Eddy-fluxes and spectra in the GATE sub-cloud layer

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SUMMARY

An investigation of the structure of the GATE sub-cloud layer carried out using turbulence sensors attached to a tethered balloon cable is described. The observations were made at one or two levels up to 400 m near the centre of the C-scale ship array during the final phase of the experiment. The data were used to derive the vertical eddy fluxes of momentum, sensible and latent heat and the spectra and cospectra of the turbulence parameters, all over one-hour long periods. Surface fluxes were estimated using the bulk aerodynamic formulae.

The results were classified according to the convective activity prevailing during each one-hour period. Marked changes in the vertical flux profiles with increasing convective activity are demonstrated. Spectra and cospectra in conditions of suppressed convection (small cumulus clouds only, no showers) show the increasing importance of larger scale mixing processes as heights increase to about 300 m, but above this (near the top of the mixed layer) processes on a smaller scale are found to predominate. On these latter scales there is an upward flux of momentum which is a consequence of rather shallow vertical mixing in a region where wind speed decreases with height: in more disturbed conditions deeper convection, coupled with the reversed vertical gradient of wind, causes an upward momentum transfer on larger scales.

1. INTRODUCTION

The central area of the GATE experiment lay in a region of the tropics in which large convective cloud systems ('cloud clusters') developed frequently and where the synoptic variability was large. The convective activity was modulated strongly by the field of divergence associated with easterly waves passing over the area at two- or three-day intervals. The corresponding changes in the boundary layer structure were often substantial and rapid. Major transformations of the boundary layer occurred over large areas during disturbed periods with persistent rain. However, even quite small convective features such as small squall lines developing within an hour or so were able to produce considerable exchanges of air between the boundary layer and the dry and potentially warmer layers above, affecting areas of tens of square kilometres (Thompson 1976a). In the undisturbed periods the thermodynamic structure of the boundary layer often resembled closely that for the undisturbed Trades such as the South Easterlies discussed by Augstein (1972). For this reason it is often convenient in this paper to describe the region below cloud base in the conventional terms of a well-mixed layer capped by a transition layer formed by compensating sinking motion between clouds.

Changes in the structure of the sub-cloud layer associated with the major cycles of convective activity were demonstrated clearly by surface observations of temperature and specific humidity from within the central area (Fig. 1); these showed a progressive increase of both quantities to maximum values, followed by much sharper decreases at the onset of periods of prolonged precipitation. Sea–air temperature differences were close to zero at these maxima and the vertical flux of water vapour then made the major contribution to the buoyancy flux right down to the surface. After the disturbed periods the Bowen ratio was substantially larger and the sensible heat flux carried most of the buoyancy flux near the

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surface. Significant differences in the structure of the boundary layer are expected to be found, therefore, when comparing data at the beginning and ends of disturbed periods: examples have been given by Echternacht and Garstang (1976) for BOMEX and by Thompson (1976b) for GATE.

There have been numerous studies of the mean properties of tropical sub-cloud layers using budgeting techniques to deduce, for example, variations with height of the vertical

![Figure 1. Surface data at 0847N 2305W during the first half of GATE phase III. (a) 1-hourly values of air temperature and specific humidity at 10 m height. (b) Duration of precipitation (short arrows indicate brief showers). (c) Estimated surface fluxes of latent heat, and the Bowen ratio. (Arrows under the abscissa axis indicate approximate times of passage of troughs in the easterly waves.)](image)

fluxes of heat and moisture (e.g. Augstein 1972, Holland and Rasmusson 1973, Esbensen 1975, Betts 1975). These studies suggest that with suppressed convection the vertical flux of water vapour decreases only slowly with height in the mixed layer and this has been confirmed by some direct measurements by aircraft (Bean et al. 1972, Donelan and Miyake 1973). However, Le Mone and Pennell (1976) found that the flux fell to near zero at the top of the mixed layer on an occasion of suppressed convection with small cumulus. They deduced from this that 'suppressed conditions' in the budget studies embraced a range of convection which included some larger clouds interacting strongly with the sub-cloud layer to produce substantial area-averaged fluxes in the upper mixed layer. Grossman (1975) gave some preliminary results from aircraft measurements in undisturbed conditions during GATE which showed water vapour fluxes at the top of the mixed layer about one-half of those at the surface; similar results were obtained in cloudless conditions in GATE by Andreev et al. (1975), using a tethered balloon technique.

