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A preliminary analysis of two GATE convective systems

(GATE Report No.2)

by

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Summary

Tethered balloon and surface data obtained during GATE have been used to study the sub-cloud structure of the boundary layer during the passage of two convective systems during Phase III. The systems are shown to produce strong coupling between cloud and sub-cloud layers and a marked increase in surface sensible and latent heat fluxes.

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1. Introduction

Observations of turbulence structure were made near the centre of the GATE C-scale array from HMS "Hecla" during Phase III, using instruments attached to a tethered-balloon cable at one or two heights up to 400 m. A total of about 200 hours of data were obtained in conditions ranging from strongly suppressed convection when the boundary layer was less than 300 m deep, through to situations with deep convection, line squalls and neighbouring thunderstorms. The data were biased to some extent because of the inability of the tethered balloon system to work satisfactorily in very light winds. Some of the observations were spoiled by sensor failure or by heavy rain and squalls where, apart from problems caused by moisture, the strong down draughts associated with some of the squalls occasionally produced large changes of flying height of the balloon, making the data difficult to interpret. However it is expected that at least three-quarters of the total data can be usefully analysed.

The ubiquitous feature of the GATE weather was convection which was usually cloud-forming and often very deep, and had a range of horizontal scales from perhaps a few tens of metres in some non-condensing cases up to tens of kilometres in disturbed situations. All of these convective systems produced fluctuations of parameters such as wind and temperature which might be called turbulent, but as the scale of the processes involved increases it becomes less profitable to describe the fluctuations in purely statistical terms and often

more sensible to study directly the times series of the parameters rather than only derived quantities such as spectra or eddy fluxes. In this note a preliminary analysis of two GATE convection systems is made from both viewpoints.

2. Instrumentation

The instrumentation was a developed version of that described by Thompson (1972). The main change in the airborne equipment was in the separation of sensors from the signal-conditioning and telemetry circuits, and mounting of the former on a light vane placed a metre or so above a box containing the circuits. The battery capacity was increased to allow about 10 hours operation before recharging. The telemetry and recording systems were essentially unchanged. The balloon was tethered to the after end of "Hecla's" flight deck. Its cable passed from there through a hydraulically-driven cable accumulator and then on to the winch. The accumulator was controlled by integrated signals from accelerometers on the flight deck and it continuously adjusted the amount of cable it held to reduce the effects of ship motion on the balloon system.

3. Data and data-processing

Parameters measured by the balloon system were the magnitude of the wind vector, wind inclination to the horizontal and wet and dry-bulb temperatures. Sensor heights were estimated from the amount of cable paid out, cable angle at deck level and balloon elevation (the highest instrument package was about 25 m below the balloon). Data was played back through 4-pole Butterworth low-pass filters with cut-off (-3 db) at 0.1 Hz and roll-off of -24 db/octave, and recorded on UV charts for manual digitising at a rate of 5 scans/minute. The results were converted to horizontal and vertical wind speeds, temperature and specific humidity.

Supplementary data included surface data from the ship or buoy.

4. Results and discussion

a. 13 September 1974

On this occasion there was widespread moderate convection with a fair number of showers falling from large cumulus, and also some much larger cumulonimbus. The amount of convection suggested that the average low-level flow over the area was convergent. The general surface flow was south-westerly, about 8 ms^{-1} , and the upper flow which was approximately easterly was bringing over the ship anvils from thunderstorms some 30 Km away to the east. After about 0900Z one of the larger cumulus on the starboard forward quarter began to develop quickly vertically and then laterally and soon there was a line of showers orientated roughly north-south associated with it. The line then approached the ship, intensifying and deepening to become an obvious line squall. The main rain areas passed on either side of the ship but the precipitation there was still fairly heavy during a period of about 20 minutes starting at about 1041. The rain lasted about an hour in all. The tethered-balloon system was flying with instruments at heights of approximately 96 m and 280 m while the squall developed and measurements were continued until shortly after 1100Z when a haul-down was necessary because of an impending aircraft mission. The ship was nearly stationary at 08 47.ON, 23 00.7W.

Parameters derived from the tethered-balloon data for the period 1000Z to the end of recording are plotted in Figure 1. Winds were around 9 ms^{-1} initially with a small increase with height. At the upper level the speed increased steadily after 1020 until the squall reached the ship but at the lower height this increase was delayed until about 1030. Prior to the squall's arrival temperature fluctuations were small at both levels, probably because of the small air-sea temperature difference ($\sim 0.5^{\circ}\text{C}$),

but at the lower level in particular the variations of specific humidity were more marked. Vertical velocity fluctuations were very small at 280 m but much more pronounced nearer the surface where they are seen to be well correlated with fluctuations of water vapour.

