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DIRECT MEASUREMENTS OF RADIATIVE AND TURBULENT FLUX
CONVERGENCES IN THE LOWEST 1000m OF THE CONVECTIVE
BOUNDARY LAYER

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Summary

Results derived from simultaneous measurements of turbulent heat flux and radiation convergences in the daytime convective boundary layer are presented. Problems arising from making fixed point measurements at different heights are discussed. It is shown that the derived longwave radiation fluxes are consistent with there being significant longwave warming near the surface and cooling at higher levels, in good agreement with infra-red radiative transfer models. The shortwave warming in the lowest 1000m of the atmosphere is measured and is found to be between 10% and 41% of the turbulent heat flux convergence across the same slab. Finally an attempt is made to relate the measured shortwave warming to pollutant concentration.

Introduction

In recent years there has been an increasing interest in energy exchange mechanisms involving radiation and the atmosphere. The emphasis has been on numerical modelling of possible climatic change caused by man's interaction with his surroundings, for example Charlson and Pilat (1969), Braslau and Dave (1973) and Harshvardhan and Hess (1976). Radiative effects are also of short term importance in the heat budget of the daytime boundary layer. Glazier, Monteith and Unsworth (1976) and Zobel (1966) have inferred the existence of significant warming due to short wave radiation absorption in the lowest 2000m of the Earth's atmosphere. Direct measurements, all of which indicate radiative warming in the daytime convective boundary layer, have been made by Roach (1961) Murai et al (1976) and Kondratiev (1961). In a recent study of boundary layer energetics Moores et al (1979) have shown that the total heat input into the boundary layer significantly exceeded that transferred by turbulent mechanisms and advective fields. As a result of these observations it was decided to investigate the relative importance of radiative and turbulent heating mechanisms, in the convective boundary layer, using the tethered balloon facility available at Cardington. With this system it is possible to measure, at a fixed point, radiative and turbulent fluxes simultaneously at a number of heights.

2.(i) Instrumentation

All the radiation measurements quoted are flux densities, in units of Wm^{-2} , averaged over wide bands of the radiation spectrum. Shortwave measurements are flux densities, averaged over a hemisphere, in the wavelength region 0.3 to 2.5 micron. Net radiation measurements cover

both the solar and terrestrial wavelength regions. In the nomenclature used in this paper $SD(x)$ denotes the downward solar radiation at a height x m above the ground. Similarly $SU(x)$, $LU(x)$ and $LD(x)$ denote the upward (originating at the surface of the earth) shortwave and longwave components and the downward longwave radiation respectively. The net radiation, at any height x , is given by

$$N(x) = SD(x) + LD(x) - SU(x) - LU(x)$$

During the summer of 1976 net radiation measurements, using Funk type radiometers, were made at two heights, usually 150 and 1200m, on days with little or no low cloud. Further information was obtained from the routine surface radiation measurements made at Cardington. These included total downward shortwave radiation $SD(1)$ and diffuse solar radiation measured by Kipp-Zonen solarimeters. In addition two Kew pattern radiation balance meters, measuring net radiation, were in operation 1m above a grass surface. Good data was gathered on six days during the period 12 August to 7 September with the balloon tethered at site B (see the Cardington site plan, Fig 1). Comparison runs, with the instruments side by side, were made on three occasions to check for drift in calibration factors. During these ground runs the Funk net radiometers agreed to within 5 Wm^{-2} , even when sampled at 0.1Hz. Over averaging periods of 10 minutes the Kew radiation balance meters (sampled once every minute) differed by less than 10 Wm^{-2} from the Funks.

Further data was gathered on five occasions between 29 July and 11 August 1977, in an attempt to resolve some of the ambiguities that were apparent on analysis of the 1976 results. In addition to the equipment used in 1976 the shortwave component, SD , was measured at height using a gimbal mounted solarimeter which was attached to and free to rotate about the balloon tethering cable.

All the solarimeters used in this study (Kipp-Zonen type) have a temperature dependant sensitivity. They are calibrated at 283K and the sensitivity decreases by approximately 0.1-0.2% for every 1K the ambient air temperature (assumed to be the temperature of the thermocouple cold junction) exceeds 283K. The solarimeter readings are corrected for this effect. As in the case of the net radiometers, all shortwave measuring instruments were intercalibrated at ground level. This was done on three separate occasions and a consistent small overestimation in SD, by the solarimeter used aloft, corrected for. All the radiation instruments were calibrated on a yearly basis, prior to being used, at the British Meteorological Office to standards defined by the National Radiation Centre.