In undisturbed conditions the turbulence through most of the mixed layer is maintained
by the vertical flux of water vapour; air entrained across the sub-adiabatic region above maintains a significant downward flux of sensible heat. The region of upward heat flux is confined then to near the surface. In disturbed conditions this upward heat flux is substantially larger (Fig. 1) and provides a correspondingly greater contribution to the turbulence production in the mixed layer. However, downdraughts induced by precipitation may then produce locally large upward fluxes of heat right through the mixed layer and transition layer and in these circumstances the horizontal structure of the sub-cloud layer becomes so inhomogeneous that to describe it in purely statistical terms may be misleading as well as unprofitable (Thompson 1976a).

Observations of boundary-layer structure which were made during GATE were very comprehensive and it is hoped that when finally analysed they will increase greatly our knowledge of the properties of moist convective boundary layers as well as resolving apparent inconsistencies between the results of earlier investigations. The present paper will describe some of these observations, made in the sub-cloud layer using a tethered balloon technique. The data will be used to deduce some details of eddy flux profiles and spectra and cospectra in suppressed or only slightly enhanced convection. Direct observations of interactions between individual cumulus clouds and the sub-cloud layer will be presented in a further paper.

2. INSTRUMENTATION

The observations used in this study were made from the naval survey vessel HMS *Hecla*. A tethered-balloon system based on that described by Thompson (1972) was flown from the stern of the ship. Sensors measuring magnitude of the wind vector (a cup anemometer), inclination of wind to the horizontal (hot-wire inclinometer), and dry- and wet-bulb temperatures (fine platinum wires, cotton-covered in the latter case) were mounted on a light vane pivoted about the steel balloon cable. Time constants of the sensors in a wind of 5 m s⁻¹ were respectively 0.25, 0.0035, 0.015 and 2 s. The outputs were led to signal-conditioning circuits in a box mounted on the cable about 1 m below the vane and then transmitted to the ship as an audio-frequency multiplex which was recorded on magnetic tape. Previous experience had shown that the wave-induced motion of the ship produced large spurious contributions to the measured velocities. The displacement of the tethering point of the balloon cable on the ship was mainly in the vertical, causing an alternate tightening and relaxing of the cable catenary. The corresponding motion of sensors attached to the cable had both horizontal and vertical components which affected directly the measured wind speed and inclination of airflow. The inclination data were affected also by the periodic accelerations in the horizontal, which displaced from the vertical the pendulum on which the inclinometer was mounted. An attempt was made to reduce the magnitude of the undesirable effects by introducing a cable accumulator between the balloon winch and tether point of the cable. The accumulator consisted of groups of fixed and moveable pulleys round which the cable was passed and whose separation was varied by the displacement of a hydraulic ram. The ram's movement was controlled by integrated signals from accelerometers mounted on the ship near the cable's tethering point, thus adjusting the amount of cable paid out in response to heave and roll of the ship.

The ship took up a position close to an anchored buoy which carried sensors measuring wind speed and direction, wet and dry bulb temperature, sea temperature and atmospheric pressure; sensor outputs were logged at 10 or 15 minute intervals on an internal digital recorder. Instruments on the ship included sensors for the routine measurement of wind speed and direction, sea temperature and pressure, an aspirated psychrometer, all-sky camera and radar wind-finding system.
3. Data

*Hecla* was positioned at 08°47′N 23°05′W (near the centre of the GATE C-scale ship array) during most of the final phase of the experiment and the tethered balloon system was flown on most days during the period from 30 August to 19 September 1974. The data which were obtained were biased by the inability of the system to function satisfactorily in prolonged or heavy rain, or in very light winds, and also by restrictions on its operation when the GATE research aircraft were flying in the C-array. In all, some 200 hours of data were obtained at 1 or 2 levels up to heights of 400 m; about half were of satisfactory quality for the present investigation.