The data were used to obtain vertical fluxes of sensible and latent heat by eddy correlation over the period 1000-1036 and the results are plotted against height in Figure 2. The surface estimates were obtained using bulk aerodynamic relations with values for the transfer coefficients for sensible and latent heat of respectively 2×10^{-3} and 1.3×10^{-3} (Muller-Glewe and Hinzpeter 1975, Duncel et al 1974). The striking feature of the Figure is the strong convergence of the water vapour flux. It is possible that the shortness of the length of record used has resulted in the loss of significant low-frequency contributions to the fluxes at the upper levels (the lowest resolved frequency was about 10^{-3} Hz) but the convergence is probably genuine in view of the small fluctuations of vertical velocity at the upper level: if unchanged it would lead to near-saturation in the layer up to 280 m in a few hours. In fair-weather Trade Wind conditions it has been found (eg Donelan and Miyake 1973) that the rate of decrease with height of the water vapour flux is small and the present results suggest therefore that the boundary layer structure was being or had been modified considerably by large convective systems in the vicinity.

Corresponding momentum fluxes were $-1.0 \times 10^{-1} \text{ Nm}^{-2}$ at the surface and -2.5×10^{-2} and -0.5×10^{-2} at 96 m and 280 m respectively. The decrease with height appears to be rather large but may be a result of the short averaging time: at 96 m for example the successive 6-minute averages for $w'u' \times 10^2$ were -1.4, -1.6, -10.0, -5.0, +6.5 and -1.9, with a mean of -2.2.

The surface wind backed slightly (from 225 to 210 degrees) a few minutes before arrival of the squall, began to increase significantly after about 1037, and veered temporarily to 270 degrees and increased further just before the start of the rain (Figure 3). The line was orientated roughly from 020 to 200 degrees and the wind component perpendicular to the line increased from about 2 to 7 ms^{-1} during its passage between 1038 and 1041Z. Successive radar pictures suggested a speed of propagation of about 5 ms^{-1} (or 900 m in 3 minutes) and the corresponding divergence was therefore about -5×10^{-3} . It was not possible to calculate divergence from the tethered balloon measurements in the absence of wind direction data, but at 280 m the divergence was almost certainly numerically smaller than that at the surface because of the smaller change of wind speed on passage of the squall. After about 1110 the surface wind had decreased to near 8 ms^{-1} , little different from its value before arrival of the squall.

The squall's arrival was marked by a rapid fall of temperature at the surface and the two tethered balloon levels (Figure 1) and a brief increase in specific humidity. The air then became drier and by 1100 the specific humidity at 280 m was about 3×10^{-3} lower than initially, with about half this decrease at 96 m but little change at the surface. The largest fall of temperature was at the surface, about 2.5°C , with the least change at 280 m. The vertical velocity fluctuations became considerably larger at the upper level when the squall arrived and on average there were updraughts at both heights for a few minutes after temperatures began to decrease but later the average motion was downward. The differential fall of temperature produced a strongly stable layer away from the surface, especially between 96 m and 280 m and this seems to have inhibited vertical velocity fluctuations at the lower of these two levels but at 300 m where the stability changes may have been smaller the level of turbulence remained high.

Both tethered balloon levels experienced a double downdraught superimposed on the generally rising motion in the squall line's vicinity. The downdraughts were delayed about 25 seconds at the upper level and allowing for the angle of the balloon cable this implies a backward slope of the undercutting cold air of around 10 degrees, but this value is very sensitive to the speed of travel of the squall which was known only approximately. The mean upward velocity at the upper level over the period 1038 to 1046 was 0.25 ms^{-1} and at the lower level (1038-1042) 0.15 ms^{-1} . Assuming that the divergence was close to zero apart from a 3-minute period centred close to 1040, and that it was constant with height, the calculated vertical velocities are 0.4 and 0.7 ms^{-1} respectively. If the divergence decreased linearly to zero at 280 m the calculated values become 0.3 and 0.35 ms^{-1} , still significant overestimates.

In general the data support the classical picture of the line squall maintaining itself through wind shear and evaporative cooling (Figure 4). Air behind and within the squall must have been cooled by evaporation of rain into it and since even then it is drier than the air originally at the same height it must therefore have originated at higher levels. There are no representative radiosonde data for the period from which the temperature and humidity structure above the surface can be deduced (a sonde was released from Hecla at 1102Z but this ascended through the main rain area) so it is not possible to draw any firm conclusions about the level from which the dry air at 280 m originated. However rough calculations based on the average of radiosonde ascents made from Russian ships in the A/B array in Phase III (Antsipovich et al 1975) suggest that the air descended from a level near 1500 m if it is assumed that insignificant mixing with air at lower levels took place. The vertical wind shear separated the updraught and downdraught regions and allowed the latter to develop over a wide area.

