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Diurnal Variation in the Turbulent Structure of the Cloudy Marine Boundary Layer During FIRE 1987

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During the 1987 FIRE marine stratocumulus experiment the U.K. Meteorological Office operated a set of turbulence probes attached to the tether cable of a balloon based on San Nicolas Island. Typically six probes were used; each probe is fitted with Gill propeller anemometers, a platinum resistance thermometer and wet and dry thermistors, to permit measurements of the fluxes of momentum, heat and humidity. The orientation of each probe is determined from a pair of inclinometers and a three-axis magnetometer. Sufficient information is available to allow the measured wind velocities to be corrected for the motion of the balloon. A full description of this turbulence system can be found in Lapworth and Mason (1988).

On the 14th/15th July measurements were made over the period 1530-0200 UTC and again, after a short break for battery re-charging and topping-up the balloon, between 0400-0800 UTC. Data were therefore recorded from morning to early evening, and again for a period overnight. Six probes were available for the daytime measurements, five for the night. Data were recorded at 4 Hz for individual periods of a little over an hour. The intention was to keep a minimum of one probe at or just above cloud top; small changes in balloon height were necessary to accommodate changes in inversion height.

The most direct comparison, and contrast, can be drawn between the overnight period and that around local noon. In both cases the mean inversion height was very similar and the parameter u_*/fz_i (=R) was equal to $\sim$3.5. This parameter, being proportional to the ratio of the height of a steady neutrally-stable boundary layer to that of the capping inversion, is useful in establishing the broad relationship between the current observations and those of other experiments. For example, Nicholls(1984) and Nicholls and Leighton(1986) present observations for which R varied mainly from 0.6 to 3, with a single strong wind case at $R \sim 7$. This latter case is similar to the observations of Brost et al(1982) for which $R \sim 10$. Hence we might expect the current observations to show most similarity to the buoyancy dominated flows of Nicholls and Nicholls and Leighton.

The ability of the balloon system to make simultaneous measurements at several levels allows the vertical structure of the boundary layer to be displayed without resort to composites. Figures 1 and 2 show the velocity vectors of the longitudinal and vertical components over 30 second averages (giving a spatial resolution of ~170 metres), with the mean horizontal wind subtracted. The daytime data of Figure 1 are from 1908-1958 UTC (i.e. immediately before local noon) and correspond to an horizontal length scale of 18km, based on the mean wind. The upper 2 levels were above cloud, while the third was just below cloud top; the cloud base in this period varied from about 220 to 300 metres. The nocturnal data in Figure 2 were taken between 0645-0738 UTC, and again correspond to a length scale of 18km; the top level is just below cloud top and cloud base was approximately 140 metres.

There is a striking contrast in the degree of variability between the velocity fields in Figures 1 and 2. Both show regions of divergence and convergence near cloud top and organised up and down draughts; however, at night the magnitudes of these gust velocities are much higher and coherent structures occupy the whole depth of the boundary layer, rather than just the cloud layer.

Turbulent statistics were calculated from 2-hour periods, one straddling local noon and one at night. These were sub-divided into half-hour averaging intervals for the evaluation of variances and fluxes. The vertical velocity variances for the day (closed squares) and night (open triangles) are plotted on Figure 3; the heights have been normalised by the inversion height. The daytime profile characteristically shows very low values above cloud, a distinct maximum in the cloud layer and evidence of a second weak maximum below cloud. In contrast, the nocturnal data show a more turbulent layer well-mixed from inversion to surface in a manner analogous to that of a convective boundary layer heated from below (e.g. Lenschow et al,1980).

These features are also reflected in the behaviour of the equivalent potential temperature flux, shown in Figure 4. During both day and night the flux maxima are located close to cloud top; however, whereas the nocturnal data give the appearance of a single mixed layer driven by a cloud-top buoyancy flux, the daytime profile shows a distinct minimum in the region of cloud base increasing again to a weak surface flux.