The data were divided into consecutive periods an hour long after digitizing at 10 Hz, and the instantaneous horizontal and vertical wind speeds were calculated following an axis rotation which made the mean vertical speed equal to zero for each period. Differences between *Hecla*’s actual position and that deduced by dead reckoning from the measured speed through the water were used to calculate the near-surface current velocity in the buoy’s vicinity: the average value was 0.5 m s⁻¹ towards 070° deg. Horizontal wind speeds measured by the tethered balloon system were corrected for this current and for the ship’s measured speed and heading on the assumption of insignificant wind direction changes between the surface and the heights of the balloon-borne sensors. Eddy fluxes of momentum (τ), sensible heat (H), water vapour (E) and latent heat (λE) were calculated after removal of linear trends in the data. Spectra and cospectra were deduced using the Fast Fourier Transform (Rayment 1970) from data lengths about 55 minutes long which were selected to correspond approximately to the periods used in the flux calculations.

Surface eddy fluxes of momentum, sensible and latent heat (τ₀, H₀, λE₀) were estimated from the ship and buoy data using the conventional bulk formulae

\[ \tau_0 = -\rho C_D U_c^2 \]  
\[ H_0 = \rho c_p C_H (T_0 - T_{w}) U_c \]  
\[ \lambda E_0 = \lambda \rho C_E (q_0 - q_{w}) U_c \]

(1)  
(2)  
(3)

ρ is the air density, \( c_p \) the specific heat, \( T_0 \) and \( q_0 \) the sea temperature and the saturation specific humidity over sea water at this temperature, \( T_{w} \) and \( q_{w} \) the temperature and specific humidity at 10 m, and \( \lambda \) the latent heat of vaporization; \( U_c \) is the wind speed at 10 m relative to the sea surface, obtained by correcting the 10 m wind vector for the mean current of 0.5 m s⁻¹ and then reducing the result by 4% to allow for the surface drift produced by the wind (Keulegan 1951). \( C_D, C_H \) and \( C_E \) are the bulk transfer coefficients for the eddy fluxes of momentum, heat and water vapour. The most appropriate values for the transfer coefficients remain a matter for conjecture. Values of 1.4 × 10⁻³ were obtained for \( C_D \) and \( C_E \) from ‘Meteor’ buoy data during GATE (Hasse et al. 1978) and have been used here. They include a correction for the average instability observed during the experiment. Values close to these were also obtained over the tropical Atlantic by Pond et al. (1971), Dunckel et al. (1974) and Muller-Glew and Hinzpeter (1975). Hasse’s value for \( C_H \) of 1.6 × 10⁻³ has also been used here but this is less well established and some other investigators have obtained values closer to 2 × 10⁻³ in the tropics (e.g. Dunckel et al. 1974).

The buoy’s wet-bulb and sea temperature circuits failed soon after launch and it was necessary therefore to use ship’s data for humidities and sea temperatures. Additionally, the shipboard observations, which were made for most of the time at only hourly intervals, had to be used exclusively for about one-third of the periods because of buoy malfunctions. Buoy observations were made at 2 m above the surface. The ship’s anemometer was at 18 m and its psychrometer at 10 m. Observations used in Eqs. (1)–(3) were corrected where
necessary to a height of 10 m by a method similar to that described by Thompson (1972).

The calculated surface fluxes were used to derive estimates for the Bowen ratio $B (= H/\lambda E)$ and the virtual heat flux

$$H_v \approx H(1+0.075/B)$$

(4)

Other data used in the investigation were extracted from all-sky photographs taken at two-minute intervals during daylight hours, and from occasional radiosonde and wind-finding ascents from the ship.

4. **Convection classification**

The scheme used to classify the state of convection during the GATE experiment at any particular point in the experimental array has been described in detail by Garstang and Aspliden (1974) and was found to be a very useful one for many purposes. However, the scheme was less useful as an indicator of the convective state of the boundary layer since it was intended to be applied to convection occurring up to any height in the troposphere. In particular it sometimes gave a misleading picture of the boundary layer structure in very disturbed conditions where horizontal variations at lower levels were very large, and where at times the main convection no longer had its roots in the boundary layer, being driven presumably by moisture advected in by large-scale convergence rather than extracted from surface layers underneath the cloud mass (Simpson 1976). In the present study the state of the boundary layer during the periods over which the fluxes and spectra were calculated has been classified as shown in Table 1. This differs from Garstang and Aspliden's scheme