The surface fluxes were estimated from the ship's surface data using the bulk aerodynamic formulae. The sensible heat flux increased by a factor of about 8 on arrival of the squall, and the Bowen ratio changed from 0.08 to 0.5, with a doubling of the total heat flux ($H + LE$) to about 290 Wm^{-2} . The squall therefore appears to be a successful mechanism for producing enhanced vertical transfers, first by removing moist lower boundary-layer air from an area of some tens of square kilometres, pumping it upwards and replacing it with dry air, and secondly by enhancing the surface fluxes themselves.

b. 16 September 1974

Hecla lifted her meteorological buoy on this day and steamed to 08 26.6N, 23 25.7W to carry out intercomparisons with "Meteor's" systems. The buoy was relaunched and attached to Meteor's profile buoy by a tether about 200 m long. The tethered balloons on both ships were operating from about 1535Z, with two sensor packages at nominal height of 200 and 400 m, and with the ships about 0.5 Km apart. Meteorological conditions were relatively disturbed (GATE convection code 3 or 4) with a nearly full cover of medium and high cloud, a few embedded cumulonimbus and fair amounts of smaller cumulus. A number of showers were visible, and at approximately 1708 and 1800 there were a few spots of rain at the ship. Cloud base was relatively low at times and at 1650 dropped below 400 m for a short while, with the balloon just in cloud. Surface flow was mainly WSW'ly about 7 ms^{-1} but there was a temporary veer of about 40 degrees after about 1747 and a simultaneous increase of wind speed.

Figure 5 shows time series obtained from Hecla's tethered balloon observations over the period from 1703 to 1811Z. The magnitude and variation with time of wind speed at both heights were broadly similar, with general increases

at 1717 and after about 1742. Temperatures fell sharply at 1747 but prior to this their fluctuations were relatively small, though somewhat larger than on 13 September (before the line squall's arrival) where the sea-air temperature difference was only about one third of that in the present case. At the upper level in particular there was often a clear negative correlation between temperature and vertical velocity, and for a period of about nine minutes starting at 1729 both levels showed a mean downdraught associated with a significant increase of temperature. Specific humidities decreased significantly after 1729 and remained low for the rest of the period shown. Prior to 1747 then there was evidence for vertical transfers on time scales up to around ten minutes: also in the latter part of this period the temperature and humidity changes were consistent with coupling over a depth significantly greater than the vertical spacing of the two balloon-borne instruments.

Figure 6 shows the variation with height of the vertical fluxes of sensible and latent heat for the period 1703 to 1745Z. As before the fluxes above the surface level were calculated by eddy correlation: surface values were obtained using bulk aerodynamic formulae in conjunction with sea-surface and 10 m data from Meteor's buoy (10-minute averages). The obvious feature is the strong convergence of water vapour which, as suggested earlier, might be due to attenuation of low-frequency contributions to the vapour flux resulting from the relatively short sampling times. However the characteristic vertical wind shear produced by upper easterlies and low-level south westerlies, and the frequent showers in disturbed conditions during GATE inevitably resulted in frequent injections into the lower boundary layer of dry cool air from above via mechanisms similar to the line squall already described: thereafter rates of warming and moistening in the lower boundary layer usually decreased rapidly with height because of enhanced vertical

stability away from the near-surface layer. Large flux convergence may therefore turn out to be the norm rather than the exception in the lower boundary layer during GATE. (For example, Andreev et al (1975) found the vertical flux of water vapour in cloudless conditions during GATE roughly halved in going from surface to 500 m, and in disturbed conditions changing sign at about 300 m. Grossman (1975) found compatible results in GATE fair-weather conditions (some non-precipitating cloud present), with the vapour flux less than half its near-surface value at heights above about 400 m).

The vertical flux of momentum over the period 1703 to 1745Z was estimated to be $-7.5 \times 10^{-2} \text{ Nm}^{-2}$ at the surface and calculated (by eddy correlations) as $+2 \times 10^{-2}$ at both tethered balloon levels. The implied rapid variation with height near the surface may be unrealistic and merely the result of working with an inadequate length of data at the 178 m level. Alternatively it may be due to relatively large contributions from the acceleration or advection terms in the equations of motion, or to strong baroclinicity. The large horizontal inhomogeneity during the run makes it impossible to distinguish between the latter possibilities.

At 1747Z, a minute or so after the start of an updraught lasting about 6 minutes at both balloon levels, there was a marked fall of temperature with magnitude ranging from about 1.3 degrees C at the surface to 0.7C at the upper balloon level. Temperature at the surface remained a degree or more lower than the original value for at least an hour after this time but began to increase again rather sooner at the upper levels. Specific humidities showed an increase at first but then decreased at all heights. There was a small but sharp rise in wind speed, and a veer of about 40 degrees at the surface, at around the time of the temperature fall. A comparison of

the parameters' variations close to 1747Z with those which occurred on passage of the line squall on 13 September reveals many similarities, such as the surface wind veer and increase, the variation with height of the temperature fall, the temporary rise in specific humidity and the overall updraught, and yet an important driving mechanism of the line squall - heavy rain - was absent in the present case: the only precipitation was a very brief, very light shower at 1800Z. Nevertheless, since the cool air which arrived at 1747 must have originated from well above the surface because of its dryness, and therefore must have been cooled by evaporation of rain into it in order to reduce its otherwise high potential temperature, a system similar to the line squall with separated updraught and downdraught regions must have existed some time earlier to bring about this situation. What appeared to have been observed therefore was a decaying system possibly still producing close coupling between cloud and sub-cloud layers.