The daytime boundary layer, around local noon, therefore consists of a cloud mixed layer, driven by a cloud-top buoyancy flux, surmounting a weakly-driven layer of depth $\sim 0.2u_*/fz_i$, a value reminiscent of the results of the JASIN experiment (e.g. Slingo et al (1982), Nicholls(1985)). The top of this layer, however, and the base of the cloud mixed layer are not clearly associated with cloud base, as observed from the surface, which tended to be variable and ill-defined during this period. Mixed-layer similarity of the two datasets can be shown by normalising and replotting against 1-z/h, where h is the mixed layer depth. The vertical velocity variances were normalised by w_*, the convective velocity scale, and the fluxes by the maximum value at cloud top. The results are displayed on Figures 5 and 6. A satisfactory collapse of the data is achieved except for w^2 as 1-z/h approaches unity; the lower boundary condition for the daytime mixed layer will be different from that at night when w^2 must go to zero at the surface.

The evidence presented strongly supports the notion that, for at least part of the daytime, the cloud layer becomes decoupled from the surface following the absorption of solar radiation at depth within the cloud layer. The surface fluxes on this occasion are weak and the growth of any surface Ekman layer is limited. Further evidence, derived from the TKE budget and turbulence length scales, for this argument will be presented.

References

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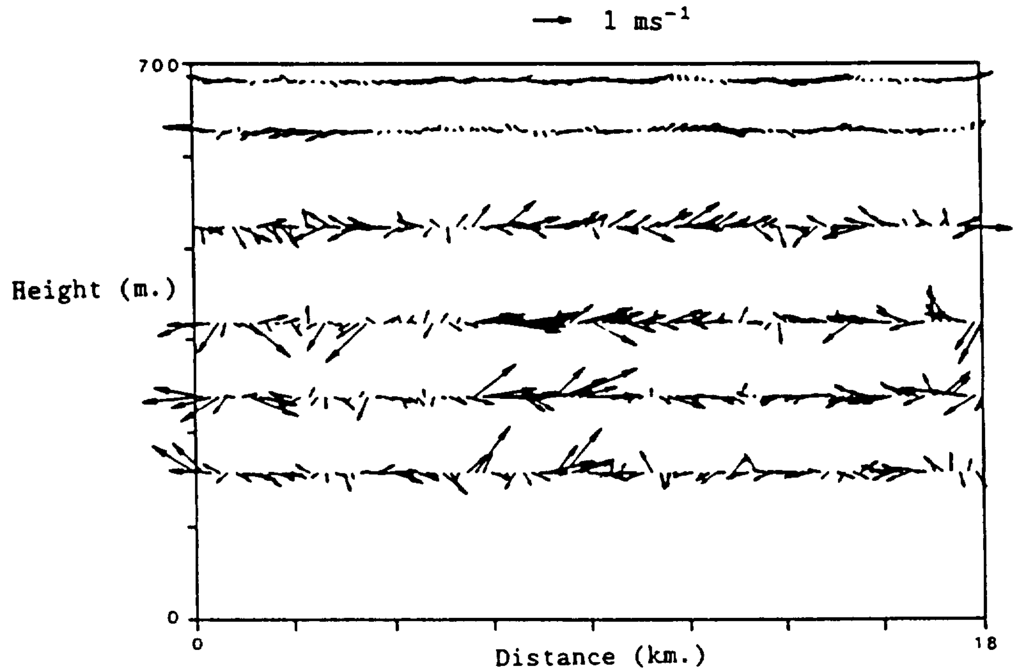

Figure 1: height-distance velocity cross-section for 1908-1958 UTC 14th July. Details in text.

