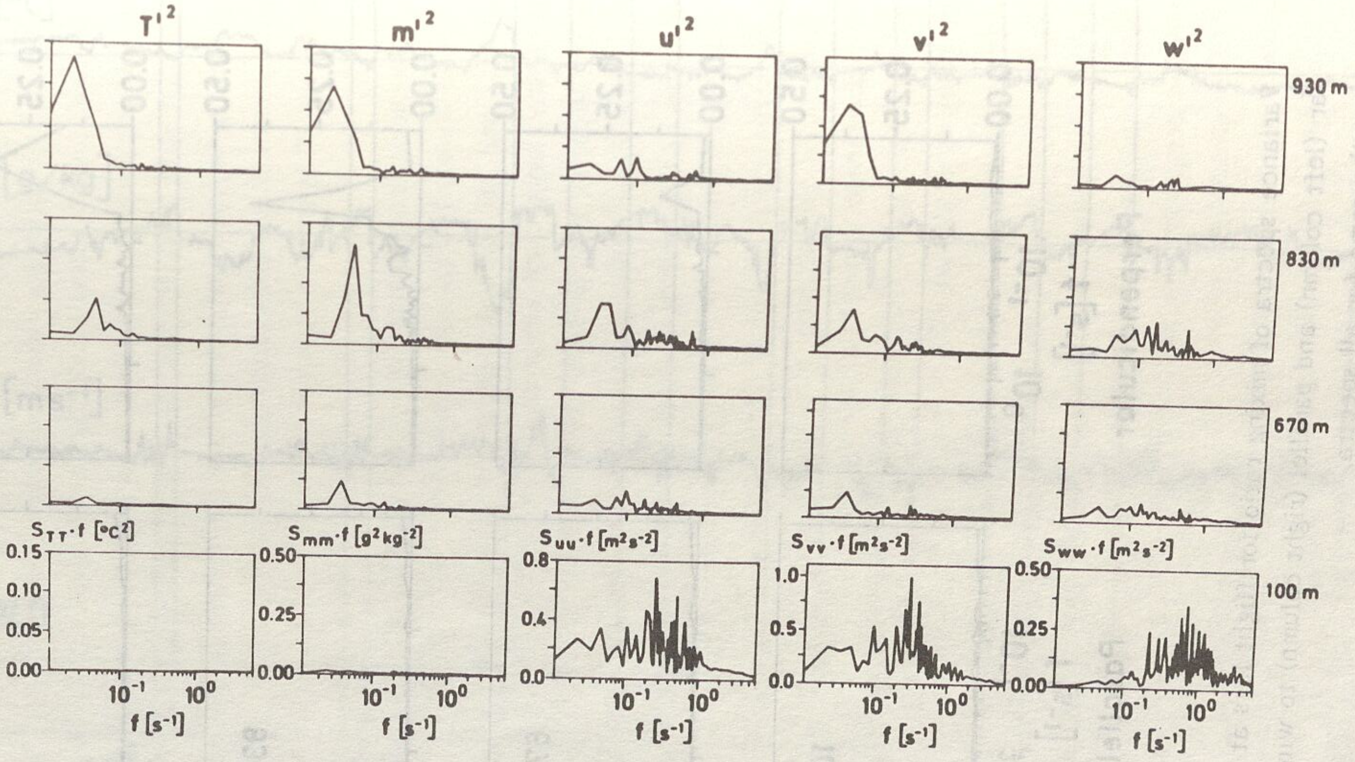

Fig. 6: Variance spectra of temperature (T), mixing ratio (m), E-W (u), N-S (v) and vertical (w) wind component for flight legs at four levels perpendicular to cloud streets. The scales for the lowest spectra hold for all spectra of the respective column.

In Fig. 7 the covariance spectra of w'T', w'm', w'u', and w'v' are presented. In the spectral range of cloud streets (2-5 · 10^{-2} Hz corresponding to 5 - 2 km wavelength) the covariances have the opposite sign of the mean vertical gradients of temperature, mixing ratio and horizontal wind components (see Fig. 2). Accordingly heat is transported downward (except in the mixed layer), moisture is transported upward and u- and v-momentum is also transported downward (except for the two upper levels which are near the wind maximum). Transports in the spectral range of turbulence dominate at 100 m height. For the humidity and momentum transport the peak is near 3 · 10^{-1} Hz (300 m). The turbulent transport decreases with height. Considerable transports in the spectral range between 1 and 3 · 10^{-1} Hz (1000-300 m) are found at higher levels, especially in the cloud layer (flights at 830 and 930 m). This is particularly obvious in the heat and moisture fluxes and seems to be associated with individual clouds within a cloud street as already discussed in connection with Fig. 4. At cloud base transports in this frequency range have the same sign as those due to the cloud street scale circulation (i.e. cool, moist upward or warm, dry downward) but they have opposite signs at 930 m (i.e. warm, dry upward or cool, moist downward). Inspecting the time series at 930 m, cool and moist downdrafts are found in or near the region of the cloud streets, probably indicating downdrafts at the cloud edges driven by evaporative cooling. Warm, dry updrafts are found between cloud streets for which we have no explanation yet.

