OBSERVATIONS
OF THE PLANETARY BOUNDARY LAYER DURING GATE

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1. INTRODUCTION

The Atlantic Tropical Experiment took place over a very large area but the main investigations of the boundary layer were concentrated in a much smaller central region. This core region was centred about 1000 Km southwest of Dakar and was selected primarily for the high frequency of occurrence of major convective systems, with some compromise to allow several hours over-flying by aircraft based at Dakar. The climatological average position of the intertropical convergence lies close to this core area in the Northern summer but the day-to-day variations of the low-level wind field are often very large. One of the major causes of the variability appears to be the so-called "easterly waves" which move westwards in the troposphere at about 3-day intervals with speeds of around 8 ms^{-1}. The development of the major convective systems which have been rather loosely described as "cloud clusters" is usually intimately related to the passage of the waves, but the systems often have a relatively short lifetime since normally they do not propogate with the waves. The characteristic of the cloud clusters at low levels is their spatial inhomogeneity. The satellite pictures of the clusters are misleading because they often suggest homogeneity over areas of the order of 100 Km square, but underneath the cirrus canopy which the satellites see is a much more complex structure. This complexity comes about partly because the vertical mass flux due to the large-scale convergence is smaller than the mass flux within the convective clouds: the resulting compensating downward motions tend to suppress convection in the vicinity of each active cloud group and maintain the spatial variations. A consequence is that the most highly suppressed boundary layers occur in association with the most vigorous convection.

In relatively undisturbed conditions, for example near the ridge of an easterly wave, a thermodynamic structure similar to that in the main Trade winds was frequently observed during GATE. The characteristics of this boundary layer are variations of wind, temperature and humidity in the lowest few tens of metres which follow the usual profile relationships for slightly unstable conditions: above this is a mixed layer where the temperature lapse is close to dry adiabatic and where specific humidity decreases rather slowly with height. The mixed layer is capped by a thin stable transition layer produced by compensating downdraughts between cumulus clouds. In at least one respect though the GATE suppressed boundary layer near the central area differed from the Trades in that the associated horizontal divergence was not usually positive right down to the surface: there was often weak convergence up to about 900mb.

An indirect coupling between the cloud and sub-cloud layers comes about either through turbulent entrainment of air in the transition layer into the mixed layer below or by moist bubbles or thermals from the mixed layer breaking through the transition layer. Direct coupling occurs where the clouds have roots in the mixed layer. This type of boundary layer structure was destroyed usually when widespread deep convection broke out, typically as a result of the large-scale horizontal flow becoming convergent over a greater depth. Thereafter a direct coupling between cloud and sub-cloud layers was reinforced sometimes by precipitation downdraughts.

A time series of surface observations from the centre of GATE is useful in showing how the lower boundary layer was modulated and changed by the passage of the easterly waves. The major boundary layer modifications had significant magnitudes right down to the surface and those with longer time scales are identified easily from routine surface data (Figure 1). If the short period fluctuations are ignored the major changes of temperature and humidity are seen to be linked closely with rainfall and show the typical 3-day periodicity. There is a sort of charging/discharging cycle during which the lower layers become so warm, moist and buoyant that a fairly modest external trigger is sufficient to initiate widespread deep convection. For example a decrease to zero of the divergence in the lower and middle troposphere, coupled with radiational cooling of about 1°C per day would soon allow deep convection to occur (the external trigger was usually more vigorous, typically strong low and middle-level convergence). The aftermath of the disturbed rainy periods is in each case a near-surface layer which is cool and dry.

In undisturbed conditions the typical surface wind field showed only a very weak convergence between the North Easterly and South Easterly Trades: at 700mb there was usually a ridge in an otherwise fairly uniform Easterly flow (a good example was observed during Phase II of GATE, on 11 August 74: on this occasion there were no significant radar echoes within 200 Km of the centre of the core area even though the line of convergence in the surface wind lay across this circle - see Dugdale 1975, page 100).

In disturbed conditions the flow became more convergent with circulations sometimes developing on the main convergence line, and the main precipitation areas tended to be associated with the troughs of the Easterly waves. However the detailed structure of the flow differed considerably from one disturbed period to the next (see for example Dugdale (1975), page 144 for active systems which were observed in Phase III on 2 September). The major rain areas were often very complex and because of their associated effects on the boundary layer this led to equally complex variations in both the horizontal and the vertical of the boundary layer structure. The amount of precipitation during a highly disturbed period was very variable but locally could reach about 100mm.

Mean vertical profiles of divergence and vertical velocity over the A/B hexagon of ships surrounding the core area (Petrosiants et al 1975) showed as expected very large differences between the disturbed and undisturbed cases (Figure 2). One might note here the typical surface value of 10^{-5} for convergence in the disturbed cases and then recall that the major regions of convergence were usually much smaller than the 700 Km size of the A/B hexagon. It is not particularly surprising then that the convergence across some of the active rain areas was found to be one or two orders of magnitude larger than the average over the hexagon.

2. DETAILED OBSERVATIONS OF BOUNDARY LAYER STRUCTURE

2.1 INTRODUCTION

Comprehensive boundary layer data were obtained during GATE, particularly by aircraft, and by those tethered balloon systems which were able to reach well into the cloud layer but published results from these platforms are very sparse at present: it seems likely that at least another two years will pass before a reasonably full set of results is available. The data to be discussed here were obtained in nearly all cases from a single ship near the centre of the core area, at heights below the transition layer.

2.2 HIGHLY SUPPRESSED CONVECTION

This corresponds to the GATE convection code 1 which applies to conditions with, at most, small amounts of thin transient cumulus. Some results from tethered-balloon observations made in these conditions at two heights, one near the middle of the mixed layer and the other close to the top, just below the transition layer are shown in Figure 3. There are a number of features here which might be noted:

(1) The mixed layer, or at least its middle part is indeed well-mixed: despite a sea-air temperature difference of nearly a degree Centigrade the r.m.s. temperature fluctuations are very small at 200m, roughly one quarter of those at 400m.

(2) The temperature and humidity fluctuations are generally in antiphase at 400m and are consistent with a positive lapse of potential temperature at around the level, and a strongly negative lapse of specific humidity at, or just above this level.