During the 1977 experimental period a more comprehensive array of surface instrumentation was used. A third Funk radiometer, with its lower hemisphere shielded by a black body at a known temperature, was mounted 1m above a grass surface. The shortwave radiation, SU(1), reflected by a short grass surface was measured using a downward pointing solarimeter with its cold junction shielded from direct solar radiation. The output from the downward pointing solarimeter, the shielded Funk radiometer NC(1) and the temperature of the black body (assumed to have unit emissivity), as measured by a small bead thermistor, were recorded once per minute on paper tape. This instrumentation, coupled with the net radiation measurement at 1m, provides a complete breakdown of the radiation balance at the surface -

$$N(1) = SD(1) + LD(1) - SU(1) - LU(1) \quad (1)$$

$$NC(1) = SD(1) + LD(1) - \sigma T^4 \quad (2)$$

T is the absolute temperature of the black body, σ the Stefan-Boltzmann constant and NC(1) the reading from the shielded Funk radiometer.

An independent measure of LU was attempted; Robinson (1950) found that the radiative temperature of a grass surface could be measured to within 2K or so using an alcohol thermometer lying on the surface. A distant reading version of an alcohol thermometer was constructed by encapsulating a very small bead thermistor in a test tube (5mm x 50 mm) full of spectroscopically pure ethanol. This device read, on average, 0.5K lower than an alcohol in glass thermometer. A second small bead thermistor was positioned under the grass canopy. Platinum resistance thermometers were used to measure air temperatures at 0.05, 0.15 and 0.5m above the surface (soil rather than grass top). These were mounted horizontally in radiation screens and aspirated. Further information on temperature, humidity and windspeed structure upto 16m was obtained using a 6 level profile mast system, see Richards (1979).

In addition to the radiation equipment, measurements of the turbulent heat flux were made at two or three heights whenever possible. Details of this instrumentation and of the telemetry equipment used to transmit all signals to the ground (including radiation measurements) have been given by Caughey (1977). The radiation data was digitised in real time at 0.1 Hz. Data from the turbulence probe was recorded in analogue form on a multichannel tape recorder and subsequently digitised, at 8Hz, onto a computer compatible 7 track magnetic tape.

2.(ii) Errors

Wherever possible instruments measuring the same quantity have been intercompared, under a variety of conditions, at ground level to ensure internal consistency. Therefore errors in the flux convergences (the difference between radiative fluxes at two heights) should be minimal, certainly less than 10Wm^{-2} . There will be larger errors in the longwave flux densities obtained using equations 1 and 2. The shielded net radiometer reading $NC(1)$, which is critical to this calculation, is

certainly affected by the temperature gradients set up across the Funk as a result of the lower hemisphere being shielded. During the experiment the black body temperature exceeded the ambient air temperature, at times, by as much as 7K with the maximum difference occurring on days with light winds. The two polythene hemispheres, protecting the sensor surfaces of the Funk, were kept inflated using a forced dry air circulation which should have minimised the effect of the temperature gradient. Kano et al (1973) have investigated the effect of external temperature gradients on Funk sensitivity but it is not obvious how applicable their results are to instruments having an internal air circulation. As it is difficult to define an absolute error, results based on the use of the shielded net radiometer have to be treated cautiously.

The Cardington turbulence probe, used in obtaining the turbulent heat flux, has been compared against tower mounted sonic instrumentation, Haugen et al (1975). In general the agreement was good, though there was some evidence for systematic underestimation (10-15%) by the probe system for heat fluxes in excess of 150 W m^{-2} .

3. Discussion

In this section the data are discussed in relation to the difficulties associated with a) the breakdown of the net radiation into its component parts and b) the spatial representativity of SU and LU as functions of height. It will be shown that, for the 1977 data, the measured short-wave convergence can be deduced fairly accurately from the net radiation measurements. A similar technique is then applied to the 1976 data to estimate shortwave warmings. An attempt is made to correlate these short-wave warmings with indicators of boundary layer pollutant concentration. Finally, radiative and turbulent boundary layer heating rates are compared and discussed.

3.(i) Results

The data gathered in 1976 has been tabulated elsewhere (Moore (1977)), but as reference will be made to the data, run average values of the net radiation at these different heights are reproduced in table 6. Extensive amounts of high level cloud persisted on all days except the 24th August.

Tables 1-5 contain information about the radiation data collected in 1977. In these tables 20 minute averages of radiation measurements are given together with derived quantities, when available, such as LD(1), LU(1) and black body (unit emissivity) temperatures as determined by the thermistor lying on the surface and the platinum resistance thermometer at 0.05m. Additional information regarding hourly observations of cloud amounts is also tabulated.