<table>
<thead>
<tr>
<th>Code number</th>
<th>Corresponding GATE code</th>
<th>Description of convection and boundary layer structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Highly suppressed with little or no cu</td>
</tr>
<tr>
<td>2</td>
<td>1-2</td>
<td>Suppressed, small cu, no showers</td>
</tr>
<tr>
<td>3</td>
<td>2-3</td>
<td>Mainly small cu, some showers</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Moderate showers, line squalls, some layered cloud</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Heavy rain, much layered cloud</td>
</tr>
<tr>
<td>6</td>
<td>—</td>
<td>Often much layered cloud, occasionally with rain or showers nearby – mixed layer cool, dry and shallow with strong capping inversion</td>
</tr>
</tbody>
</table>

chiefly through the addition of a sixth category which refers to a very shallow, cool and dry boundary layer produced by outflows near large convective systems (Thompson 1976b, Augstein and Garstang 1977). The revised scheme has been applied *post facto* using all available data, particularly the all-sky photographs, but the classification of the night-time periods in the absence of the latter was often difficult to decide with any certainty.

5. **Results and discussion**

(a) **Effects of sensor motion**

Thompson (1972), using a tethered balloon system without a device to reduce the sensor motion caused by heave and roll of the ship, found that the horizontal and vertical spectra were contaminated by noise peaks about two orders of magnitude larger than the spectral values associated with true wind fluctuations. Much of the noise was the result of
quasi-horizontal motion of the sensors caused by alternate tightening and slackening of the balloon cable, with consequent oscillating tilts of the pendulum supporting the inclinometer. Noise contributions to the temperature and humidity spectra were much smaller because they were produced by relatively small vertical displacements in an atmosphere with only small vertical gradients. The effectiveness of the cable accumulator used in GATE may be judged from Fig. 2 in which are plotted spectra, and the cospectrum of momentum flux, measured during a run in which sensors were suspended near the midpoint of the balloon cable. A vertical velocity spectrum from Thompson (1972) is plotted for comparison; this also was measured near the midpoint of the cable, on an occasion with similar windspeed (6–8 m s$^{-1}$). The GATE $w$-spectrum shows about an order of magnitude less noise than the spectrum obtained using the unstabilized system. Spectra of temperature and humidity (and cospectra of heat and water vapour flux) include no recognizable contributions from sensor motion, but measured momentum fluxes are clearly affected, although by an order of magnitude less than those discussed by Thompson (1972). Simple procedures used to smooth out noise in the $U$ and $w$ spectra, and the $Uw$ cospectra are described below.

Figure 2. Spectra, and the cospectrum of momentum flux, measured at a height of 180 m, 1535–1630 GMT, 16 September 1974.
GATE EDDY-FLUXES AND SPECTRA

(b) Vertical flux profiles of latent, sensible and virtual heat

Eddy fluxes calculated from the tethered balloon data were normalized by surface fluxes estimated from buoy and ship data using Eqs. (1), (2) and (3), and plotted against height in Fig. 3 after sub-division into the four convection categories shown in Table 2.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Number of data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>Highly suppressed, small cu</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>Suppressed, some larger cu, no showers</td>
<td>43</td>
</tr>
<tr>
<td>2-3</td>
<td>Slightly enhanced, some showers</td>
<td>24</td>
</tr>
<tr>
<td>6</td>
<td>Highly suppressed, associated with more disturbed conditions</td>
<td>18</td>
</tr>
</tbody>
</table>

Eight sets of data from code 4 cases were analysed but have not been included in Fig. 3 because their large scatter, coupled with the small number of data, obscured any systematic variations of fluxes with height. No usable results were obtained in code 5 conditions.

The circled points in the diagram represent layer-averages of the fluxes in 100 m thick slabs; they are placed at the average height of the observations in each layer. Sensible and virtual heat flux profiles were not plotted on those occasions when the estimated surface sensible heat flux was small (less than 3 W m⁻²).