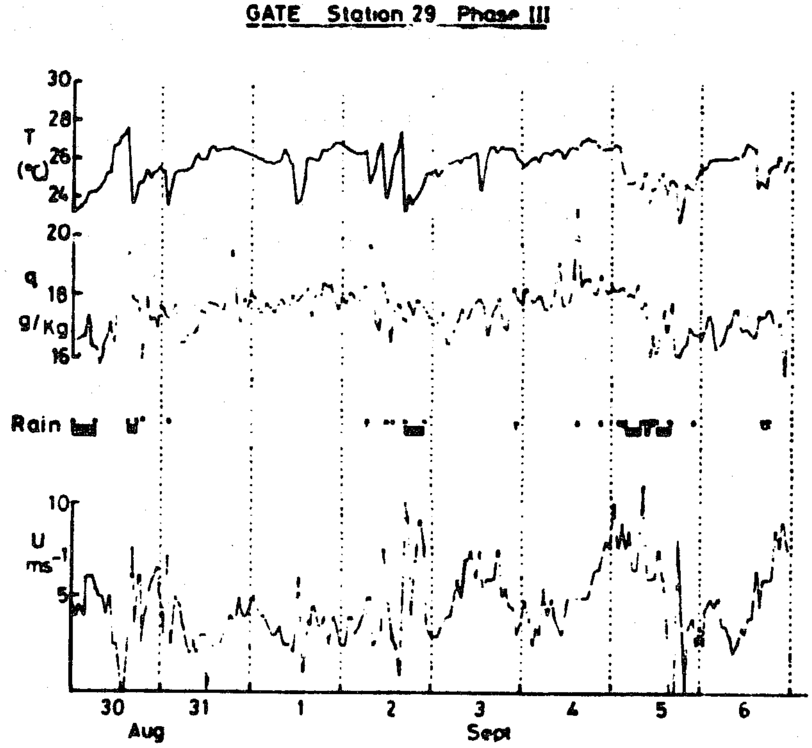

Figure 1 Surface observations from GATE Core Area at 0847N 2305W

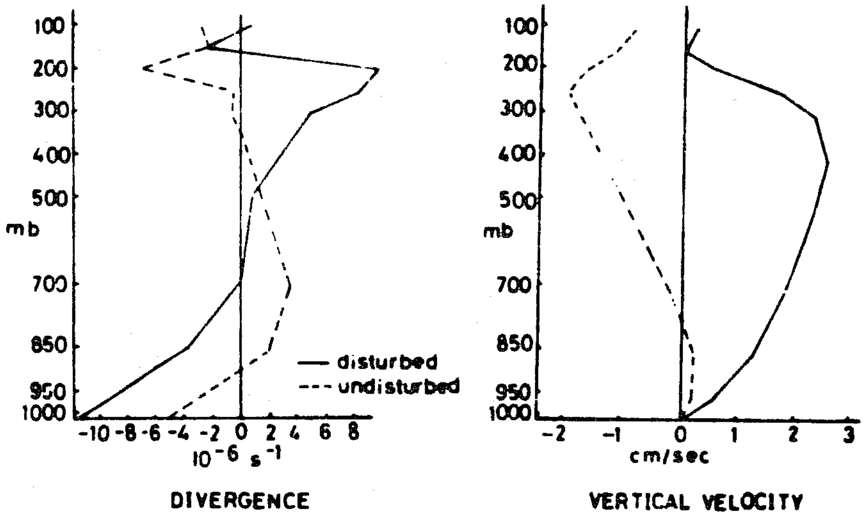

Figure 2 Mean divergence and vertical motion in A/B Hexagon, Phase I

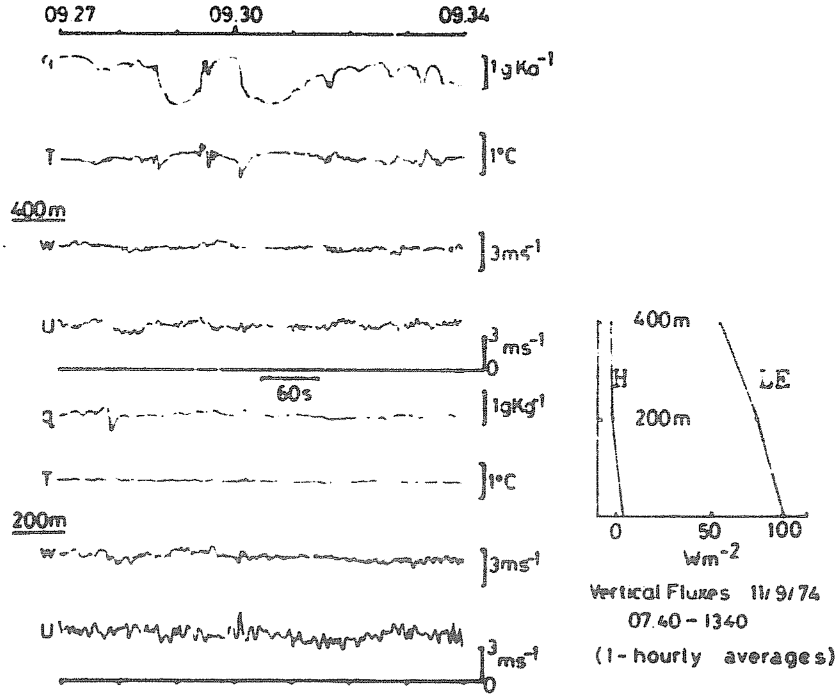

Figure 3 Tethered balloon observations and vertical eddy-flux profiles in suppressed conditions, 11 September 1974

q - specific humidity (gkg^{-1})
T - air temperature (deg C)
w - vertical wind speed (ms^{-1})
U - horizontal wind speed (ms^{-1})
H - vertical flux of sensible heat
LE -vertical flux of latent heat

(3) The vertical flux of water vapour (derived by the bulk-aerodynamic method at the surface and by eddy-correlation at the tethered balloon levels) decreases fairly uniformly with height but is still relatively large at the top of the mixed layer: thus there appears to be a substantial transfer of water vapour through the transition layer immediately above.

(4) The sensible heat flux is very small at all levels. The Bowen ratio at the surface is about 0.05 and the flux is downward through much of the mixed layer, which is of course consistent with entrainment of sensible heat across the transition layer into the mixed layer as a result of buoyancy produced by the vertical flux of water vapour. Over this particular six-hour period the downward heat flux at 400m was about one quarter of the virtual heat flux at the surface: the virtual heat flux at 400m was still directed upwards, though nearly an order less than at the surface.

(5) The correlation between temperature or humidity fluctuations and vertical velocity at 400m is very small. For example the r.m.s. vertical velocity was about 0.2 ms^{-1} and the humidity fluctuations about 0.7 gKg^{-1} whereas the $w'q'$ average value was about 0.015 or one tenth of $\sigma_w \sigma_q$. At 200m on the other hand the correlation coefficient was about four times as large. A possible explanation for at least part of this low correlation at 400m is that evaporation of the transient cumulus clouds occasionally produced downdraughts which were relatively cooler and moister than would have been expected to result from purely dry convective overturning.

(6) Another point which cannot be seen directly from the Figure is that there seems to be no strong coupling between the shallow transient cumulus which were present on this occasion and the air in the mixed layer below. The transit times of a number of these cumulus clouds were obtained from all-sky cloud pictures and compared with the corresponding records of turbulence but without finding any consistent evidence for coupling, such as organised updrafts into the clouds. Admittedly the clouds were very shallow and this together with their small sizes and short lifetimes suggest that they were initiated by moist bubbles breaking through the transition layer, but thereafter they existed without development or maintenance of significant roots in the mixed layer.

The average properties of the structure of turbulence may be represented by the frequency spectra and cospectra of the fluctuations. Figure 4a shows vertical velocity spectra (plotted as means from 4 1-hour periods) from the 6-hour period just described. The most striking feature apart from the reduction of energy with height is the rather small scale of the turbulent fluctuations. At 200m the predominant period is about 200 sec, which corresponds in this case to a horizontal scale of about 0.7 Km, and the energy falls off very sharply at periods beyond 500 sec. At 400m the spectrum is flatter and there are indications of a binodal structure but again the energy decreases rapidly for periods beyond 500 sec. Thus for this case which is typical of highly suppressed convection in fairly light winds it may be concluded that there is negligible organisation of the convection on horizontal scales beyond about 2 km.

The corresponding cospectra for the heat and water vapour fluxes (Figure 4 b) confirm the insignificant contributions to vertical transfer from the low frequencies. In interpreting these heat flux cospectra it must be remembered that the measured flux was only about 1 or 2 Wm^{-2} at both 200 and 400m. The lower level shows a positive contribution at a frequency corresponding more or less to the peak of the vertical velocity spectrum. This is produced by warm rising parcels of air. The slightly larger negative contribution at lower frequencies is associated with warm downdraughts. This type of flux distribution is typical also of observations in suppressed maritime boundary layers in middle latitudes (Thompson 1972). At 400m the low-frequency downward contribution begins to predominate. The small positive contribution at the lowest frequencies is scarcely significant but it could be caused by weak downdraughts from evaporating cumulus. The causes of the two positive peaks at higher frequencies are not clear, though the heat flux associated with each is only a few tenths of a Watt per square metre. In the case of the water vapour flux the predominant scale of vertical transfer at 200m is 1 to 2 kilometres. Minor departures from an otherwise smooth cospectrum correspond closely to the minor peaks in the vertical velocity spectrum. At 400m the structure is rather more complicated - the large double peak is associated with the low-frequency peak of the w-spectrum and the