3.(ii) Surface data

On days when all instrumentation on or near the surface was working (ie 4, 10 and 11 August 1977) a complete radiation breakdown is possible. In general when the temperature gradients near the surface are large the derived value of LU(1), which is representative of a grass surface, lies between the black body (unit emissivity) radiation at temperatures of $T(0.05)$ and $T(0)$. Oke (1978) quotes a value of 0.95 for the emissivity of a short grass surface. It is interesting to note that for the period 1523-1533 on the 10 August (not given in table 4) when the lapse rate near the surface was nearly neutral, the measured value of 422 Wm^{-2} for LU(1) compares favourably with the surface black body radiation of 433 Wm^{-2} .

The derived downward longwave radiation LD(1), given in tables 3-5, can be compared with the downward longwave radiation computed by infra-red radiative transfer schemes. Roach and Slingo (1978) have developed such a model in which the absorption effects of water vapour (both band and

continuum), water droplets, carbon dioxide and ozone are considered.

In this study the model is applied to cloud free atmospheres i.e. the effects of water droplets have been ignored. Temperature and humidity profiles required as input to the model are derived from three sources:

a) up to 16 m from the temperature and humidity profile mast system at Cardington,

b) between 16 and 900 m from the Cardington Balthum (see Painter (1970)) and above 900 m from the midday Crawley radiosonde ascents.

The computed values of $LD(1)$ and the measured value, averaged over the periods of the Balthum ascents, are given in table 7. Agreement is good, the measured values averaging 21 W m^{-2} more than the theoretical which compares favourably with the observation by Dalrymple and Unsworth (1978) who suggest that emission by aerosols (not allowed for in models) is responsible for the difference.

It was noted earlier that the longwave radiation components derived using $NC(1)$ were likely to have the largest error but the encouraging values for $LU(1)$ and $LD(1)$ suggest the absence of any serious error in $NC(1)$. Indeed, all results from the surface instrumentation seem to be consistent and plausible.

3.(iii) Measurement at height

While analysing the data gathered in 1976 it became apparent that fixed point net radiation measurements made at altitude were subject to spatial averaging effects. The average daily net radiation convergence in the lowest slab (usually 1-150 m) for the 1976 data, excluding the period 1615-1700 on 7 September, is 57 W m^{-2} which can be compared with a value of 17 W m^{-2} for the 1977 data. The earlier data were obtained with the balloon anchored at site B (see Fig 1) whereas in 1977 the balloon was moved to site A. Measurements made at 1m by the net radiometer and downward pointing solarimeter are representative of the grass

surface directly beneath the instruments. and are independent of site. Therefore the difference in the convergence must be related to the varying surface characteristics, over the much larger area, which affect the instruments at 150 m. The figures for the average daily net radiation convergences for the 1-1000m slab are 80 and 87 Wm^{-2} for the 1976 and 1977 data respectively (the data have been either interpolated or extrapolated to give an estimate of $N(1000)$) implying that at 1000 m the instruments detect upward radiation representative of the Cardington area.

In order to obtain more information about spatial effects, the variability of albedo (SU/SD) with height was measured. Data were gathered, at sites A and B, on a number of occasions in the late summer of 1977. As albedo depends upon solar elevation, Paltridge and Platt (1976), measurements were made as quickly as possible during the two hour period around midday. Figure 2 gives the measured albedo, as a function of height, with the data plotted as a change with respect to the albedo at 1 m. The albedo decreases with height as the patchwork character of the land beneath the instruments becomes more representative of the Cardington area. Both Roach (1961) and Murai et al (1976) found that in the lowest 1000 m of the atmosphere the albedo increased slightly with height. Roach explained that the increase is due to backscattering of incoming shortwave radiation by aerosol particles.

To first order (using Roach's terminology) the albedo A at any height x can be written

$$A(x) = R(x) + A_0(s) \quad (3)$$

where $R(x)$ is the contribution to the albedo from aerosol backscattering and $A_0(x)$ is the effective area averaged surface albedo relevant to the instruments at a height x . Roach and Murai et al, who both made measurements from aircraft, measure only $R(x)$ whereas, in the data presented here, the variability of A_0 with height is the dominant

term. As the variability of albedo with height is the same at sites A and B the difference between the measurements made in 1976 and 1977 must result from the variability of $LU(150)$ in the horizontal.

At site A the upward longwave radiation at 150 m is significantly affected by the 60 m high, metal skinned hangars, Fig 1. During periods of high insolation the hangar skins become very hot and have a higher thermal emission than the surrounding grassland leading to a larger $LU(150)$ and hence a lower $N(150)$ at site A. It is worth noting that the net radiation convergence in the lowest 150 m is smallest in the low windspeed conditions of 11 August 1977. It is hoped to measure the variation of LU as a function of both height and site in the future.