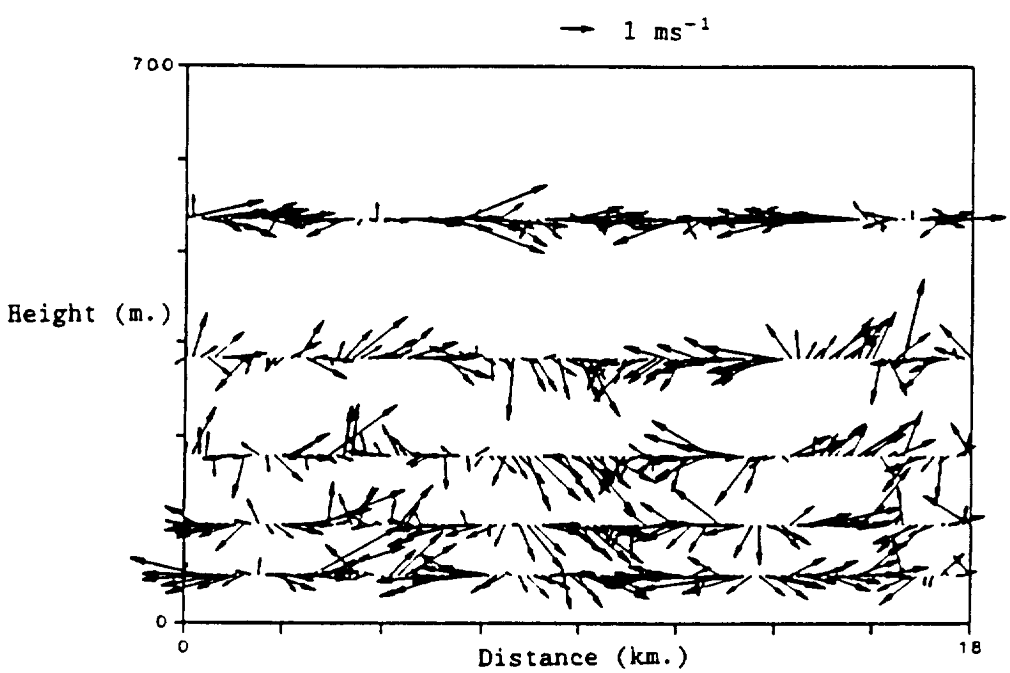

Figure 2: as Fig. 1 but for 0645-0738 UTC 15th July

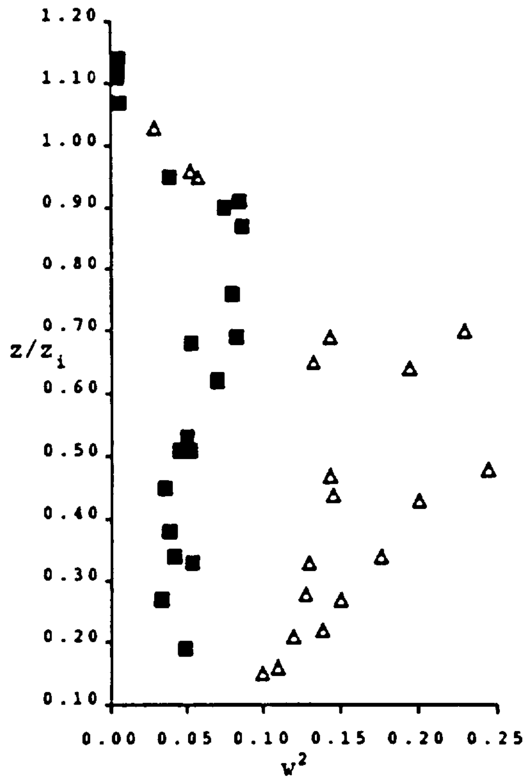

Figure 3: vertical velocity variance versus normalised height: day(squares), night(triangles)