Considering first the latent heat fluxes, in the most suppressed case (code 6) they showed the rapid decrease with increasing height which is expected in very shallow boundary layers. Observations obtained in convection class 1-2, and class 2 showed considerable scatter but profiles of the layer-averages were very similar and suggested that at the top of the mixed layer (typically 400–500 m height) the fluxes decreased to about one-half the surface value. This is consistent with most other data from suppressed boundary layers (section 1) and in marked contrast to the results of Le Mone and Pennell (1976) where the flux was found to be near zero at the top of the mixed layer. The latter data were obtained on five crosswind flights over legs of about 20 km, occupying about 30 minutes in all, so effects of non-stationarity or sampling variations would be expected to be small. However, the vertical flux profile they measured had a pronounced maximum at about 200 m height and in the absence of any confirmatory data must be considered anomalous. The scatter in the data in the present study, particularly noticeable at the upper levels, was partly the result of statistical variations caused by the relatively short sampling period; for example, individual cumulus clouds were able to produce fluxes as high as 5000 W m⁻² in the upper part of the mixed layer, sustained for several minutes while passing over the measuring system (Thompson 1976b), and giving 1-hour average fluxes sometimes larger than the surface values. Scatter was also the result of including data from occasions with negligible cloud where insignificant transfers occurred above the mixed layer and the flux was near zero at heights near 400 m. The number of data in the more disturbed conditions (code 2–3) was too small to provide a definitive flux profile, but the results are consistent with a negligible variation of flux with height. Data from VIMHEX-2 (Betts 1976) showed that in the case of vigorous convection over land the latent heat flux may increase with increasing height, and the present data suggest that with increasing convective activity an approach to this situation may also occur over the sea. In general, extrapolation of the tethered balloon fluxes down to the surface confirms that the value of 1.4 × 10⁻³ which was selected for the transfer coefficient in the bulk aerodynamic formulation of the surfaces flux is a satisfactory one on average.
The vertical flux of sensible heat in the highly suppressed (code 6) conditions on average decreased rapidly with height to a value near zero at and above 100 m. With more vigorous convection the flux became zero at a similar height on average, but continued to
decrease above, with the largest downward fluxes occurring in the two least-suppressed convection categories. The region of the downward flux is the result of the turbulent entrainment of sensible heat out of the transition layer, with the positive buoyancy required for this process supplied by the upward flux of water vapour. An analogous situation is observed over land (Betts 1976) but the Bowen ratio is then much larger and the major contribution to the buoyancy flux comes from the flux of sensible heat which changes sign, therefore, much nearer the top of the mixed layer than it does over the sea. An anomaly in the present data is that extrapolations of the mean profiles to the surface (excluding code 6 cases) appear to indicate that the surface fluxes have been substantially overestimated. However, the scatter in the plotted points is very large and it is possible therefore that the apparent overestimation results from the use of relatively small number of estimates in deriving the layer averages. It is perhaps relevant to note that Wucknitz (1976) showed from cospectral analysis of surface eddy flux data obtained during the Atlantic Trade Wind Experiment that only part of the heat flux could be parametrized in terms of $U_e(T_0-T_{10})$ and that above a certain frequency the contribution to the flux was largely independent of this product. Also for most of GATE the sea-air temperature difference was less than 1 K and in these circumstances the use of a bulk water temperature rather than the usually lower skin temperature of the sea surface could lead to some overestimation of the flux.

Average virtual heat fluxes in convection categories 1–2, and 2 decreased to zero in the upper part of the mixed layer, with small negative values above. This agrees with profiles deduced for a dry, inversion-capped boundary layer (Cattle and Weston 1975), and in mixed layers beneath cumulus clouds over land (Betts 1976) where the flux was found to change sign at about three-quarters of the height of the mixed layer, with maximum downward fluxes around one-quarter of the surface values. This value cannot be confirmed exactly by the present data because of the scatter, the uncertainty in the surface flux of sensible heat and the variations in height of the mixed layer, but such a value is certainly not inconsistent with the tethered balloon data. The average profile for more disturbed conditions (code 2–3) shows a substantially more rapid decrease of flux with increasing height but is biased strongly by four points lying well outside the range of the remaining observations. Eliminating these most scattered points leads to a mean profile similar to those found for the lower convection categories. The figure also shows that in undisturbed conditions the virtual heat or buoyancy flux changes sign at heights between 250 and 300 m on average. Results from an acoustic sounder used aboard Oceanographer during GATE showed the presence of buoyant plumes which became undistinguishable from the environment at a mean height of about 325 m (Gaynor 1977), confirming the present results in showing only a small buoyancy flux at around this height.