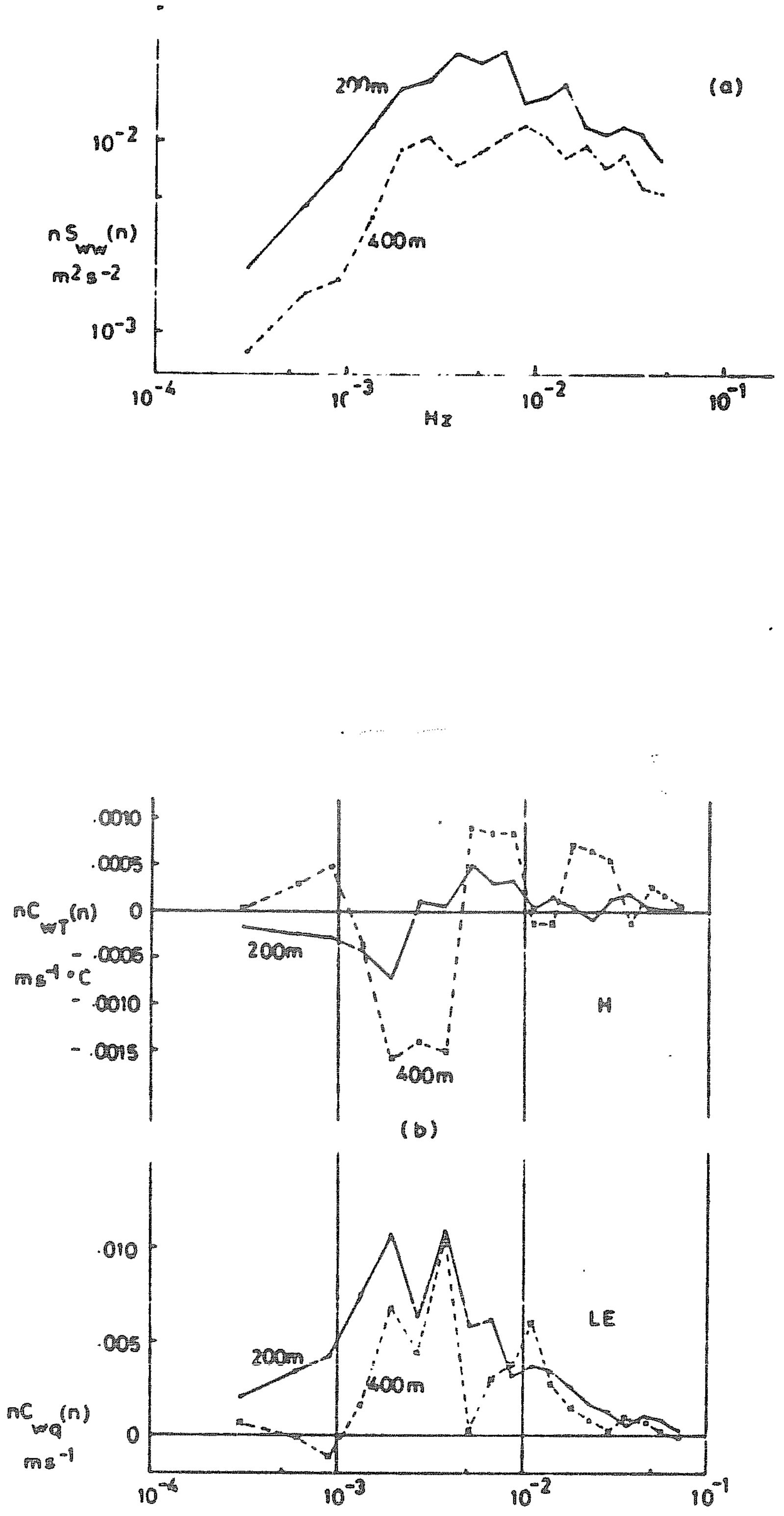

Figure 4 Spectra and cospectra in suppressed conditions, 11 September 1974
(a) Vertical velocity spectra
(b) Cospectra of heat and water vapour fluxes

pronounced peak at higher frequencies to the other major w-peak. The sharp fall-off at larger scales and the small negative contributions may again be the result of moist downdraughts produced by cloud evaporation.

2.3 SUPPRESSED BOUNDARY LAYERS IN MORE DISTURBED CONDITIONS

The most highly suppressed boundary layers in GATE occurred in conjunction with the more vigorous convective systems. The mechanism here was often deep convection through a layer with significant vertical wind shear which led to a separation of the precipitation from the main updraft region. The rain thus fell through dry air into which it evaporated freely, so cooling it to below the potential temperature of the air in the surface layers. This cooled but still fairly dry air then descended to the surface and spread out to produce strong zones of convergence and divergence, with squall-like characteristics. The overall result was that away from the convergence regions the surface layers became highly unstable: however the cooling a little above the surface was less and thus a significantly stable lapse of temperature developed in what was previously part of the mixed layer.

An example of this type of thermodynamic structure which occurred during fairly vigorous convection, and also for comparison a radiosonde ascent made towards the end of the 6-hour long run in suppressed conditions described above are shown in Figure 5. Clearly the ascent in the disturbed conditions is generally moister and colder than the other but near the surface it is very stable and significantly drier with the boundary layer depth probably less than 200m. Whether or not this very shallow boundary layer is a transient phenomenon depends very much on whether the outbreaks of rain continue. The large sea-air differences of temperature and humidity produce large surface fluxes and vigorous turbulence which would fairly quickly restore the original boundary layer and once again allow cumulus convection to develop from within the boundary layer, unless the outbreaks of rain continued and produced fresh cooling of the lower layers by precipitation downdraughts.

A short sample of turbulence data obtained in these conditions at a height of 190m, close to the top of the region with vigorous turbulent mixing is shown in Figure 6. Interesting features here are the very large fluctuations of temperature and humidity. The vertical fluxes over 1-hour periods starting at about this time show insignificant changes in the sensible heat flux over a 3-hour period, and , reflecting the large sea-air temperature difference, a Bowen ratio of 0.25. Heat flux at 190m is small and downward for the whole period. The first hour shows a significant convergence of water vapour but as the boundary layer deepens the flux variations with height become rather small. Soon after the end of this 3-hour period the heavy showers were renewed and the lowest layers were cooled down again and presumably the very shallow mixed layer was reformed.

It is worth stressing that although in disturbed conditions one may observe these shallow boundary layers with strong capping inversions which effectively decouple them from the rest of the troposphere, none the less there may still be vigorous deep precipitating convection aloft, presumably driven by or at least coupled with strong convergence. It was apparently not uncommon for the GATE airborne missions to report the lower troposphere clear of all but shallow cumulus in disturbed conditions while vigorous convection with precipitation was occurring from middle levels upwards (Simpson 1976).

2.4 LARGER-SCALE CONVECTION WITHOUT PRECIPITATION

The convection tends to become organised on larger scales in both space and time as it becomes more vigorous and it is then probably less profitable and certainly more difficult to describe or catalogue the processes in a statistical sense by, for example, the corresponding boundary layer spectra or vertical flux profiles. Where one draws the dividing line between combining the effects of all the convective systems on a particular occasion and thus considering their net effect or alternatively considering each convective system as a case history is difficult to judge. A possible rough working rule is to assume that any system which produces strong coupling between the cloud and sub-cloud layers should be treated as a separate entity because of the related

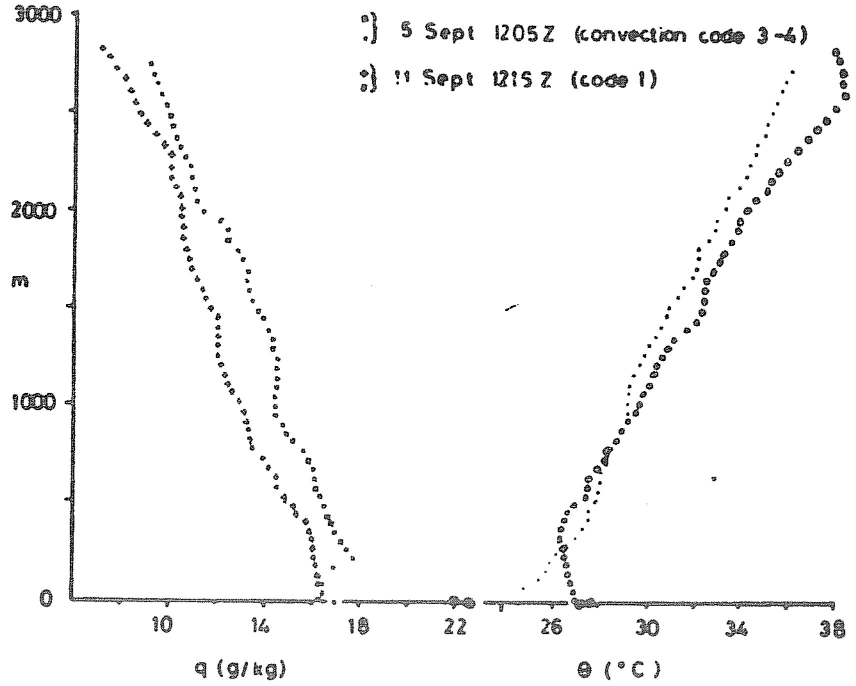

Figure 5 Thermodynamic structure of lower troposphere in suppressed and disturbed conditions (code 1 = highly suppressed convection: code 3-4 = widespread vigorous convection with heavy showers)