Fig. 8 presents the total fluxes of sensible and latent heat and u- and v-momentum as function of height for legs perpendicular and parallel to the 500 ft wind. The flux of sensible heat decreases from the surface to cloud base and increases in the cloud layer. The latent heat flux is roughly constant with height for the cross-wind case and decreases upwards for the along-wind case. This could reflect the different numbers of cloud street intersections for the parallel flights (1-3) and for the perpendicular flights (9-12, see e.g. Fig. 3) because a large part of the total flux is due to the convective scale flux (Fig. 7) which mainly occurs in the cloud street areas. The larger fluxes at 100 m height for the along-wind leg could be due to the higher water temperatures in this part of the flight pattern. The momentum fluxes are essentially the same for both legs. They are down gradient, are largest at 100 m and vanish near the level of wind maximum.

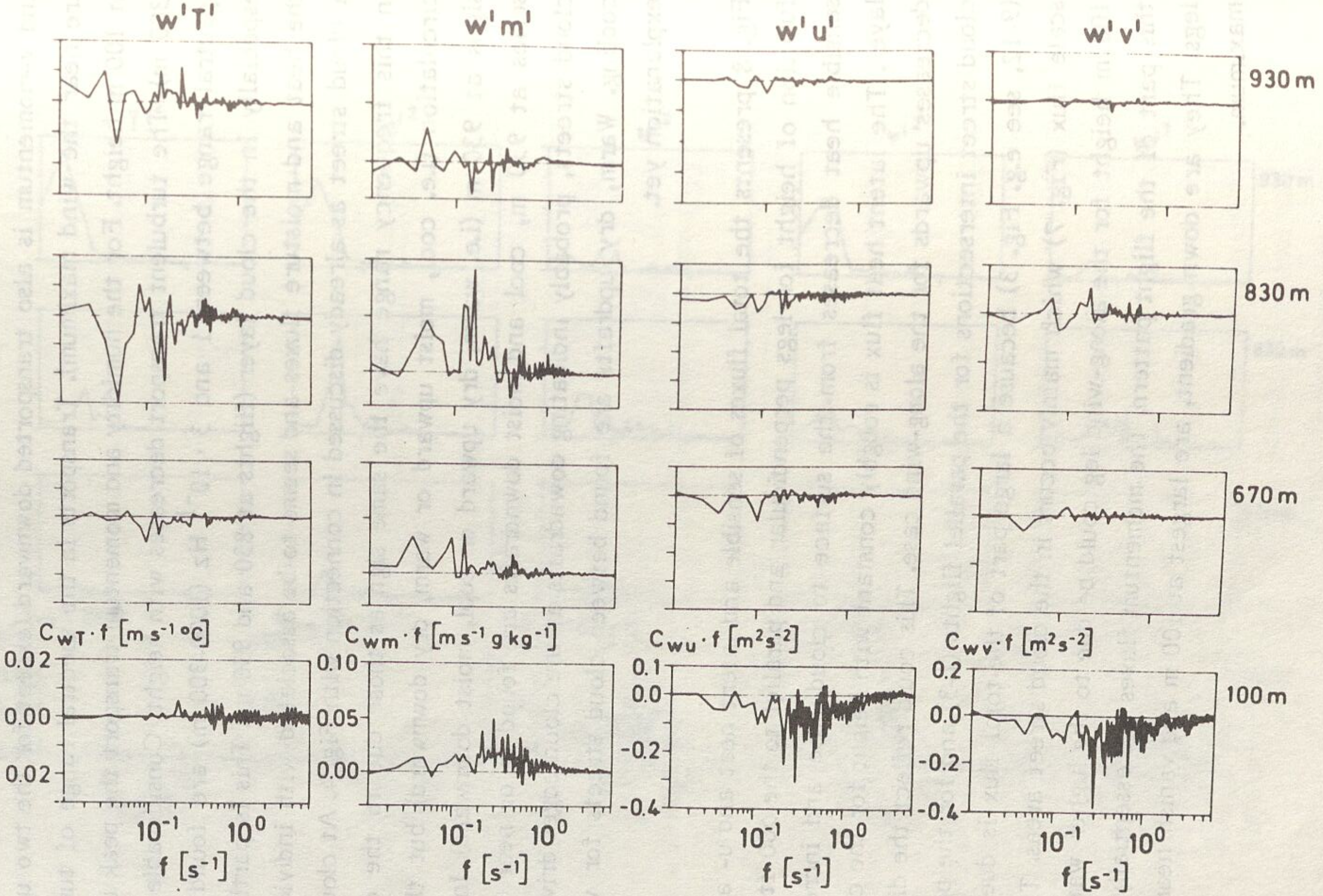

Fig. 7: Covariance spectra vertical wind with temperature, mixing ration, E-W and N-S wind components for flight legs at four levels perpendicular to cloud streets. The scales for the lowest spectra hold for all spectra of the respective column.

