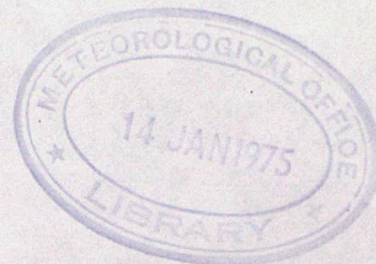


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The development of the atmospheric boundary layer:
three case studies

by
L.G. Chorley

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The development of the atmospheric boundary layer: three case studies

by L. G. Chorley

1. Introduction

Early theoretical work, e.g. by Ball (1960), and later experimental studies such as those of Rayment and Readings (1974), have shown the need to study the development of the boundary layer below an overhead inversion. Such studies should ideally monitor the morning erosion of the nocturnal inversion and the ensuing convective development (with possible interaction between this and an overhead inversion) which dies away in the evening as the surface inversion is re-established. However it must be admitted that, on many occasions, this ideal diurnal cycle will be only partially realised. The work described in this paper concentrates on the evaluation of the vertical heat flux and energy balance within the boundary layer during the day time period. A test of the applicability of a rate equation, for predicting the rise of inversions during dry convection, was carried out using data for two of the cases considered.

The observations discussed here were made at Cardington during August and September 1973. On three days in this period the Balthum (tethered balloon) sonde (see Painter 1972) was used to provide temperature and humidity profiles. Sensible heat flux profiles were deduced by downward summation of the flux divergences (see for example Cattle and Weston 1973) over 5 mb layers ($\overline{W'T}$ was assumed to be zero above the level of the inversion top and no allowance was made for subsidence). Surface values of sensible heat flux, Q_H , were also evaluated by the residual technique i.e. $Q_H = Q_N - (Q_G + Q_E)$, (Munn 1964), the values of net radiation Q_N , soil flux Q_G and evapotranspiration Q_E having been continuously monitored at Cardington by a net radiometer, soil flux plates and a lysimeter respectively. On two of the days $\overline{W'T}$ was also measured directly using a Cardington turbulence probe mounted on top of a Clarke mast at a height of 16 m, (Readings and Butler 1972).

2. The three cases

i. 24th August

Generally anticyclonic conditions prevailed during the 24th August with a high 'cell' over the Southern North Sea and a ridge over the British Isles. However the upper cloud thickened at times, causing the net radiation to vary as shown in figure 1. No major air mass discontinuities were shown on the synoptic charts but the routine radiosonde ascents for the 24th indicated that small advective changes may have been occurring.

The sequence of potential temperature profiles derived from the Balthum ascents on this day is shown in figure 2. (A sounding at 1200 GMT has been omitted from this plot as the temperature readings are suspect). These four profiles indicate the changes which occurred as the nocturnal inversion was steadily 'warmed out' by surface heating and convection developed. The base of this inversion was lifted from 28 mb (above ground level) at 0838 GMT to 44 mb at 1031 GMT and by 1654 GMT convection was established throughout the layer monitored by the Balthum, (viz θ is approximately constant on the 1654 plot in figure 2).

Before applying the summation technique to the temperature profiles an attempt was made to allow for the presumed warm advection indicated above the 40 mb level (0838-1031 GMT). This was done by adjusting the 1031 GMT plot to become approximately aligned with the previous (0838) plot above 44 mb. (Sensible heat flux values evaluated from the original unmodified profiles were large when compared with the probe and energy balance values. It is possible that an instrumental error was responsible for this apparent warming). The final sensible heat flux profiles are reproduced in figure 2 (inset) and show the decrease of heat flux with height. Sensible heat values (near the surface), obtained by the three methods described in the previous section, are shown in figure 1. Reasonable agreement is indicated and the simple correction for advection, discussed above, seems justified.

The following equation (see Carson and Smith, 1974) can be used to predict the rate of use of an inversion (ignoring the effects of entrainment

and the vertical velocity):

$$Z_i^2(t) = \frac{2 \overline{W\theta}_s(t)}{\frac{d\theta^+}{dz}}$$

where Z_i is the height of the inversion base and $\overline{W\theta}_s$ is the surface heat flux (the latter were taken as means of the probe values for the time intervals considered). An estimate of $\frac{d\theta^+}{dz}$ was obtained from figure 2.