The accuracy of the data can be further checked by calculating the measured downward short convergences from the net radiation data using

$$SD(1-A) = N-LD+LU$$

Now $LD(x)$ can be computed using the longwave radiation scheme of Roach and Slingo but, as noted earlier, the theoretical downward longwave radiation is approximately 20 Wm^{-2} smaller than the observed. Therefore the theoretical estimates are increased by this amount at all heights. By assuming a) a surface temperature that gives the average of the observed upward longwave radiation at 1m and b) that this temperature is representative of the Cardington area, the variation of LU with height can be inferred from the model. Comparisons of the computed downward shortwave convergence, calculated by using such a scheme, against the measured values for the three occasions 1235-1535 on 1 August 1977 (across the 1-819 m slab), 1015-1235 on 4 August 1977 (1-971 m slab) and 1000-1340 on 10 August 1977 (the lowest 698 m) give values of 52 Wm^{-2} against 36 Wm^{-2} , 57 Wm^{-2} against 74 Wm^{-2} and 47 Wm^{-2} against 49 Wm^{-2} respectively. Although the data are scattered, the computed shortwave attenuations are sufficiently accurate to encourage the use of net radiation data in estimating the downward

shortwave convergence.

As neither LU(1) nor the surface temperature was measured in 1976 the above method is not directly applicable and it is necessary to resort to the rather cruder technique of assuming that the downward shortwave convergence is a fixed fraction of the observed net radiation convergence over a slab approximately 1000 m thick. For the periods on the 1, 4 and 10 August 1977 when both short wave and net convergences were measured the ratio of short to net convergences is 0.54, 0.8 and 0.52 respectively. On the basis of these observations the shortwave convergences for the 1976 data are derived by assuming that the downward shortwave convergence is 60% of the net convergence, which has to be measured across the bottom 1000 m of the atmosphere. The data, derived using this relationship, for 1976 are given in table 6 and show a mean daily downward short wave convergence of 48 Wm^{-2} across a 1000 m slab. The mean daily short wave convergence for the 1977 data using directly measured values whenever possible is 49 Wm^{-2} .

3.(iv) Net longwave contribution to the heat budget

It is instructive to examine the radiative contributions to the heat budget in the lowest 150 m of the atmosphere, for which the discussion has to be restricted to the data gathered at site B, where hangar effects are minimal. Assuming SD(1) averaged over the periods in table 6 is known, SD(150) and SD(1000) can be deduced using the calculated short wave convergence for the 1-1000 m layer. Using the measured albedo variation with height, Fig 2, and a surface albedo of 0.2, SU(150) and SU(1000) can be computed. The net long wave radiation is given by

$$LD(x) - LU(x) = N(x) - SD(x) + SU(x)$$

for $x = 1, 150$ and 1000 . Taking the difference between these three net longwave values gives the longwave heatings for the respective slabs.

Reliable measurements of SD(1) were obtained on the 12, 19, 20, 24 and 26 August 1976. Using the above technique, for data gathered on these 5 days, indicates a net longwave radiation warming in the lowest 150 m. This varies between 4 and 26 Wm^{-2} (daily mean of 16 Wm^{-2}) distributed in the bottom 150 m (0.08 to 0.52 with a mean of 0.32 K hr^{-1}). For the 150-1000 m slab the net longwave effects is a cooling amounting to a loss of between 12-24 Wm^{-2} (-0.04 to -0.09 K hr^{-1}). These figures agree reasonably well with the net longwave effects computed using the longwave radiation model applied to the 1977 data, with the surface temperature fixed to give the experimentally observed value of LU(1). For the 4, 10 and 11 August 1977 the model predicts a longwave radiation warming arising from the absorption of between 9 and 17 Wm^{-2} in the bottom 150 m, most being absorbed in the lowest 20 m. The theoretical net longwave divergence across the 150-1000 m slab amounts to 11 Wm^{-2} .

3.(v) Relationship between short wave convergence and aerosol concentration

An original aim of this study was to find a correlation between the observed downward shortwave convergence and a readily measured quantity such as horizontal visibility. Table 8 contains values of possible quantities (available during this study) that might correlate with the observed convergence. Measurements of smoke and sulphur dioxide concentrations are made on a routine basis at Cardington as part of the Warren Springs Laboratory national pollution monitoring network. The values are averages over 24 hour periods (1500 to 1500) and, in the case of Cardington, measure the concentration roughly 2.5 m above the ground. The surface visibility is an average, over the run period, of the hourly observations made routinely at Cardington and the total water vapour content up to 1000 m is computed from the Baltrum data.