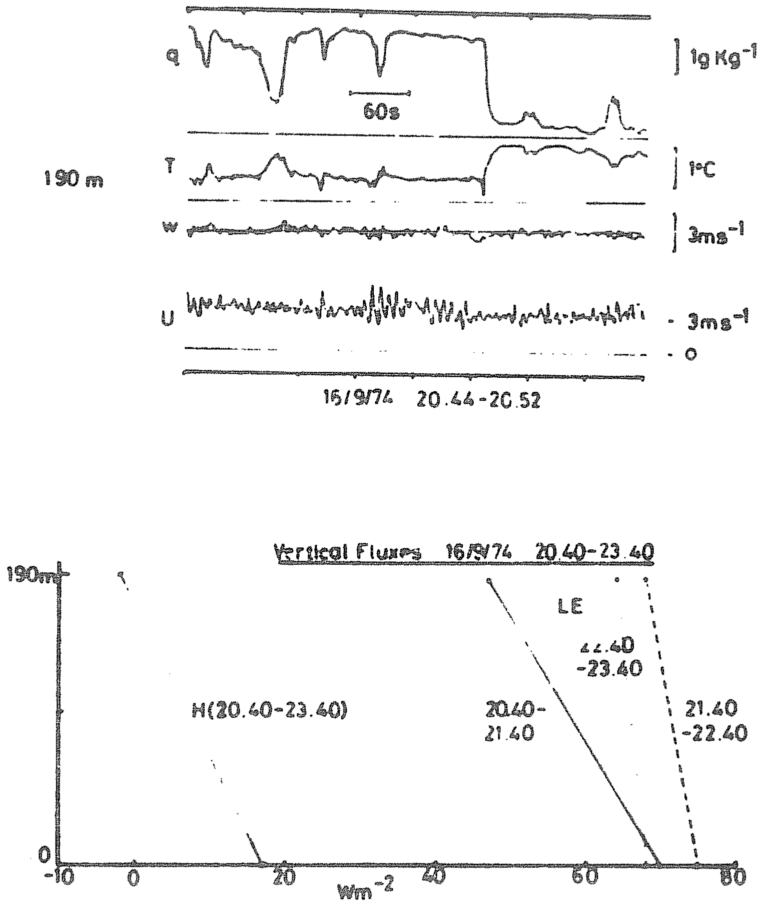

Figure 6 Tethered balloon observations and eddy fluxes in shallow boundary layer which developed in disturbed conditions, 16 September 1974

feedback processes which are likely to modify the environment very significantly in its vicinity.

Successive all-sky cloud photographs are a valuable aid in the analysis of cloud-subcloud coupling, especially in the case of isolated clouds. However the utility of the cloud pictures is tempered somewhat by the difficulties in interpreting them. If the clouds are reasonably well defined with obvious bases and simple vertical structure, and in particular if the sky is generally clear of upper cloud layers then the angles subtended on the photographs by cloud tops and cloud bases may be extracted with comparative ease. The cloud height, horizontal dimensions at base and speed of travel may then be estimated provided a single vertical dimension is assumed. The obvious vertical dimension is the cloud base which is typically around 100m above the lifting condensation level determined from thermodynamic data at 10m (Augstein 1972).

The passage of a large cumulus cloud was analysed in this way from successive photographs at two-minute intervals (Figure 7): a section of cloud passed directly over the camera. The cloud began to break up as it moved away and within 20 minutes it had become completely fragmented - this last time was around 70 minutes after it was first observed in the photographs. The vertical extent was estimated to be about 2 km but there wase no observations of precipitation from it. The average speed of the cloud from the photographs was about 2 ms^{-1} which was reasonably consistent with upper air data at around this time.

Tethered balloon velocity data (Figure 8) showed clearly that the cloud had roots extending right down to the bottom part of the mixed layer. The main updraught lasted about 6 minutes and increased rather slowly with height, indicating that convergence below cloud base decreased quickly with increasing height. The mean updraught at cloud base was probably around 1 ms^{-1}. The general boundary layer suggested that the ascending air at cloud base was about 2 gkg^{-1} moister than the ambient air at this height and so the updraught was sustaining a vertical flux of 5000 Wm^{-2}, nearly 100 times larger than the surface flux. If the cloud had an active lifetime of 40 minutes then it transported out of the mixed layer roughly twice the moisture evaporated in one day from an area of the sea surface equal to its own. Equivalently similar clouds passing over at 10-hour intervals would have extracted all the water evaporated from the sea in that time. On this occasion the rate of passage of clouds interacting with the mixed layer in a similar way to that described above was observed to be several times larger than 10-hourly. The result was either a draining of water vapour from the mixed layer which would have become progressively drier if turbulent entrainment across the transition layer maintained the depth of the mixed layer, or alternatively a reduction in height of the transition layer.

The surface flow during the passage of this particular cloud is shown in Figure 9. The observed 2-dimensional flow is expected since the cloud was not symmetrical and only the edge of it passed over the ship. However the flow relative to the cloud represented not only inflow but also a marked anticlockwise circulation round the cloud's edge. It is not known at present whether this circulation was typical of GATE cumuli: its significance is not clear at present.

3. SUB-CLOUD STRUCTURE OF DEEPER CONVECTION WITH PRECIPITATION

3.1 INTRODUCTION

Coupling between the cloud and sub-cloud layers becomes more obvious as soon as precipitation occurs. Considering for the moment an active isolated cumulus cloud, the coupling which begins as an organised updraught into the cloud is then reinforced by the downdraughts caused by evaporation of precipitation. If a significant vertical wind shear is present it will separate the main updraught and downdraught regions which therefore can coexist. In favourable circumstances a feedback mechanism may be produced which can maintain the identity of the convective system for hours by continually encouraging a rebuilding of the convective towers on the forward side of the main down-

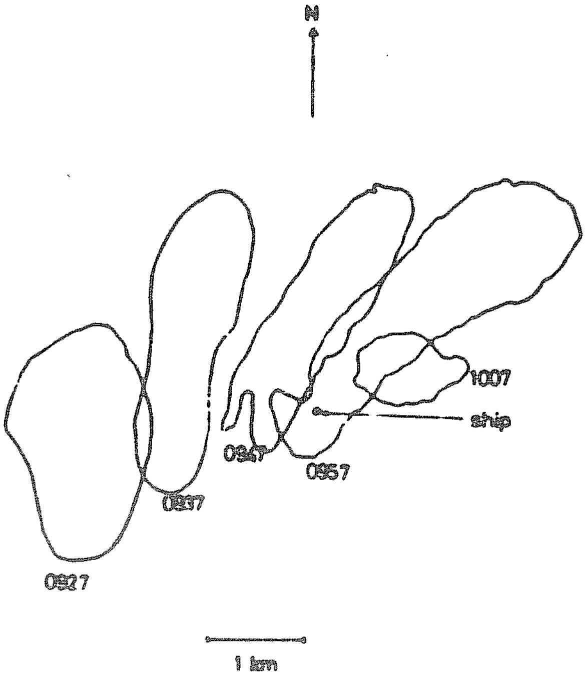

Figure 7 Cloud base dimensions during pasage of an isolated cumulus, 6 September 1974

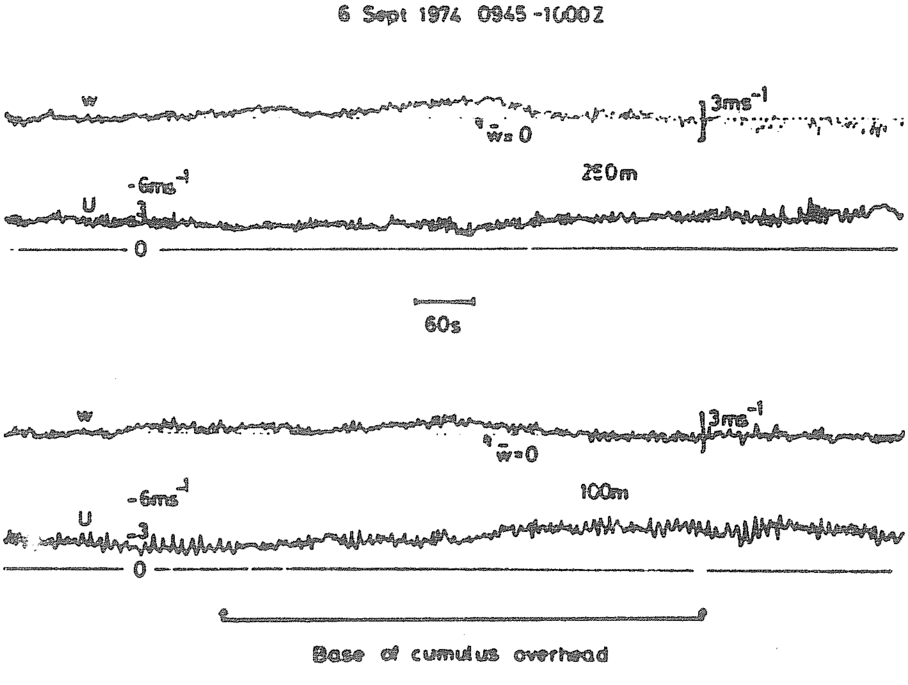

Figure 8 Tethered balloon observations during passage of cumulus, 6 September 1974