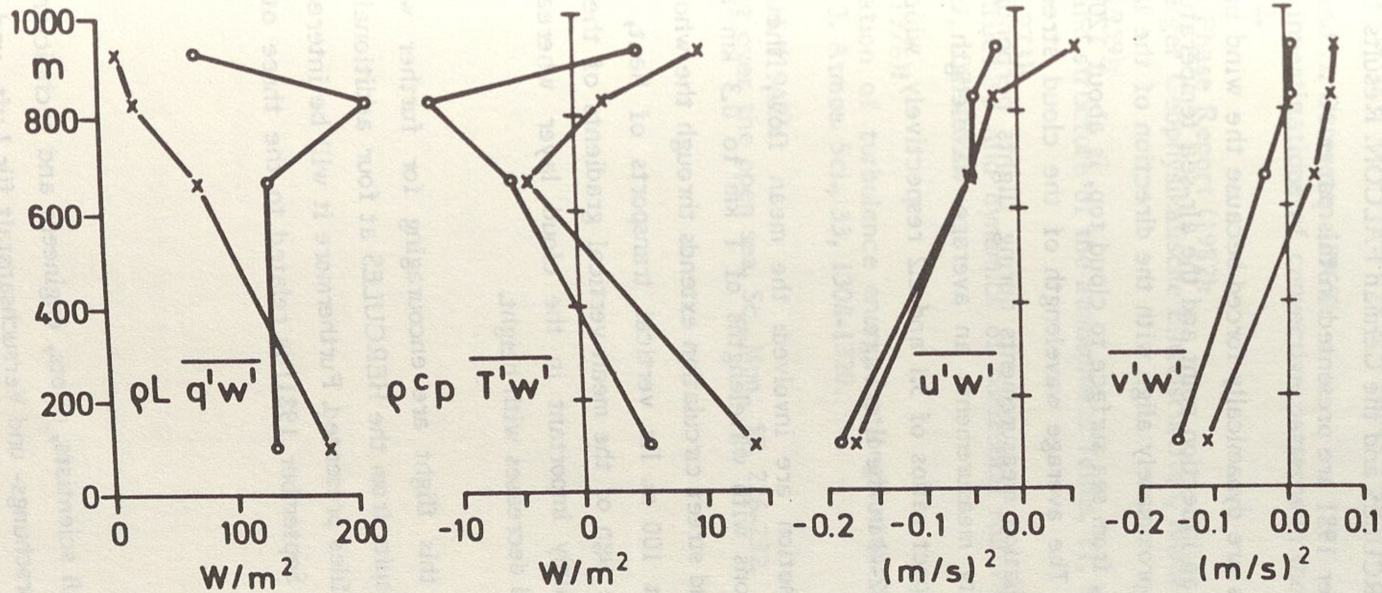

Fig. 8: Vertical transports of latent heat ($\varrho L \overline{w'm'}$), sensible heat ($\varrho c_p \overline{w'T'}$). E-W ($\overline{w'u'}$) and N-S ($\overline{w'v'}$) wind component for flight legs perpendicular (o) and parallel (x) to wind at 170 m.

4. Summary and Conclusions

During the KonTur experiment in September/October 1981 over the German Bight area, cloud street observations could be performed on four days by co-ordinated flights of two aircraft, the British HERCULES and the German FALCON. Results from FALCON measurements on 20 September 1981 are presented in this paper.

Presumably the cloud streets are dynamically forced because the wind profile perpendicular to the streets shows an inflection point and the air-sea temperature difference is small. The cloud streets approximately align with the direction of the layer-averaged wind. The depth of the layer, from sea surface to cloud top, is about 1200 m including a 400 m thick cloud layer. The average wavelength of the cloud streets is 3.7 km derived from shortwave radiation measurements during flights perpendicular to the cloud streets. From humidity measurements an average wavelength of 2.6 km is suggested. This results in aspect ratios of 3.1 and 2.2 respectively, which agree with theoretically derived values (2-4) in the literature.

Four different scales of motion are involved: the mean flow, the cloud street circulation, convective motions with wavelengths of 1 km to 0.3 km and turbulent motions (300 m to 1 m). Cloud street circulation extends through the whole layer from cloud top down to at least 100 m. Its vertical transports of heat, moisture and momentum have the opposite sign of the mean vertical gradients of these quantities. Convective motions are mainly important in the cloud layer whereas turbulence dominates at lower levels and decreases with height.

The preliminary results of this flight are encouraging for further work. We are interested to see how the results from the HERCULES at four additional flight levels match with the FALCON profiles presented. Furthermore it will be interesting to know how this particular day (20 September 1981) is related to the three other cases of cloud street observations.

Acknowledgement

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