(c) Momentum fluxes

Figure 2 demonstrates that substantial noise due to sensor motion is present in the cospectra of the momentum fluxes at frequencies above about 0.05 Hz. The fluxes plotted in Fig. 3 were obtained by integrating the cospectra up to 0.04 Hz and some estimate is required, therefore, of the likely percentage contribution to the flux from higher frequencies. The cut-off frequency of the integration corresponds to a reduced frequency ($f = nz/u$) of 0.7 in typical winds of 5 m s$^{-1}$ at a lower measurement height of about 100 m. Cospectra from the surface layer over the sea (e.g. Pond et al. 1971, Leavitt 1975) suggest that the resulting loss of covariance is around 7%, decreasing at greater heights. Strictly, the surface-layer universal cospectra cannot be used at heights of more than a few tens of metres since it is well known that the reduced-frequency scaling of both spectra and cospectra breaks down as height above the surface increases, with the cospectral peak moving to higher
reduced frequencies (e.g. Bean et al. 1972). On this basis the actual loss of covariance will be larger than just estimated. On the other hand it will be shown that the shapes of cospectra deduced from data obtained above the surface layer differ significantly from those measured near the surface, with the major contribution often appearing at low frequencies, the results of cumulus-scale turbulence. This lessens the importance of the higher-frequency contributions but at the same time makes it impossible to use surface-layer data to provide an accurate correction. It will be assumed that the average loss of covariance introduced by the high frequency cut-off is negligible through most of the mixed layer, and even at heights as low as 100 m is unlikely to exceed about 10%, except perhaps in code 2 conditions where the average wind speed at this height was near 8 ms\(^{-1}\). Here the corresponding reduced cut-off frequency was 0.5 for which the surface-layer data of Pond et al. and Leavitt suggest a loss of covariance of around 11%. Because of the stronger wind and hence larger surface exchanges it is more likely that the general shape of the surface-layer spectrum will be preserved in this case in the lower mixed layer. Using the data of Bean et al. (1972) on the increase with height of the reduced frequency of the cospectral peak leads to an upper limit for the reduction in covariance of about 17% at 100 m.

Normalized fluxes in convection categories 1–2, and 2, showed very large scatter but the mean profiles were very similar, with a near-linear decrease to zero at heights between 300 and 400 m. Individual observations departing most from the average were associated usually with light winds. In the case of code 1–2 for example, six of the seven most scattered points were from occasions with the surface wind between 2.0 and 3.2 m s\(^{-1}\). The four occasions with lightest winds in code 2 conditions produced three of the four most scattered points. A probable cause of the observed negative normalized fluxes, apart from sampling variations associated with the use of rather short data lengths, was convective coupling between the cloud and sub-cloud layers. The typical surface flow was from the southwest and this was overlain usually by northeasterlies which extended down to heights below 2000 m at times. The corresponding maximum in the near-surface flow was often observed below cloud base and in these circumstances momentum exchange between cloud and sub-cloud layers would occasionally produce negative normalized fluxes, particularly in the upper part of the mixed layer and during more vigorous convection. This is confirmed by the present results in code 2–3 conditions which show on average a flux reversal above about 200 m, although it was not possible here to derive a reliable average flux profile because of the very large scatter and the relatively small number of observations.

The average flux profiles in code 1–2, and code 2 conditions are in reasonable agreement with results obtained in a suppressed Trade Wind boundary layer by Le Mone and Pennell (1976). There the winds in the mixed layer were around 15 m s\(^{-1}\) with a significant maximum below 300 m, but although the speeds decreased somewhat above they were still about 12 m s\(^{-1}\) at a height of 2000 m. Thus the relative decrease with height was much less than was often observed in the present case and this may be the reason the fluxes observed by Le Mone and Pennell near the top of the mixed layer although small were all positive.

In code 6 conditions most of the fluxes measured at heights above 100 m were scattered about zero. A few relatively large positive values measured below 200 m produced a mean flux profile decreasing to zero between 200–300 m, consistent with the mixed layer depth being substantially less than in more convective conditions.