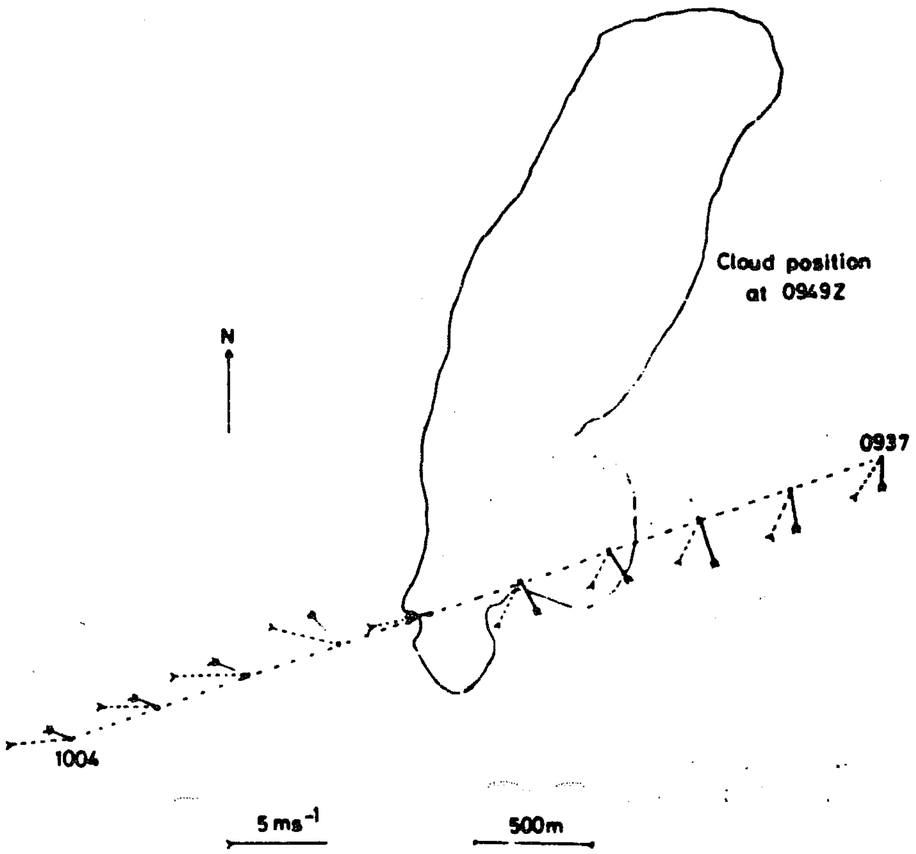

Figure 9 3-minute averages of surface wind vectors,
6 September 1974
≻------ actual surface wind
➤——— flow relative to cloud

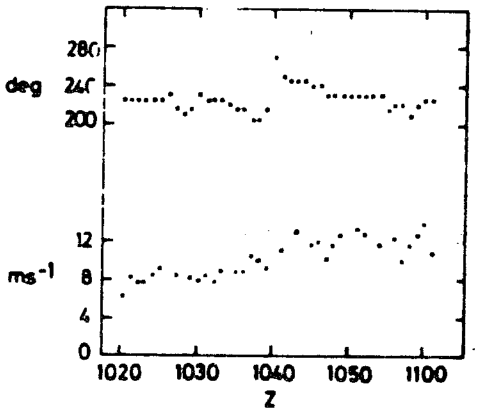

Figure 10 Surface wind during passage of squall,
13 September 1974

draught region. Ultimately the air cooled by precipitation may spread out far enough to cut off the low-level supply of moist air and hence prevent continuous convection from near the surface up to the middle troposphere or higher (Zipser 1969). However as indicated earlier the active convection in GATE at times was able to persist from middle levels upwards, maintained presumably by strong low and middle level convergence: it is probable though not yet confirmed that some of these higher-level systems originated at the surface and later lost their near-surface roots by the mechanism outlined above. (It is arguable whether one should talk about a boundary layer in these circumstances, or attempt to quantify it because the space and time variability near the surface become very large: each active cloud system effectively produces its own lower atmospheric structure which in turn is likely to show large horizontal variations over the scale of the system).

3.2 AN ACTIVE LINE SQUALL

Some observations obtained in the very shallow boundary layer which was observed in disturbed conditions were described earlier and consideration will now be given to the process of modification of an initially moist warm boundary layer by an active precipitating cloud system which leads eventually to the characteristic thin surface layer of dry cool air. The observations were obtained in an area of active convection with showers falling from large cumulus. The tropospheric structure was very inhomogeneous - typical of relatively disturbed conditions in GATE - with a large area of active cumulonimbus 20 or 30 Km away to the North East and convergent and highly distorted wind flows at the surface and 700mb. The observation point was nearly underneath a line joining centres of convergence at the surface and 700mb, leading to a marked vertical wind shear with the surface South Westerlies of about 8 ms^{-1} giving way to a North Easterly flow at higher levels. The feature of interest was a cumulus which developed over a period of about 2 hours into a well-defined line of precipitation. This passed over the ship as a line squall and produced a temporary large change in the boundary layer structure.

Radar echoes from the system showed a roughly linear structure orientated from about 020 to 200 degrees, with a speed of propagation perpendicular to the line of about 5 ms^{-1}. The squall reached the ship at about 1040Z and the significant features of the surface flow at around this time (Figure 10) were the general fairly steady increase in speed from about 1030Z onwards, the backing in direction for a few minutes before the squall's arrival, followed by a sharp veer, and finally the fairly steady backing again which produced by 1100Z a direction similar to that at 1030Z. If these variations are translated into ones perpendicular to the squall line then there was an increase from 2 to 7 ms^{-1} over a two minute period just before the squall's arrival and then a decrease over the next 8 minutes to around 4 ms^{-1}. If the flow was assumed to be effectively 2 dimensional (the wind component along the line is ignored) then over these two periods a convergence of nearly 10^{-2} was followed by a divergence of 10^{-3}. After about 1110Z the surface wind decreased to 8 ms^{-1}. The backing of the wind ahead of the squall indicated that air was being forced or sucked into the front of the system, ahead of which therefore there should have been sinking motion.

Tethered-ballon observations in the mixed layer at heights of 96 and 280m showed 30 minutes or so before the squall's arrival only a small increase of wind speed with height, but the flows at the two levels appeared to become uncoupled to some extent after about 1020Z (Figure 11): at this time the speed began to increase at the upper level, but the increase at the lower level was delayed about 10 minutes. This is consistent with the rather small variations of velocity at 280m compared with 100m which together suggest stabilization of the upper part of the mixed layer as the squall approached: it is consistent also with the divergent flow in the surface layer a few minutes before the squall's arrival. This arrival was marked by a rapid fall of temperature and a brief increase in specific humidity (Figure 12) but thereafter the air became drier and at 1100Z was 3 gkg^{-1} less moist than initially at 280m, with about half this decrease at 96m but little change at the surface. In contrast the largest fall of temperature,