Surface fluxes obtained by using Meteor's buoy observations in the bulk aerodynamic formulae are shown in Figure 7. After 1750 the heat flux doubled and the Bowen ratio increased from 0.16 to 0.33. The total flux ($H + LE$) also increased sharply, by around 25%, and remained above its earlier value for around one hour.

5. Concluding Remarks

These preliminary analyses of data obtained during disturbed conditions in GATE have demonstrated how coupling between cloud and sub-cloud layers not only enhances considerably vertical mixing over a substantial part of the boundary layer but also results in increased surface exchanges. The coupling appears to result from vertical wind shear and cooling of air by evaporation of rain which combine to form systems such as line squalls with clearly separated main areas of updraught and downdraughts and some degree of self-maintenance. A marked convergence of the vertical flux of water vapour appears to be a feature of these conditions.

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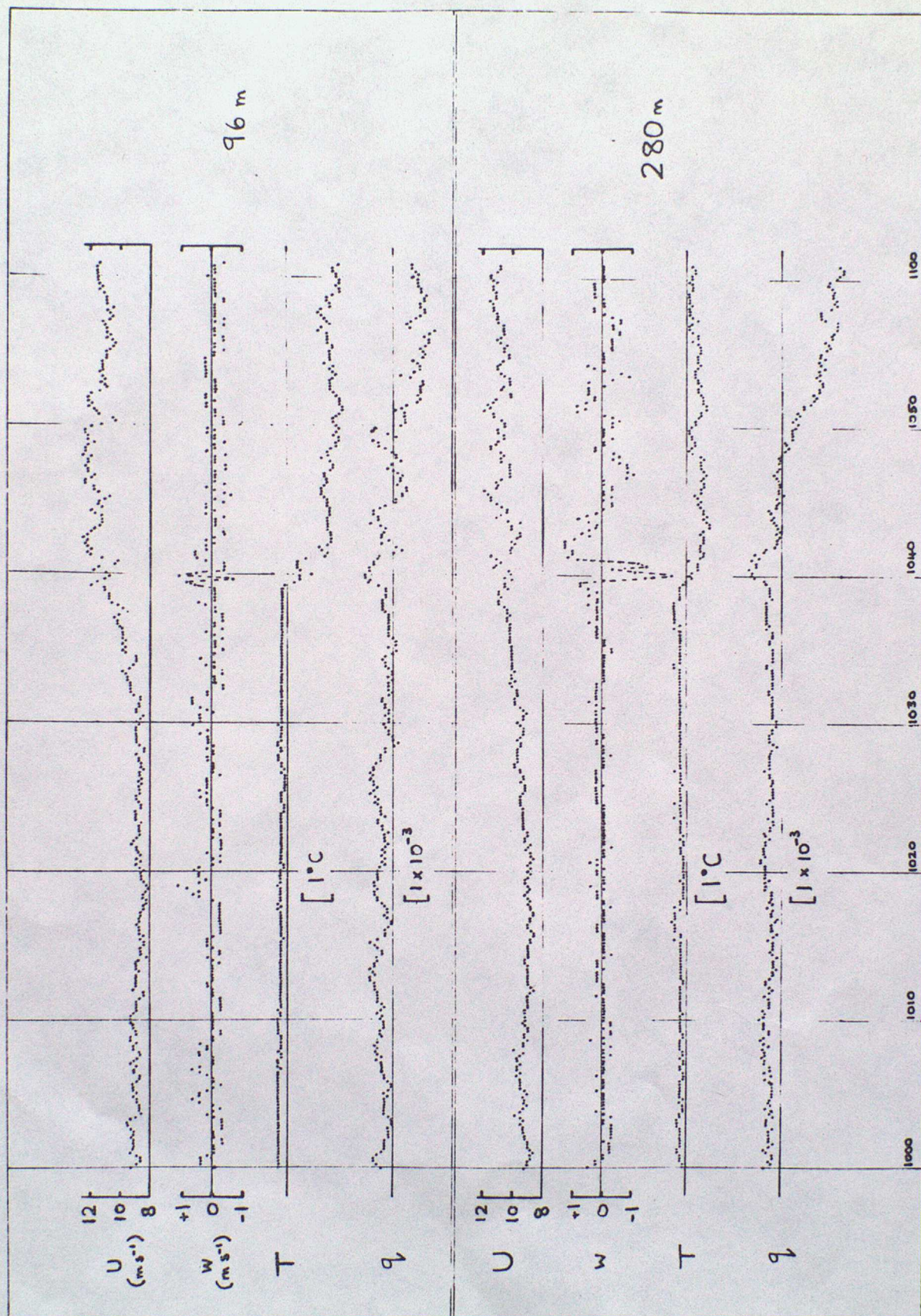