Generally the data are scattered but the best fit to the observed shortwave absorption is given by the sulphur dioxide concentration. This observation is not meant to imply that sulphur dioxide, or its derivatives, are the only absorbers of shortwave radiation; gaseous absorption is certainly important. It is possible however that the sulphur dioxide measurement is an indicator of general boundary layer pollutant concentration. The correlation with horizontal visibility is unfortunately poorer, though days with the best visibility generally have small shortwave absorptions. Unsworth and Monteith (1972) discuss the attenuation properties of the lowest levels of the atmosphere in terms of a turbidity parameter τ_a , the fractional attenuation of shortwave radiation by aerosol per unit air mass. They show how τ_a is, on cloudless days, related to the ratio of diffuse to total incoming shortwave radiation at the surface. This relationship has been used to generate τ_a for days on which there was very little high or medium level cloud and only small amounts of low cloud. Periods during which the radiation traces exhibited a local maximum in SD(1) and a local minimum in the incoming diffuse radiation have been used in calculating τ_a in an attempt to minimise cloud effects. For the 24 August 1976 the only data available are the hourly integrated values of the total and diffuse shortwave radiations and these have been used because there was little low cloud. The results of such calculations, given in table 8, show as expected that the higher values of short wave attenuations occur on days with large τ_a . It should be emphasized however that the values of τ_a given here are subject to large uncertainties because the regression given by Unsworth and Monteith (1972) is for cloudless days, a criterion which is hardly valid for most of the data presented here. In addition, the diffuse radiation as measured by the shaded Kipp-Zonen solarimeter is probably underestimated,

see Cowley (1979), resulting in small values for τ_a . It is hoped however that the variability in the τ_a values quoted here is realistic.

3.(vi) Comparison of turbulent and radiative heating

A further objective was to determine the relative importance of turbulent and radiative heating mechanisms. Values for the turbulent heat flux, as computed from the turbulence probe data are given in table 9. In general the heat flux convergence for the morning period is distorted by the presence of a nocturnal inversion. This is particularly apparent on 11 August 1977. On this day, during the period 0905-1121, the nocturnal inversion was between 150 and 910 m. One consequence of this is that the turbulent heat flux is dissipated in the lowest levels of the boundary layer resulting in large heating rates beneath the nocturnal inversion. In such periods, and in the absence of either large scale subsidence or horizontal advection, warming above the nocturnal inversion is probably due to the absorption of radiation. Such warmings have been observed by Ali (1933), Chapman (1925) and Izumi (1964), though on 11 August 1977 the temperature above the nocturnal inversion was effectively constant as a function of time indicating a balance between longwave radiation cooling, short-wave warming and advective effects. Because of such effects the comparison between turbulent and radiative warmings will be restricted to times when the boundary layer was well mixed up to the level of the highest turbulence probe. Mean values for the daily heat flux convergence over the lowest 1000 m are given in the last column of table 9. This data has to be compared with the daily average values of the net short-wave convergence, $SO(1000) - SU(1000) - SO(1) + SU(1)$. (In previous sections discussion has been restricted to the downward shortwave convergence

$50(1000) - 50(1)$. Roach (1961) has shown that, at least for the lowest 350 m of the atmosphere, that backscattering accounts for roughly 20% of the downward shortwave convergence, the remaining 80% being absorbed. Taking 80% of the downward shortwave convergence, given in the first column of table 8, gives the shortwave warming. Comparing these figures with those for the turbulent flux convergence shows that, on a daily basis, the shortwave warming varies between 10 and 41% (mean 30%) of the turbulent heating.

3.(vii) Cloud effects

The periods 1013-1153 on 1 August 1977 and 0905-1205 on 11 August 1977 have been excluded from the previous analysis because of significant cloud effects. On 1 August, the instruments between 1200 and 1400 m were for the period 1013-1110 always above the cloud top but from 1110 onwards they began to move into and out of cloud. Just before the instruments move into cloud both the total solar and net radiations increase considerably, presumably a result of an increase in diffuse shortwave radiation component arising from the high albedo of the cloud. The total solar and net radiations reach maxima of 980 and 910 Wm^{-2} respectively falling to minima of 310 and 80 Wm^{-2} in the cloud. However it is not possible to say much more about the radiative effects of clouds because the solarimeter was 90 m above the net radiometer. It does however indicate that to obtain realistic flux convergences all instrumentation has to be below the cloud base. Even if this criterion is satisfied the radiation data has to be averaged over as long a time period as possible as has been done in this study.

Concluding Remarks

The data presented show that in convective conditions there is a substantial warming in the boundary layer due to the absorption of incoming shortwave radiation. During the 4 to 6 hour period around midday this averages 0.12 K hr^{-1} , roughly a third of the turbulent heating rate. In all but the lowest region of the atmosphere the short-wave warming is somewhat offset by long wave emission resulting in a cooling of 0.05 K hr^{-1} . Near the surface, certainly at heights lower than 150 m, there is a significant long wave radiation warming, a direct consequence of high surface temperatures. As the data reported here are representative of typical summer days at an inland site, it is apparent that the effects of both short and long wave radiation should be included in numerical studies of boundary layer energetics.