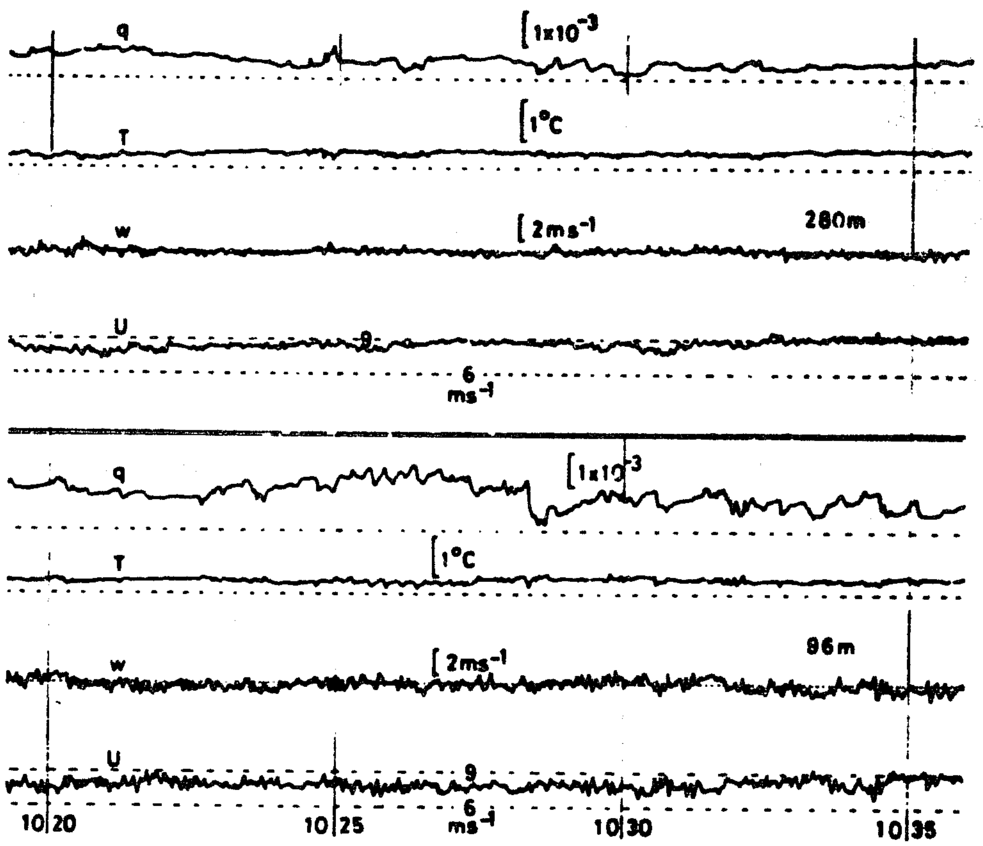

Figure 11 Tethered balloon observations before arrival of squall, 13 September 1974

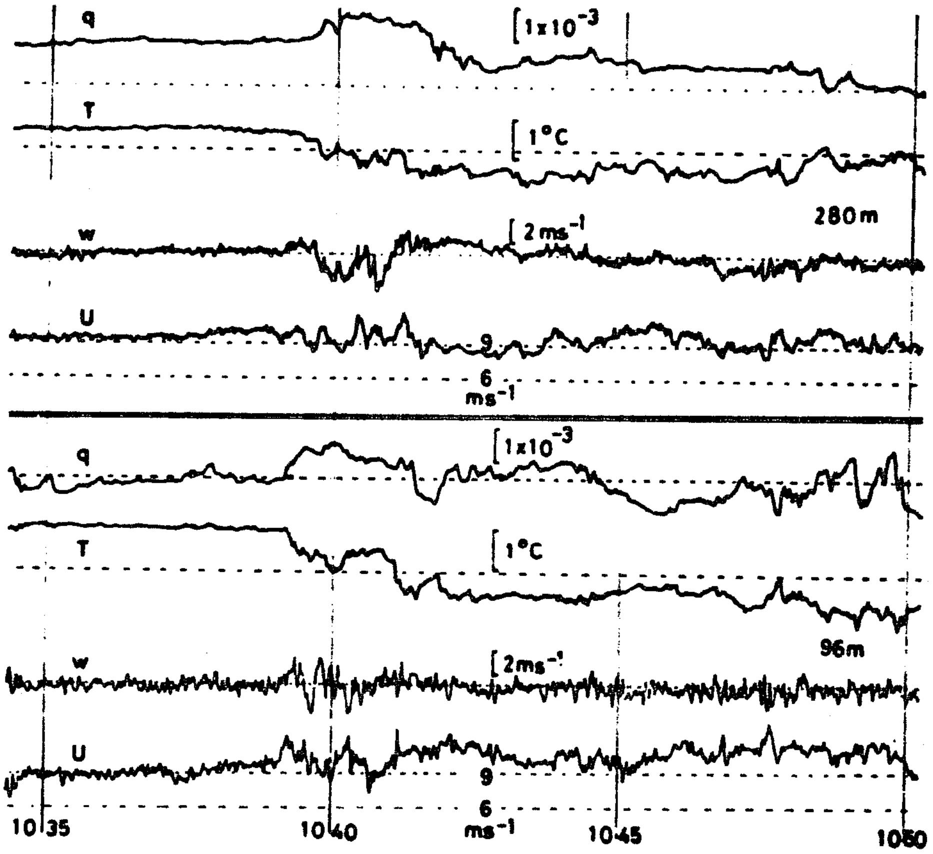

Figure 12 Tethered balloon observations during squall's passage, 13 September 1974

about 2.5 deg C was at the surface and the least change at 280m. Looking in more detail at the upper level, where the effect of wave-induced ship motion on the measured velocities was small, the squall's approach was heralded first by a few minutes of fairly smooth sinking motion followed by slowly increasing upward flow. Fairly strong downward flow was associated with the squall itself but the flow then became organised into periods of upward and downward motion several minutes long, though with an overall mean downward component. The large fluctuations of temperature and specific humidity demonstrate that the air behind the squall was very poorly mixed at first. The erratic vertical motion suggested that the local mass flux associated with the precipitation downdraught was too large to be compensated by the general divergence and so vigorous cool updraughts as well as downdraughts occurred. Mixing appeared to continue for a time after the layer between 96 and 280m had become strongly stable. These data confirm reasonably well the classical picture of the line squall maintaining itself through wind shear and evaporative cooling. However it was not possible to confirm directly the level from which the dry air at 280m originated since the only radiosonde released locally on this occasion was at 1100Z and it ascended through the main rain area. Ascents in similar conditions on other occasions suggested a descent from above 1500m if there was insignificant mixing with air at lower levels.

Corresponding surface fluxes estimated by the bulk aerodynamic method are shown in Figure 13 (the transfer coefficients used in these and other calculations of surface fluxes in this paper are $C_E = 1.3 \times 10^{-3}$, $C_H = 2 \times 10^{-3}$ (Muller-Glewe and Hinzpeter 1975, Dunckel et al 1974)). An initial total heat flux of 150 Wm^{-2} increased to nearly double this value on the squall's passage and the Bowen ratio increased about five-fold to near 0.5. Thus the immediate effect of the squall on surface transfers was very large. The buoyancy flux in particular became about five times larger.

Assessment of the importance of the squall in the longer term required estimates of its lifetime and area of effect. The length of the line was of order 10Km and with a lifetime of at least 2 hours it crossed an area approaching 400 Km^2. Its effect on the mixed layer was to produce an average cooling of around 1.5 deg C up to about 300m, and a drying out of 2 gkg^{-1} over the same layer depth, equivalent to upward vertical fluxes of sensible and latent heat out of the layer of about 70 and 250 Wm^{-2} for a two-hour period. These fluxes were of course considerably larger than usually observed at the surface and so replenishment of heat and moisture in this layer would have required a period significantly longer than the probable lifetime of the squall.

Vertical flux profiles over 3 successive 1-hourly periods starting rather less than 3 hours before the squall's arrival showed some erratic variations with time (Figure 14). In the first hour there was a fairly strong convergence of both sensible and latent heat but the next hour showed a less rapid decrease with height in the latent heat flux. However there was then a strong downward flux of sensible heat at the highest level which was repeated in the third hour together then with a small <u>downward</u> flux of water vapour at the same height. The results from this final period were obtained during non-stationary conditions with large-scale turbulence: linear trends were removed from the parameters before calculating the fluxes, a sound practice usually, but here with a risk of filtering out contributions to the fluxes from very low-frequency fluctuations. These results may therefore be unrepresentative though it is apposite to note that Russian observations of vertical fluxes in disturbed conditions in GATE (Andreev et al 1975) also indicated negative transports of water vapour above a few hundred metres.