FIGURE 1. 13/9/74

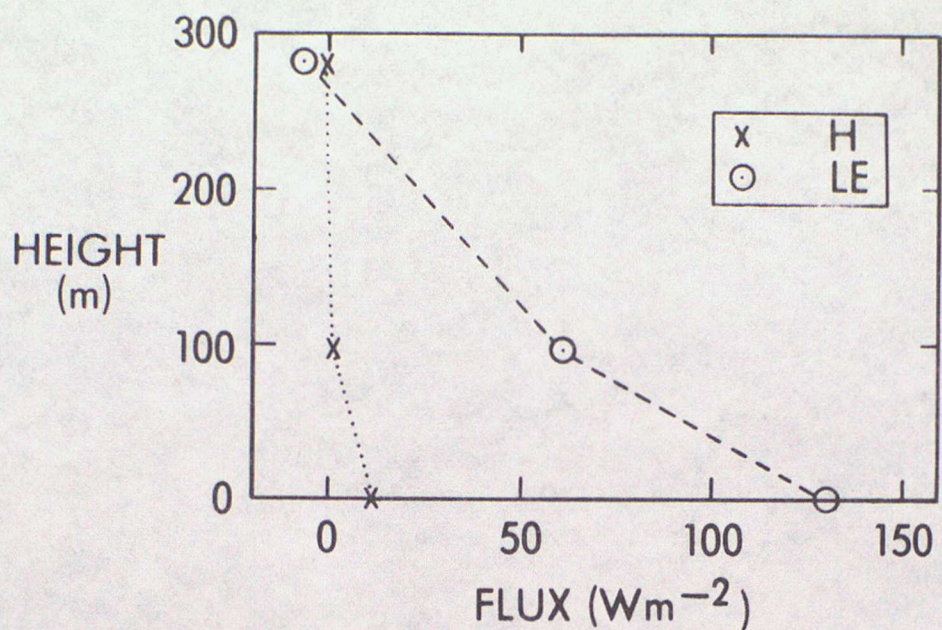


FIGURE 2. VERTICAL FLUXES 1000 - 1036Z 13/9/74

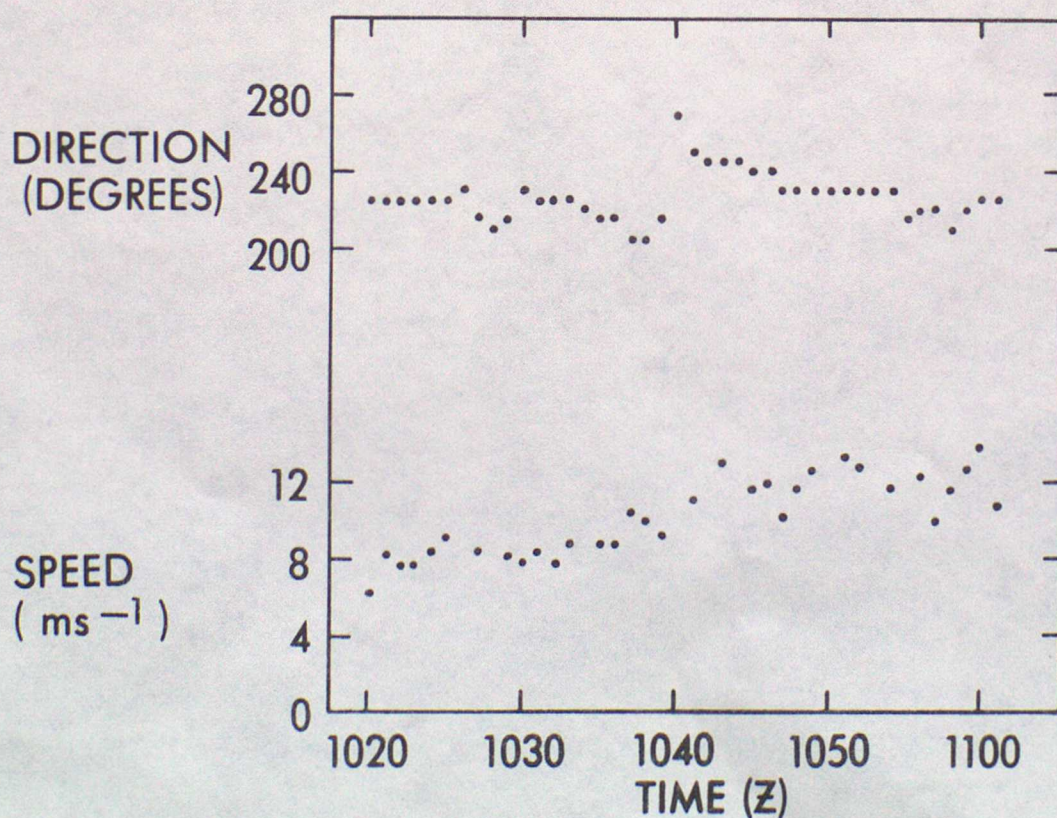