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TABLE 1

29TH JULY 1977

TIME	1048 1108	1108 1128	1128 1148	1148 1208	1208 1228	1228 1248	1048 1248	1323 1343	1343 1403	1403 1423	1423 1443	1443 1503	1503 1523	1523 1543	1543 1603	1603 1643	1323 1643
SD(1)	543	302	739	737	694	796	635	509	671	629	661	706	664	607	575	518	616
SU(1)	113	65	147	138	147	152	127	104	139	131	131	143	134	122	117	112	126
N(1)	332	177	491	485	484	530	417	336	462	424	399	416	391	351	304	265	372
N(150)	385	194	412	480	488	519	413	241	355	439	378	419	399	358	336	309	359
N(546)	390	225	421	521	559	573	448	374	502	458	483	444	407	374	319	312	408
SD(606)	566	334	643	748	780	809	647	-	-	-	-	-	-	-	-	-	-

CLOUD	TIME	TYPE	AMOUNT*	HEIGHT/ (BASE)
	1000	Cu	6	520
	1100	CuSc	7	610
	1200	CuSc	6	760
	1300	CuSc	5	760
	1400	CuSc	5	920
	1500	CuSc	4	1070
	1600	CuSc	3	1070
	1700	CuSc	4	1070

* IN OKTAS

/ CLOUD BASE HEIGHT, ESTIMATED BY EYE, IN METRES

TABLE 2

1ST AUGUST 1977

	1013 1033	1033 1053	1053 1113	1113 1133	1133 1153	1013 1153		1235 1255	1255 1315	1315 1335	1335 1355	1355 1415	1415 1435	1435 1455	1455 1515	1515 1535	
SD(1)	708	500	756	743	470	635	SD(1)	443	350	349	430	366	390	397	332	593	406
SU(1)	141	99	148	156	88	126	SU(1)	75	72	64	91	74	78	84	46	125	79
N(1)	448	308	457	514	297	405	N(1)	232	219	189	276	227	220	230	180	367	238
N(150)	413	396	521	533	370	447	N(150)	259	238	217	279	254	259	262	313	377	273
N(1274)	536	563	572	611	411	539	N(819)	245	303	181	344	225	240	262	461	485	305
SD(1365)	823	859	858	874	711	825	SD(910)	406	424	287	489	347	373	450	604	631	446

CLOUD	TIME	TYPE	AMOUNT	HEIGHT
	1000	Cl	1	-
	1100	CuSc	3	920
	1200	Cu	7	1070
	1300	CuSc	7	1070
	1400	CuSc	7	1220
	1500	CuSc	5	1070

TABLE 3

4TH AUGUST 1977

	0935 0955	0955 1015	1015 1035	1035 1055	1055 1115	1115 1135	1135 1155	1155 1215	1215 1235	1235 1255	1255 1315	1315 1335
SD(1)	-	608	609	615	731	713	659	717	744	734	769	684
SU(1)	-	126	124	126	151	144	134	147	152	148	151	140
N(1)	-	376	376	383	486	465	423	471	488	480	493	442
N(150)	460	383	390	413	522	522	479	494	504	-	-	475
N(971)	517	423	445	470	587	588	510	567	577	-	-	535
SD(1062)	735	627	652	693	824	828	714	809	836	-	-	765
LD(1)	-	-	328	343	372	363	362	371	366	357	-	358
IU(1)	-	-	437	449	466	467	464	470	470	463	-	460
σ T(0)	-	485	477	477	497	500	487	496	501	500	502	491
σ T(0.05)	-	435	434	434	443	444	440	444	449	451	454	441

CLOUD ONLY SMALL AMOUNTS OF LOW CLOUD BUT EXTENSIVE MEDIUM LEVEL CLOUD

TABLE 4

10TH AUGUST 1977

	0940	1000	1020	1040	1100	1120	1140	1200	1220	1240	1300	1320	1340	1000	1340
	1000	1020	1040	1100	1120	1140	1200	1220	1240	1300	1320	1340	1400	1340	1340
SD(1)	611	658	676	709	731	699	748	784	792	668	494	776	236	703	
SU(1)	121	131	130	137	138	124	145	147	152	127	107	158	40	136	
N(1)	360	404	422	448	470	446	487	509	524	442	321	512	128	453	
N(150)	372	429	426	464	477	474	501	529	526	456	398	512	83	472	
N(698)	428	496	496	525	529	546	555	565	566	618	608	523	76	548	
SD(758)	671	713	718	762	767	781	774	777	777	799	762	707	123	756	
LD(1)	-	348	328	336	337	305	360	344	359	342	402	367	339	348	
IJ(1)	-	471	452	460	460	434	476	472	475	441	468	473	407	462	
⁴ σ-T(0)	-	503	514	506	517	510	514	519	529	512	477	515	453	511	
⁴ σ-T(0.05)	-	430	432	440	440	440	447	453	457	449	437	452	421	443	