3.3 A SQUALL-LINE CONVECTIVE SYSTEM WITH LITTLE PRECIPITATION

The squall just described was observed shortly after its formation and the squall line and leading edge of the rain area were nearly coincident. However in a squall's later stages the downdraughts induced by precipitation are likely to spread further in front of the rain area, and ultimately the convergence and upward motion associated with the squall line will move too far ahead of the main cloud area to maintain it and so the system will decay (unless other forcing mechanisms such as large-scale convergence are present). By this time it may be

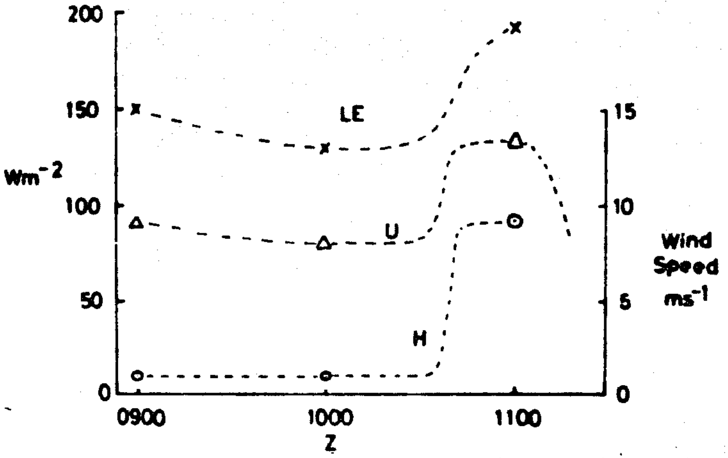

Figure 13 Surface fluxes and wind speed, 13 September 1974

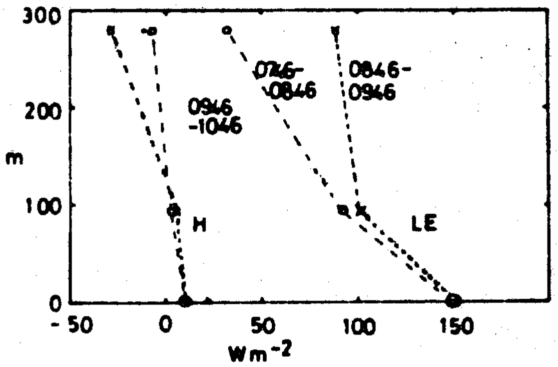

Figure 14 Eddy-flux profiles, 13 September 1974

difficult to identify the system visually for what it is especially in more disturbed conditions with layered cloud. What appears to be such a system was observed near the end of GATE in disturbed conditions while tethered-balloon observations were being made at heights of about 180 and 360m.

The squall arrived at about 1747Z. About 20 minutes before this time the turbulence decreased suddenly, particularly at the upper level, as dry and warm air spread in (Figure 15). Vertical motion was then predominantly downward apart from a significant updraught at both levels at around 1738Z. There was a marked positive correlation between vertical velocity and specific humidity, and negative correlation between vertical velocity and temperature, indicating strong upward flux of water vapour and downward flux of heat. Figure 16 shows a marked fall of temperature at 1747Z with magnitude increasing with decreasing height: the surface change was about 1.5 deg C. Temperature at the surface remained a degree or more lower than the original value for at least an hour but it increased at the upper level to close to the earlier value there after about 20 minutes. The specific humidities rose initially at all levels to about those before 1730Z but thereafter fell and remained relatively low for at least an hour. The dominant feature of the vertical motion was a 6-minute long updraught at both levels, beginning at 1745Z, which carried a positive flux of water vapour: the latter part of the updraught was associated with a strong downward flux of heat. Flow in the vicinity of the squall line was smoother and less erratic than for the one observed on 13 September and the environment at the upper level appeared to be much more uniformly mixed than in the earlier case, as demonstrated by the generally small temperature and humidity changes after about 1748Z. Probably the main difference between this squall and the one on 13 September was the almost complete lack of precipitation: the only rain was a few spots at 1800Z. On the other hand there were many similarities, for example the variation with height of the temperature fall, and a veer and increase of surface wind on the squall line which coincided with the arrival overhead of the leading edge of a roughly linear cloud structure. The change in the surface flow was equivalent to an outflow of about 5 ms^{-1} approximately perpendicular to the cloud line. The evidence in this case pointed to a decaying system which was still producing close coupling between the cloud and sub-cloud layers.

The surface fluxes (Figure 17) showed clearly the effects of this convective system. The drier and slightly warmer air ahead of the squall penetrated right down to the surface and this was the main reason for the sharp increase in the flux of latent heat. The sensible heat flux and Bowen ratio roughly doubled when the squall arrived.

Eddy-flux profiles over three successive 1-hour periods starting about 2 hours before the squall's arrival showed a progressive decrease of convergence of water vapour flux with time (Figure 18). The behaviour of the sensible heat flux was more erratic but overall there was a sharp increase in the convergence which more than doubled over the whole period: over the third hour the convergence was equivalent to a mean heating rate of about 0.5 deg C per hour over the 360m layer.

The outcome of the passage of this convective system was the production, at least locally, of highly suppressed conditions in much of what was previously the mixed layer, with a very shallow unstable layer near the surface similar to that described earlier (§ 2.3). At 360m (Figure 19) the temperature and specific humidity were both a little lower than in the area outside the squall's influence, and the small size of the turbulent fluctuations showed that the boundary layer top was below this height. The temperature and humidity at 180m were much lower than their earlier values, and the very large fluctuations indicated that these observations were near the top of the mixed layer.

4. CONCLUDING REMARKS

Some comments on the relevance of these and similar results to parameterization of sub-grid scale processes are appropriate. Two obvious distinct problems here are first the estimation of the surface fluxes and second the redistribution

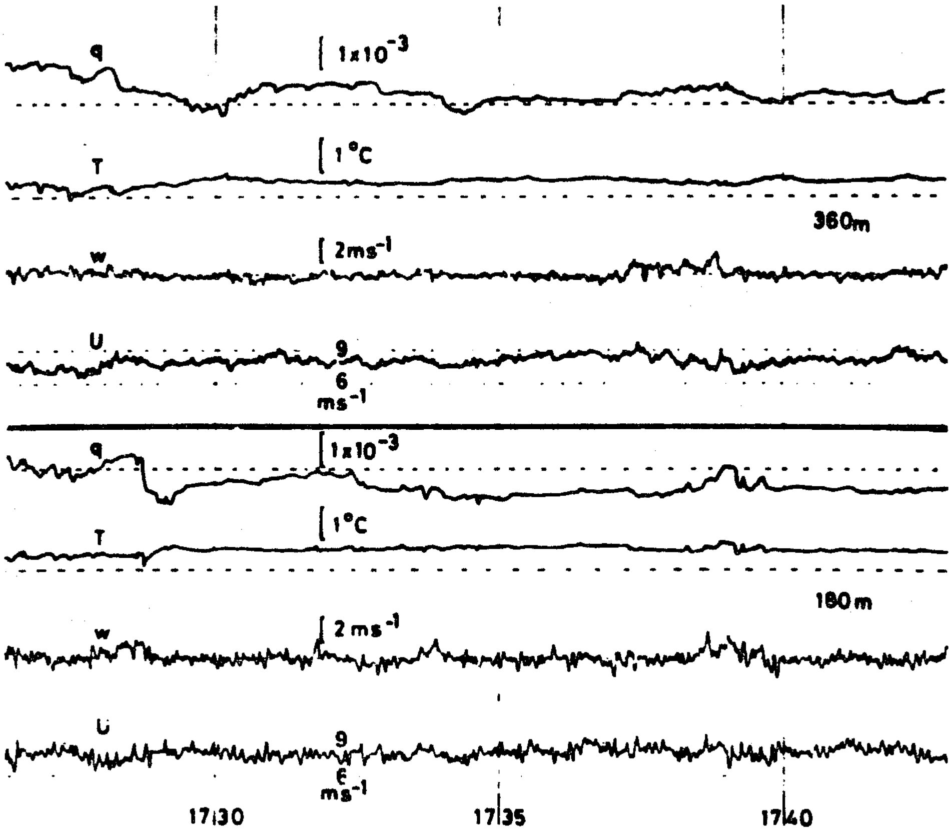

Figure 15 Tethered balloon observations before arrival of squall, 16 September 1974