(d) Spectra and cospectra

These, like the fluxes, were classified into convection categories according to the scheme given in section 5(b). A further grouping was then made according to the height of measurement into height bands 100 m thick centred at 100, 200, 300 and 400 m. Six spectra
or cospectra for each height band and convection category were then selected for further analysis: the selections were made to secure reasonably homogeneous sets, choosing, whenever possible, data segments obtained simultaneously at two measurement heights.

Most spectra showed some contamination by noise at frequencies above about 0.25 Hz, and in the case of the horizontal and vertical wind spectra the ship-induced motions of the balloon cable introduced considerable additional variance between about 0.04 Hz and 0.25 Hz; data from these suspect regions were rejected. Remaining data from the six segments in each convection category and height band were then combined after reduction to a common wavenumber scale and normalization of the spectral estimates. The conversion of frequency to wavenumber involved dividing the frequency of each estimate by the mean horizontal wind speed for the segment. The spectral estimates for temperature and humidity were normalized by the variances derived from the spectra. Speed spectra were treated in the same way except that their variances had to be corrected for the severe contamination introduced by ship motion. This was done by integrating numerically the spectra up to 0.04 Hz and estimating the contributions from higher frequencies by assuming that these lay within the inertial subrange beginning at 0.04 Hz. Cospectral estimates were normalized by the surface fluxes. Finally the six sets of estimates for each convection code and height category were divided into wavenumber classes of equal width on a logarithmic scale,

Figure 4. Log-log plots of wind spectra: vertical bars show the standard deviation of the individual spectral values used to derive the plotted values.
namely, \( \log_{10}(n_{i+1}/n_i) = 0.2 \), and averaged: the means, which were averages of between six and twelve of the original estimates were plotted at the logarithmic centres of their classes. The resulting spectra and cospectra are shown in Figs. 4 and 5. Care was taken to select data sets which were obtained under nearly identical conditions but it was impossible to avoid some heterogeneity; for example, the indicated height of measurement is only a nominal figure with the averaged spectra containing data from measurements up to 50 m from the height shown.

Horizontal wind speed spectra showed a fairly general increase in relative energy at low wavenumbers as height above the surface increased. The spectra of vertical velocity included some more systematic variations. In the two least suppressed cases the main spectral peak moved to progressively lower wavenumbers with increasing height. However, at the 400 m level there was also substantial energy at relatively high wavenumbers and in the more suppressed code 1–2 case vertical mixing at these wavenumbers predominated. The results reflect the increasing importance of coupling between the mixed layer and the air above as convection increases.

Humidity spectra were very similar in all cases, with a main peak between \( 10^{-3} \) and \( 10^{-4} \) m\(^{-1} \) and a fairly steady decrease of energy at higher wavenumbers; they have not been plotted. Temperature spectra (not plotted) showed a nearly identical behaviour but in some cases included a secondary peak at around \( 2 \times 10^{-2} \) m\(^{-1} \), almost certainly caused by sensor motion. The results from the two lower levels (100 and 200 m) show that at least over this height range a significant part of the variance of both humidity and temperature fluctuations is 'passive' in the sense of occurring outside the wavenumber range containing most of the vertical velocity fluctuations.

The cospectra of momentum flux (Fig. 5) showed at the lowest levels a downward transfer of momentum at all wavenumbers and in all conditions except code 6. At the upper levels the flux reversed sign over a wavenumber range of about a decade centred near \( 2 \times 10^{-3} \) m\(^{-1} \), and was slightly positive also at lower wavenumbers in the most convective case. A general explanation for this behaviour follows from the shape of the vertical profile of wind discussed in section 5(c). Air in the mixed layer moved from the southwest usually, rather like a slab because of the vigorous convective mixing within it. Convective coupling between this slab and the overlying flow (northeasterly above 2 km or so) was probably intermittent enough to allow a velocity discontinuity to exist in the transition layer for much of the time; this could not be confirmed by the radar wind-finding data because of their limited vertical resolution but was found by Le Mone and Pennell (1976) in measurements on a suppressed Trade Wind boundary layer. In these circumstances vertical mixing across the interface on a relatively small scale would produce an upward flux of momentum in the upper part of the mixed layer. The peaks within the wavenumber range \( 10^{-2} \) to \( 10^{-1} \) m\(^{-1} \) for the vertical spectra indicate that mixing was certainly occurring on this scale. In the more disturbed conditions (code 2–3) the deeper mixing coupled the mixed layer occasionally with the region of reversed flow (sometimes as low as 1500 m) leading to upward momentum transfer on most scales in the upper mixed layer. In the most disturbed conditions (code 4 or 5) deep convection was capable of exchanging air from the surface layers with that at heights in excess of two or three kilometres and then an upward transfer of momentum would have been observed through much of the mixed layer. An upward flux was observed over part of the wavenumber range of the code 6 cospectrum at 100 m. In view of the shallow mixed layer this is consistent with a similar behaviour at greater heights observed in the less suppressed cases.