CLOUD	TIME	TYPE	AMOUNT	HEIGHT
	1000	Cu	1	7600
	1100	Cu	2	7600
	1200	Cu	1	720
	1300	Cu St	3	1070
	1400	Cu St	5	1070

TABLE 5

11 AUGUST 1977

	0905 0925	0925 0945	0945 1005	1005 1025	1025 1045	1045 1105	1105 1125	1125 1145	1145 1205	1205 1225	1225 1245	1245 1305	1305 1325	1325 1345	1345 1405	1405 1425	1425 1445	1445 1505	0905 1205	1325 1445
SD(1)	350	503	634	682	709	688	753	768	769	767	763	744	732	714	697	657	642	604	651	678
SU(1)	83	121	134	136	139	137	143	143	144	144	143	139	142	139	131	126	127	120	131	131
N(1)	219	304	401	426	444	433	487	498	497	500	495	472	473	452	435	394	393	358	412	419
N(150)	272	354	378	416	438	428	473	487	489	-	-	-	-	445	424	394	388	-	415	413
N(910)	-	-	-	-	-	-	-	-	-	-	-	-	-	499	473	446	428	-	-	462
SD(971)	653	677	709	730	757	769	786	790	786	-	-	-	-	-	-	-	-	-	740	-
LD(1)	-	-	331	313	310	326	329	331	342	345	344	336	350	342	318	321	332	321	-	328
LU(1)	-	-	433	433	436	442	451	457	469	468	469	469	467	467	450	457	455	447	-	457
$\sigma^2 T(0)^4$	-	-	501	514	516	514	527	534	533	527	528	523	523	518	490	480	471	491	-	490
$\sigma^2 T^4(0.05)$	-	-	423	429	432	432	438	442	443	446	445	460	445	441	434	430	429	434	-	434

CLOUD

TYPE

AMOUNT

HEIGHT

0900 St 240

1000 St 460

1100 St 610

1200 St 610

1300 Cu 760

1400 Cu 920

1500 Cu 920

TABLE 6

1976 DATA

DATE	TIME PERIOD	AVERAGE NET RADIATION 1M	AVERAGE NET RADIATION LOWER FUNK (HT IN BRACKETS)	AVERAGE NET RADIATION HIGHER FUNK (HT IN BRACKETS)	SHORT WAVE * CONVERGENCE IN LAYER 1-1000 M
12 AUGUST	1120-1150	289	340 (150)	380 (1230)	44
19 AUGUST	1150-1350	399	463 (150)	496 (1230)	47
20 AUGUST	1030-1320	374	422 (150)	466 (1230)	45
24 AUGUST	1105-1355	338	395 (150)	458 (1230)	59
26 AUGUST	1220-1420	332	368 (150)	383 (1140)	27
7 SEPT	1310-1600	217	302 (60)	342 (1140)	66
7 SEPT	1615-1700	45	25 (60)	35 (1140)	-

* This figure derived using $\Delta SD = 0.6 \Delta N$ (see text). Then value either linearly interpolated or extrapolated to give shortwave absorption across 1 Km.

TABLE 7MEASURED AND THEORETICAL LD(1)

DATE AND TIME	MEASURED	THEORETICAL
4th AUGUST 1977 1015-1155	354	332
10th AUGUST 1977 1040-1200	336	318
11th AUGUST 1977 1045-1205	332	312

TABLE 8

INDICATORS OF POLLUTANT CONCENTRATION

DATE TIME	CONVERGENCE ACROSS LOWEST 1000m Wm^{-2}	SMOKE (SURFACE) $\mu\text{g m}^{-3}$	SO ₂ (SURFACE) $\mu\text{g m}^{-3}$	VISIBILITY Km	WATER CONTENT UP TO 1000m $\text{gms} \times 10^{-4} \text{m}^{-2}$	τ_a
12 AUGUST 1976 1120-1150	44	23	41	7	0.86	-
19 AUGUST 1976 1150-1350	47	7	23	16	0.88	-
20 AUGUST 1976 1030-1320	45	10	17	7	1.02	-
24 AUGUST 1976 1105-1355	59	16	29	11	0.89	0.13
26 AUGUST 1220-1420	27	16	42	11	0.78	-
7 SEPTEMBER 1976 1310-1600	66	23	89	12	0.78	-
29 JULY 1977 1048-1248	34	3	17	40	0.69	0.07
29 JULY 1977 1323-1643	40	3	17	34	0.69	0.07
1 AUGUST 1977 1235-1535	44	8	29	13	1.17	0.13
4 AUGUST 1977 1015-1235	76	7	46	20	0.81	-
10 AUGUST 1977 1000-1340	70	8	40	11	0.93	0.18
11 AUGUST 1977 1325-1445	28	6	23	15	0.86	0.09