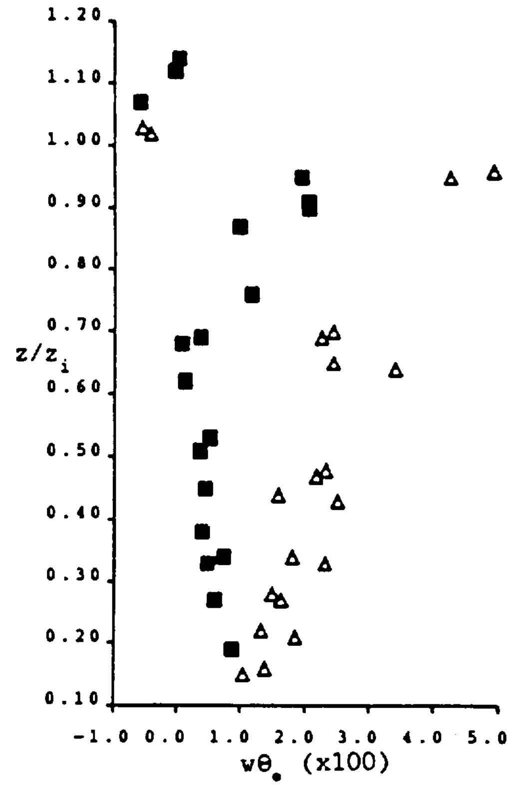

Figure 4: equivalent potential temperature flux versus normalised height.

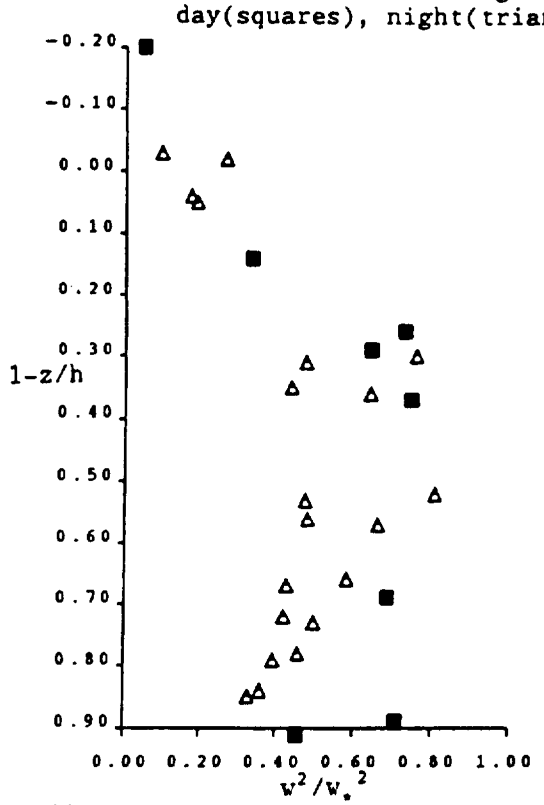

Figure 5: scaled vertical velocity variance

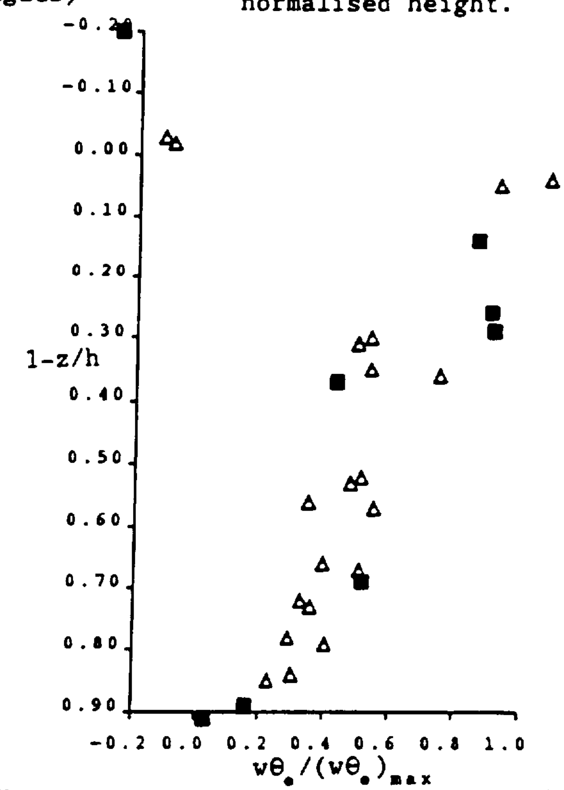

Figure 6: scaled equivalent potential temperature flux