The \( qw \) cospectrum for code 1–2 conditions showed the expected migration of the main peak to lower frequencies at heights up to 300 m, but at 400 m most of the transport occurred at relatively high frequencies. Any explanation of this point must take into
Figure 5. Cospectra: the ordinate scales are linear.
account the fact that data at 300 m and 400 m were not homogeneous, in no case being obtained simultaneously at both heights. In spite of this, the difference in cospectra at the two heights was probably real and reflects the importance of the smaller scale vertical mixing across the sharp hydrolapse within the transition layer. In slightly more disturbed (code 2) conditions the cospectral variations with height were rather smaller, with evidence for larger-scale mixing penetrating to the lowest heights of measurement, and with a reduced significance for smaller scale mixing at the upper level. Data in the most disturbed cases (code 2–3) were very heterogeneous, but the highest level showed the expected dominance of larger scale convection.

The $Tw$ cospectra demonstrated in most cases at low wavenumbers an increasing downward flux with increasing height in the mixed layer, indicating the redistribution of sensible heat entrained at the top of the mixed layer. There were also anomalous upward fluxes in most cases at the upper levels, at wavenumbers above about $2 \times 10^{-3}$ m$^{-1}$. These were associated at least in part with ‘cold spikes’ (Phelps and Pond 1971) which were often observed at the beginning of major downdraughts of dry air. The spikes occurred as a rapid fall of temperature sometimes as large as 1 K in less than 1 s, followed by a more gradual rise to a value appropriate to downward mixing in a sub-adiabatic layer. An upward heat flux occurred during the period when the spike temperature was below the ambient value. Various explanations for the spikes have been advanced. It appears most likely that they were an instrumental effect caused by evaporation from a hygroscopic (salt) layer which, near the sea surface at least, appears to contaminate initially clean temperature sensors within periods of a few tens of minutes.

6. Concluding remarks

The results from this investigation have demonstrated clearly the value of the tethered-balloon techniques in the study of turbulence structure in the atmospheric boundary layer over the sea. In spite of rather limited data with much scatter, even after classification into narrow convection categories, it has been possible to identify various changes in mixed-layer structure with increasing convective activity. The measurements in undisturbed conditions have confirmed that the latent heat flux at the top of the mixed layer decreased on average to about half of its surface value. In more disturbed conditions there is evidence that this flux is more nearly constant with height. The small downward virtual heat flux which was observed typically near the top of the mixed layer agrees well with numerous other studies. A relatively rapid decrease in the magnitude of the downward momentum fluxes with increasing height was found on most occasions and this is consistent with the presence of a wind maximum in the lowest few hundred metres of the boundary layer and a reversed flow at higher levels. A notable feature of the observed turbulence spectra is evidence for considerable vertical mixing on small horizontal scales (of a few hundred metres) just below the base of the transition layer. Cospectra for the momentum flux confirm that this mixing produced an upward flux on similar scales in the upper part of the mixed layer by interaction with the average wind in this region where $\partial U/\partial z < 0$: the observed upward flux at larger scales in more disturbed conditions demonstrates that more active convection produces coupling over a deeper layer of the atmosphere. The major peak in the $qw$ cospectra near 400 m occurs at relatively high frequencies in suppressed conditions where small scale mixing clearly predominates at the top of the mixed layer.

The results from these measurements have provided a reasonably coherent picture of some aspects of the structure and turbulent transports within the sub-cloud layer, and the changes that occur as convective activity increases. They form a set which is complementary to many other boundary layer investigations carried out in GATE. It is confidently expected
that the results from all these studies will together produce a major advance in our understanding of processes within the convective boundary layer over tropical oceans.

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