FIGURE 3. SURFACE WIND SPEED AND DIRECTION, 1020 - 1101Z, 13/9/74

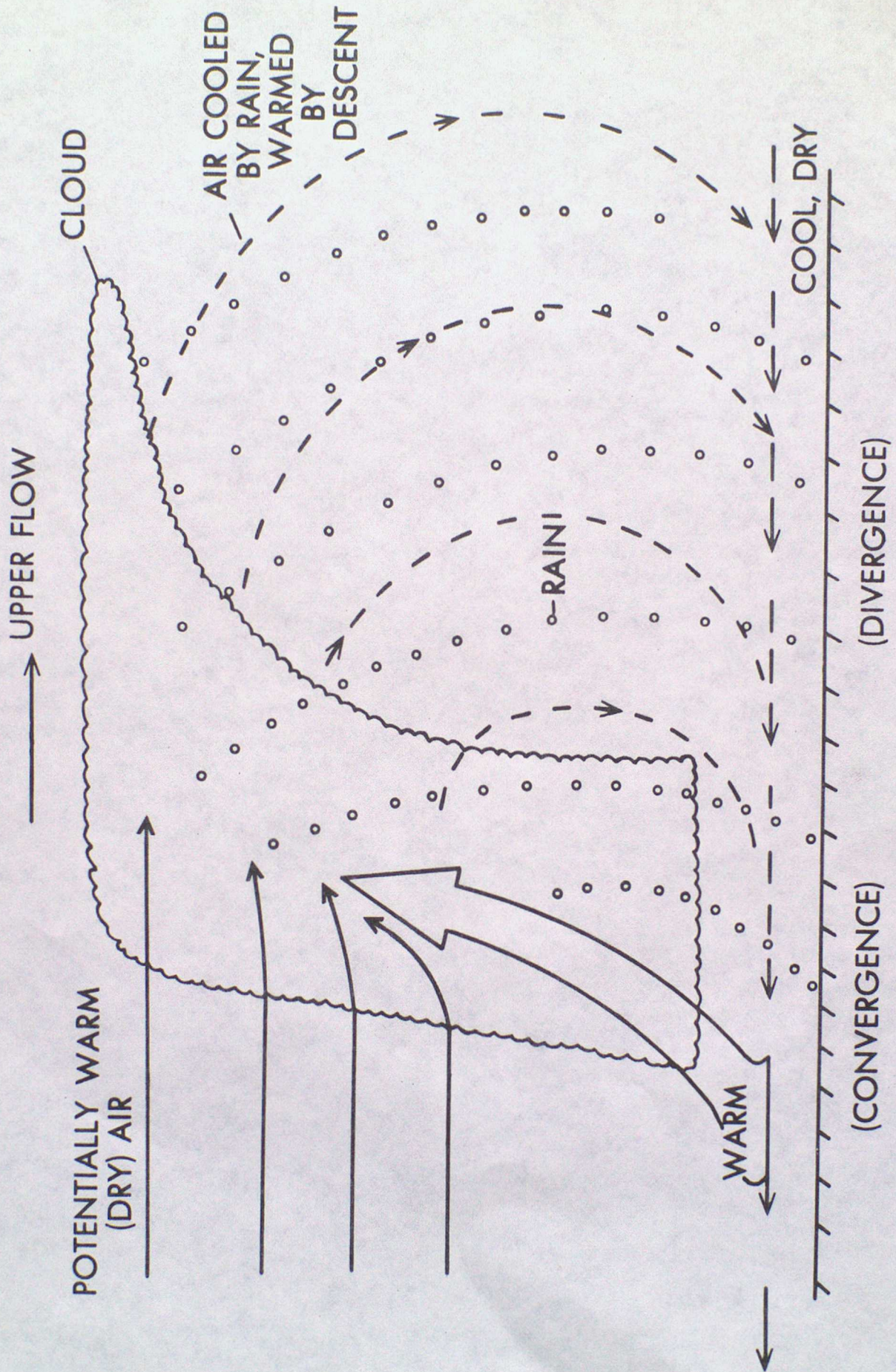