MEASURED HEAT FLUXES (Wm^{-2})

† Upper limit of convection below this height.

Figure 1 Cardington Site plan

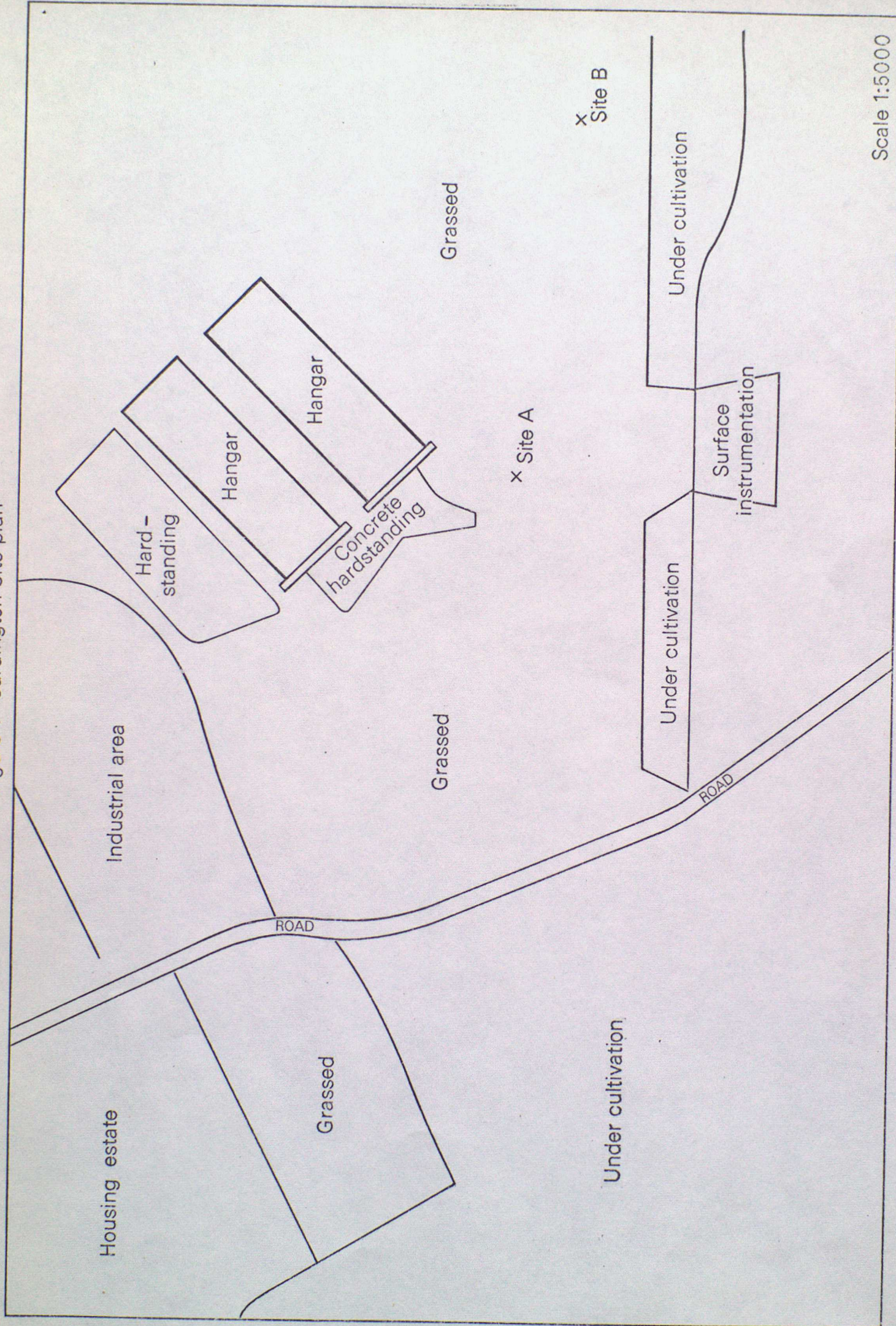


Figure 2 Variation of Albedo with height

