Vertical heat flux in the convective boundary layer

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SUMMARY

The variation of heat flux with height in inversion-capped convective boundary layers is discussed. Cospectral shapes at levels above approximately one-tenth the height of the lowest inversion base \( z_i \) are shown to depart significantly from surface layer forms. The characteristic wavelength for heat flux increases rapidly in the first 150 m of the boundary layer but shows little variation between 150 and 300 metres. Around sunset, the transition to negative heat flux occurs first in the upper regions of the boundary layer and propagates downwards to the surface.

1. INTRODUCTION

In a recent paper, Kaimal et al. (1976) described a joint experiment conducted by the Meteorological Research Unit (MRU), RAF Cardington, England, and the Air Force Cambridge Research Laboratories, Bedford, Mass., USA, in the autumn of 1973. The objectives were to make measurements of the vertical fluxes of momentum and heat, and of the profiles of wind velocity and temperature, within the planetary boundary layer. The experiment was conducted over a very flat, sparsely populated area in northwestern Minnesota. By using tower-mounted sensors in conjunction with turbulence probes, attached to the tethering cable of a large, 1500 m³, kite balloon, it was possible to obtain wind and temperature statistics at seven levels between 4 m and the height of the lowest inversion base (denoted in this paper by the symbol \( z_i \)). The paper by Kaimal et al. examined data obtained in convective conditions within the framework of mixed-layer similarity.

In this paper we consider some aspects of heat flux and its variation in the first few hundred metres above the ground, using data from eight runs, each of seventy-five minutes duration, representing cloud-free convective conditions. Additionally, data obtained during the evening transition to stable conditions are used to illustrate the breakdown of the convective boundary layer. For details of the experiment and information on \( z_i \) and other scaling parameters for each run the reader is referred to earlier papers by Readings et al. (1974) and Kaimal et al. (1976). Information on the instrumentation and data reduction techniques are in the report by Izumi and Caughey (1976).

2. VARIATION OF THE HEAT FLUX WITH HEIGHT

The heat flux in the convective boundary layer is expected to decrease monotonically with height, becoming negative in the upper half of the boundary layer. The dimensionless profiles available from this experiment (Fig. 1) show the cross-over to negative (downward) flux occurring around \( 0.6 z_i \), with a spread from 0.4 to 0.8 \( z_i \). These profiles resemble those obtained from aircraft measurements (Lenschow 1974; Pennell and LeMone 1974), laboratory experiments (Willis and Deardorff 1974), and numerical model calculations (Deardorff 1972; Wyngaard and Coté 1974), except for a tendency for the profiles of Fig. 1 to cross zero at slightly lower heights.

The negative heat flux in the upper boundary layer has been traced to downward transport of warmer air entrained into the boundary layer through the inversion base by the return flow associated with large convection cells in the boundary layer (Kaimal et al. 1976). The effects of such entrainment have been observed in the temperature and heat flux statistics down to heights of the order of 0.5 \( z_i \). The observed variation in the level of zero heat flux is probably a reflection of the variation in entrainment intensity from run to run.

3. HEAT FLUX COSPECTRA

The negative heat flux in the upper boundary layer appears in cospectral plots as large negative
contribute in the frequency range $10^{-2}$ to $10^{-4}$ Hz. Cospectral behaviour at those heights is not consistent enough to justify the development of composite plots, but in the height range of $z < 0.2z_i$, (below about 300 m for the Minnesota data) the flux is almost entirely upwards and one can expect some order to emerge. Composite curves for the logarithmic cospectra, normalized by the local kinematic heat flux $Q (= w_0)$, show a small but systematic variation with height in the first 150 m (Fig. 2) when plotted as a function of dimensionless frequency $f (= nz/U \approx z/\lambda)$; $n$ is the cyclic frequency, $z$ height above ground, $U$ mean wind speed, and $\lambda$ wavelength ($= U/m$). In the inertial subrange they all converge to a single curve as in the Kansas results (Kaimal et al. 1972) and follow the same empirical relationship,

$$nC_{w_0}(n)/Q = 0.14f^{-4/3}$$

(1)

Here $w$ and $\theta$ are the fluctuating vertical wind component and temperature, respectively, and $C_{w_0}(n)$ is their cospectral density at frequency $n$.