FIGURE 4. SIMPLIFIED LINE - SQUALL CROSS - SECTION

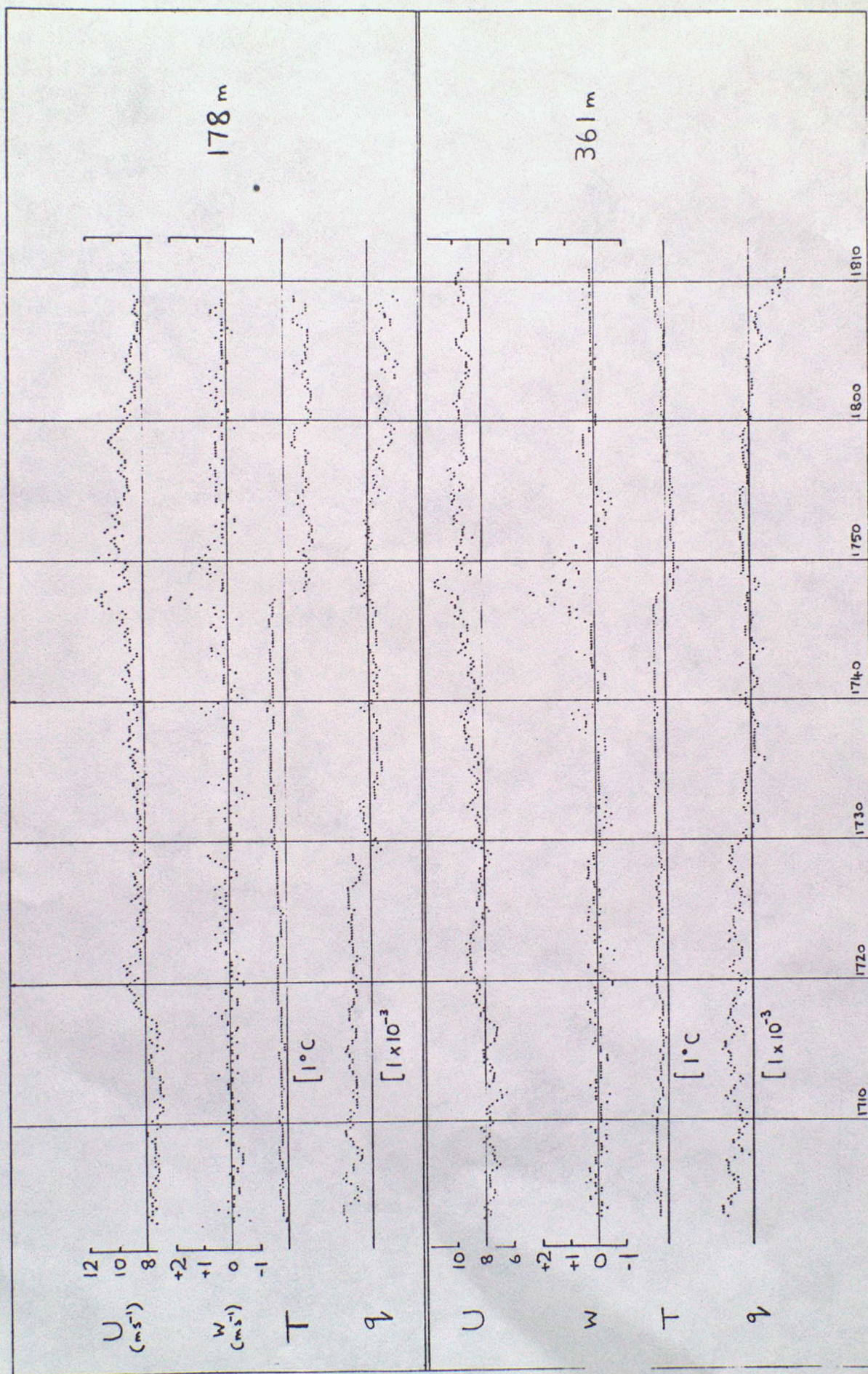


FIGURE 5. 16/9/74

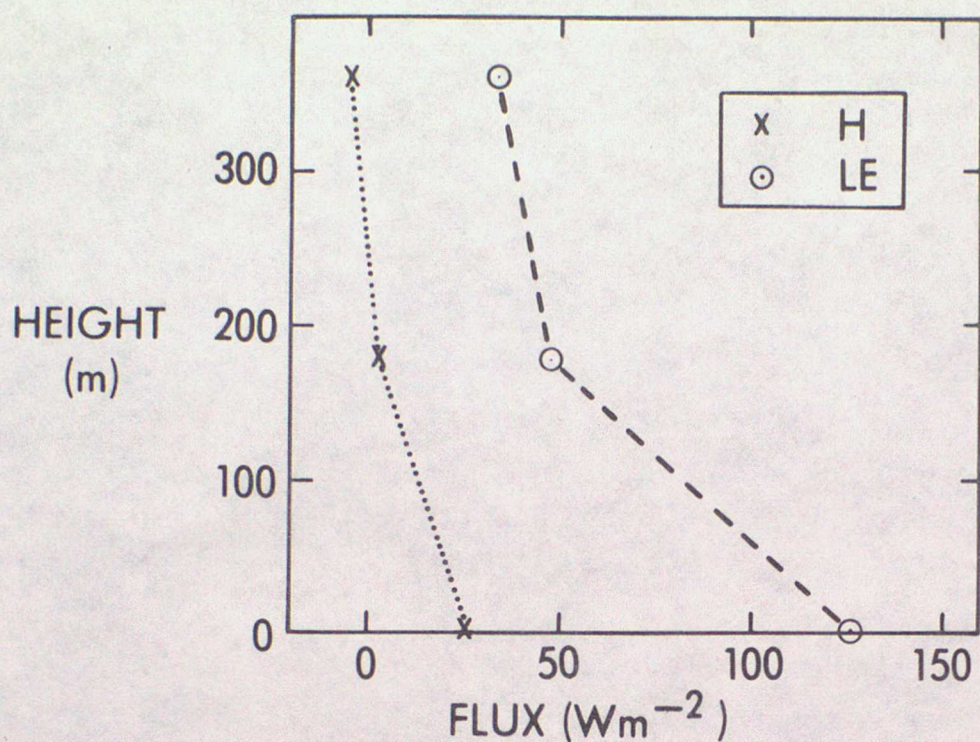