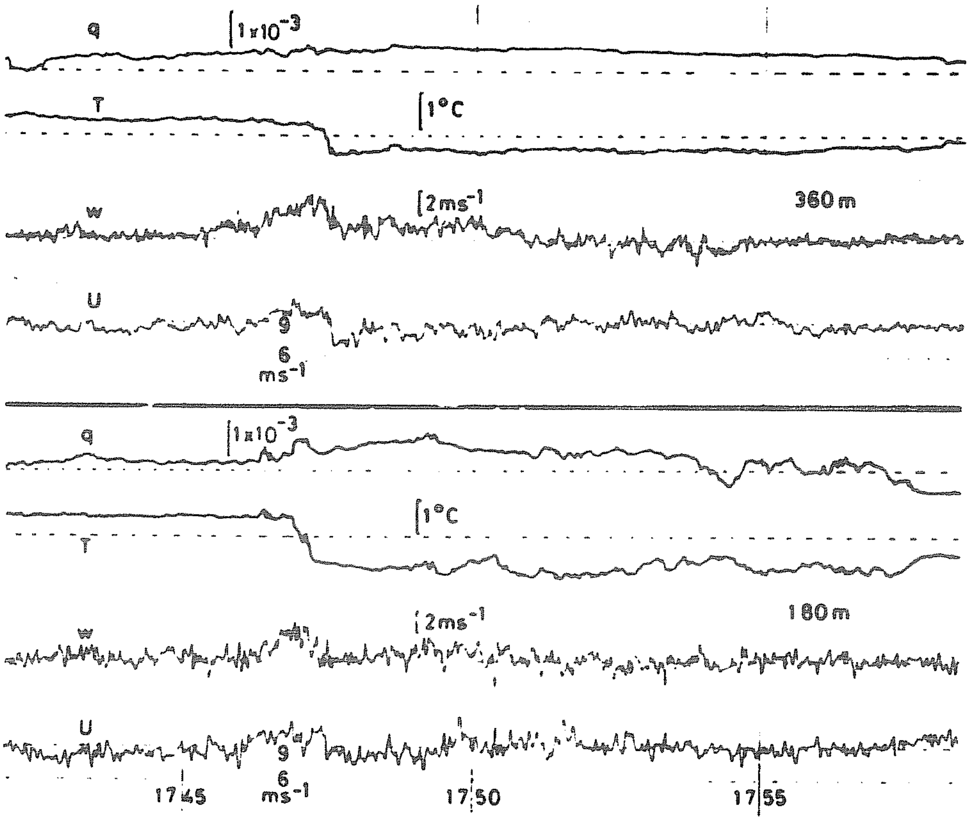

Figure 16 Tethered balloon observations during squall's passage, 16 September 1974

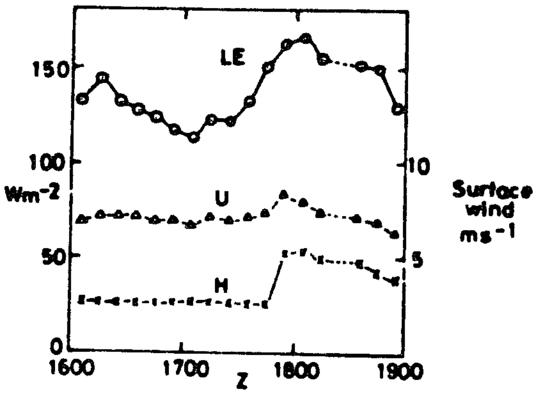

Figure 17
Surface fluxes and wind speed, 16 September 1974

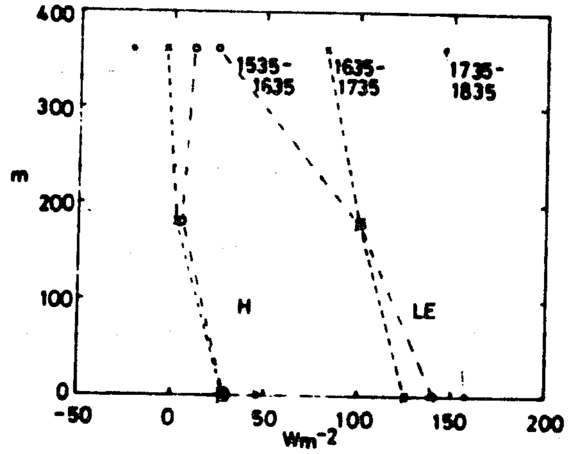

Figure 18
Eddy-flux profiles, 16 September 1974

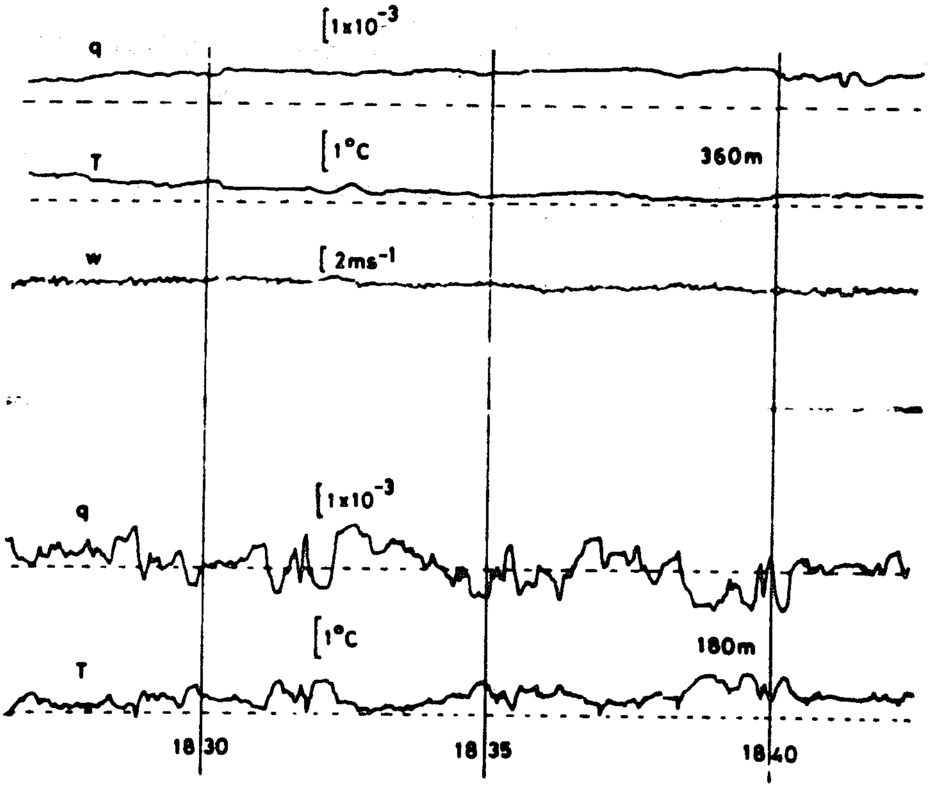

Figure 19 The shallow boundary layer after the squall's passage, 16 September 1974

of sensible and latent heat to higher levels. In the case of the surface fluxes the GATE studies have already shown that they may be estimated with satisfactory accuracy by the bulk aerodynamic method: the problem then is the estimation of the surface wind speed and the sea-air differences of temperature and specific humidity and their responses to changes in the large scale flow and degree of convection. In relatively undisturbed conditions with insignificant precipitation the thermodynamic properties are likely to be predictable with sufficient accuracy using simple 2 or even 1-layer models of the boundary layer with variable divergence imparted by the large-scale flow. The difficulties are clearly very large in disturbed conditions but as an elementary first step it may be profitable to seek at least empirical relationships between the observed increases in the sea-air differences and the large-scale convergence: however the area over which the boundary layer is modified by precipitation downdraughts must be predicted. With the wealth of data obtained during GATE there is no difficulty in exploring empirical approaches of this kind, which would also include investigation of the corresponding variations of the surface wind field.

The second problem (the vertical redistribution of sensible and latent heat) appears formidable in disturbed conditions. In undisturbed conditions the redistribution may be unimportant (except as a feedback process controlling the surface fluxes) since the layer over which the heat and water vapour can diffuse upwards is shallow. However with deep convection it looks at present as if it will be difficult to set up physical models which will represent adequately the convective systems actually observed, in particular their very variable cloud bases and sometimes their complete detachment from the boundary layer. Again a useful initial approach may be to derive empirical relations between the vertical distribution of large scale convergence and the net moistening and heating. The fact that the large-scale convective systems modify the large-scale divergence during their lifetime need not be a difficulty if initial fields of divergence are shown to be suitably correlated with subsequent convective development.

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