At lower frequencies the 4 and 32 m curves of Fig. 2 fall within the narrow cospectral band defined by the scatter in the unstable Kansas cospectra. Within this band, the Minnesota data show a systematic shift to higher $f$ values with height. But as the low frequency end continues to shift with height above 32 m, the cospectral curves move farther and farther away from the Kansas results.
Above 150 m a more abrupt change occurs as the inertial subrange cospectrum breaks away from the surface layer form represented by Eq. (1).

The plot of $\lambda_m$ (wavelength corresponding to the cospectral peak) versus height in Fig. 3 shows $\lambda_m$ increasing with height between 4 and 152 m and levelling off to a constant value between 152 and 305 m. This constant value (different for each run) is of the order of 1.5$z_0$, which is also the limiting value for $\lambda_m$ in the Minnesota temperature and velocity spectra (Kaimal et al. 1976). The Minnesota data show $z_1$, emerging as the important length scale at $z > 0.1z_1$, and the limiting wavelength of 1.5$z_1$ as the approximate spacing between large thermals in the boundary layer.

### 4. Breakdown of the Convective Boundary Layer

The Minnesota experiment provided an excellent opportunity to observe in detail the progression of heat flux at different heights as the convective boundary layer disintegrated shortly before sunset. Much recent work has been devoted to the study of the evolution of the convective boundary layer between sunrise and noon (see, e.g., Richter et al. 1974; Neff 1975; Zilitinkevich 1975; Tennekes 1975; Chorley et al. 1975; Mahrt and Lenschow 1976), yet not much is known about the details of its dissolution near sunset. The time/height plot of heat flux (15-minute averages) in Fig. 4 shows that this breakdown is rapid, occurring in a matter of minutes. During this period the level of zero heat flux, located normally around 0.6$z_1$, makes a sudden descent to the surface. This occurs almost an hour before local sunset and is typical of other evening transitions observed during this experiment. It is surprising that the transition to negative heat flux propagates downwards to the surface, and not upwards as one might expect. Following this event a surface-based inversion begins to develop in line with the conventional view of nocturnal layer build-up, and we see a gradual intensification of the downward heat flux near the surface. This surface inversion may break down and form again during the course of the evening.

### 5. Concluding Comments

These results serve to emphasize the importance of entrained heat flux in the inversion-capped
Figure 4. Isopleths of the 15-minute heat fluxes for run 7 covering the transition period around sunset. Units are cm s⁻¹K.

Convective boundary layers which were present during the Minoesota experiment. The low height values obtained for cross-over to negative heat flux is an indication of the intensity of entrainment in the upper boundary layer on these occasions. Cospectral shapes differ significantly from the surface layer forms above 0-1z, and at these heights the characteristic wavelength for heat flux approaches 1-5 times the inversion height, the length scale of the large convection systems in the boundary layer. The observed lag between the cross-over to negative heat flux aloft and at the surface around sunset needs closer study because of its implications in the modelling of stable boundary layers.

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COMMENTS ON THE PAPER 'AN ANALYSIS OF MANLEY'S CENTRAL ENGLAND TEMPERATURE DATA: I'
BY T. G. J. DYER

BY ALBERT J. KOSCIELNY

In an attempt to resolve very low frequency spectral peaks in the central England temperature data from Manley (1974), Dyer (1976) applied the maximum entropy method (MEM) using a prediction error filter containing 60 terms. I claim that the filter length is much too long, resulting in a misleading representation of the spectra of the monthly and annual series.

Ulrich and Bishop (1975) point out that one problem with MEM is objectively determining the filter length. They demonstrate that a correct filter length is essential for estimating the spectrum. Since the procedures of modelling a time series by an autoregressive (AR) process and estimating the spectrum by MEM are equivalent, Ulrich and Bishop propose the use of the Akaike final prediction error (FPE) to determine the filter length (the filter length is one greater than the order of the AR fitted to the time series). They find that the minimum FPE criterion 'works very well' not only for AR processes but also for mixed and harmonic processes.

Using the computer program in Ulrich and Bishop for computing the Burg estimates of prediction error filter coefficients, I computed the FPE for ARs of orders 0 to 100 for the 315 years of central England's monthly and annual average temperatures, without trend removal. The results for January and April, plotted in Fig. 1, are typical of those for the other months. In Table 1 are presented the filter lengths determined by the minimum FPE criterion. The spectra plotted in Fig. 2 were estimated by MEM using filters of the lengths given in Table 1 and are grouped according to

![Figure 1. Logarithm of normalized FPE for January and April series.](image)