FIGURE 6. VERTICAL FLUXES 1703 - 1745Z 16/9/74

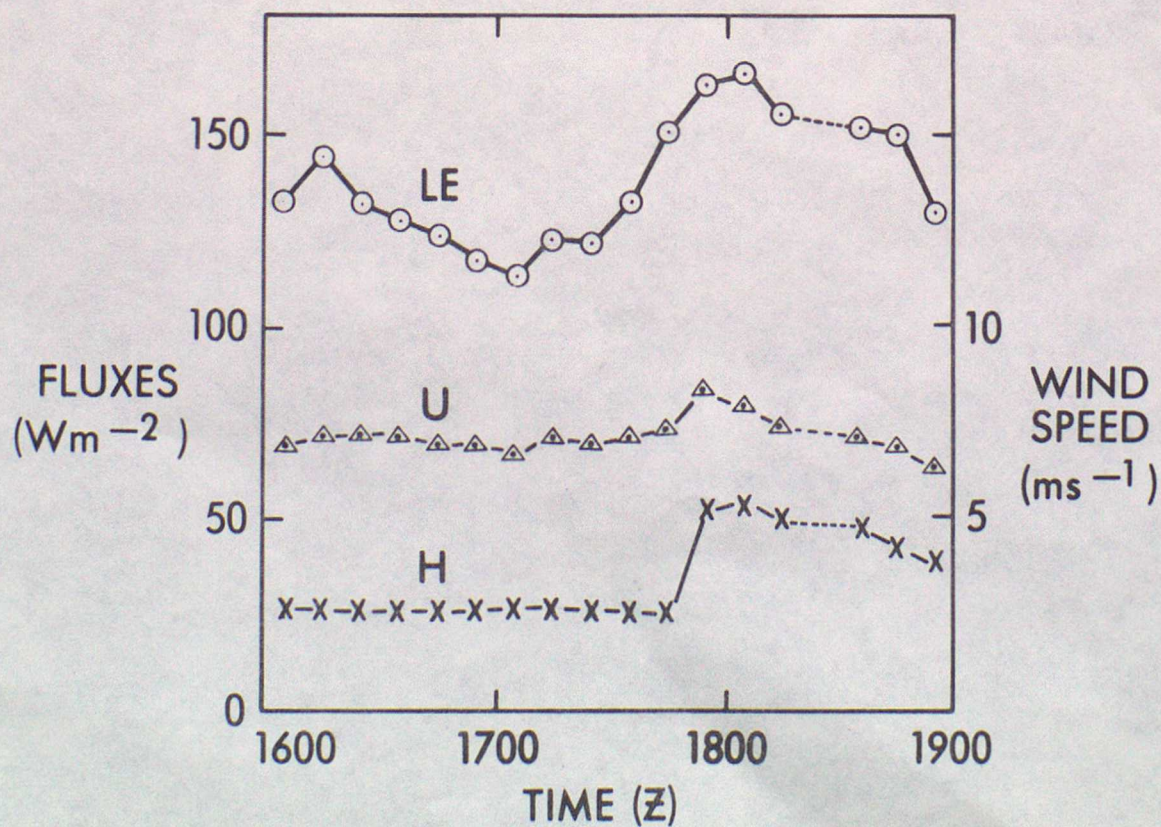


FIGURE 7. SURFACE FLUXES AND WIND SPEED, 16/9/74