Using the appropriate values of Z_i , $\overline{W\theta}_s$ and $\frac{d\theta^+}{dz}$ for the period 0846 to 1034 GMT (i.e. the actual times at which the Balhum indicated the inversion base) the calculated rate of rise of the inversion is 5.6 mb hr^{-1} compared with a measured rate of 6.1 mb hr^{-1} . This order of disagreement falls well within the value corresponding to the tolerances on Z , $\overline{W\theta}_s$ and $\frac{d\theta^+}{dz}$.

ii. 7th September

During this period anticyclonic conditions were maintained over England; the anticyclone which was centred near the Channel Isles at 00 GMT on 7th September changed little during the subsequent 24 hours. The routine radiosonde reports were studied to see if there were any discernible advective or subsidence effects in the light Westerly airstream. The horizontal wind field and temperature distribution implied negligible advection in the 850-900 mb layer, the flow being nearly along the isotherms. Isentropic analysis methods were applied to this layer and the estimated subsidence for the Cardington area (period 00 GMT to 12 GMT on 7th) was 1.25 mb hr^{-1} compared with an estimate of 'zero to 5' mb hr^{-1} obtained from the vertical motion charts available at Bracknell. The conclusion that some subsidence was occurring is consistent with a lowering of the main temperature inversion during the 24 hour period (00 GMT on 7th to 00 GMT on 8th) shown on the Crawley, Sussex and Hemsby, Norfolk soundings: from 868 to 926 mb (2.4 mb hr^{-1}) and from 850 to 896 mb (1.9 mb hr^{-1}) respectively.

At Cardington fog had occurred overnight (6th-7th) and 7 to 8 oktas of stratus cloud, base about 100 m, was advected from the West at 0805 GMT. This cloud lifted rapidly at 1000 GMT and dispersed at about 1100 GMT. Skies thereafter remained clear apart from 1 okta of shallow cumulus, base

600 m, at 1500 GMT.

The sequence of potential temperature profiles for this day (from the Cardington Balthum) is shown in figure 3. (A sounding at 1024 GMT is omitted from this plot as the changes shown appeared to be 'out of sequence' with regard to temperature and humidity changes with time shown by the remaining seven soundings. The sensible heat flux derived, if this sounding is accepted, appears anomalous). The 0715 GMT sounding gives some indication of an upper inversion with a surface (nocturnal) inversion which was considerably modified by low level cooling at 0833 GMT (associated with the advection of the low stratus cloud). This nocturnal inversion then lifted progressively, the base being at about 40 mb above ground by 1116 GMT. The next sounding (at 1241 GMT) shows an inversion base 77 mb above the surface, i.e. at 945 mb, (it is suggested that this was the higher synoptic inversion which was not affected by the heat flux from below and which is shown at 71 mb above the surface on the 1650 GMT sounding). This lowering of the synoptic inversion corresponds to a subsidence rate of approximately 1.5 mb hr^{-1} which may be compared with the similar rates previously quoted. It follows from this interpretation of the data that the lower inversion was completely eroded by 1241 GMT.

Figure 3 (inset) shows the sensible heat flux profiles. The early downward flux may reflect the evaporative cooling and radiation from the cloud layer, factors which would vitiate the summation technique. The flux shown by curve (b) for the period 0928-1116 GMT is entirely positive and is followed by a marked decrease of surface sensible heat (curve (c)) accompanied by a large negative value above 40 mb (maximum downward flux at about 54 mb) reflecting the erosion of the nocturnal inversion. Thereafter the fluxes are entirely positive. The decrease in surface sensible heat flux towards midday is difficult to explain satisfactorily. However the value does agree with the other estimates and a considerable amount of evaporation did take place during the late morning. The values of surface sensible heat flux obtained by all three methods are compared in figure 4, which shows also

the net radiation curve and the downward flux of sensible heat. It may be noted that the second peak in the sensible heat flux plot is not reflected in the plot of downward flux; presumably because by 1241 GMT the lower inversion was no longer present and the fluctuations in net radiation values before 1000 GMT were probably due to the variations in the stratus cloud cover (and presumably cloud thickness). Net radiation and sensible heat flux increased markedly as the cloud dispersed. Heat flux values derived from the Cardington probe measurements are unfortunately not available for the period 1100-1200 GMT but the general conclusion that there were two maxima in the sensible heat flux curve (i.e. near 1020 GMT and 1300 GMT) is supported by the available data.

Changes in water content (below the main inversion at 77 mb) were also examined. An increase of 0.208 gm cm^{-2} occurred during the period 0833-1350 GMT compared with a measured (lysimeter) evapotranspiration of 0.133 gm cm^{-2} . Values for periods between soundings were as follows:-

PERIOD GMT	COLUMN (Surface to inversion base at end of period)	CHANGE in WATER CONTENT gm cm^{-2}	MEASURED EVAPOTRANSPIRATION gm cm^{-2}
0833-0928	30 mb	- 0.003	0.010
0928-1116	40 mb	- 0.002	0.046
1116-1241	77 mb	+ 0.078	0.064
1241-1350	77 mb	+ 0.135	0.013

It is difficult to draw any firm conclusions from these observed changes as an assumption that the changes are the result of vertical transport only is hardly justified. Although it has been stated that advection above the 900 mb level was negligible there does appear to have been some advective change affecting water vapour content nearer the surface.

Several double theodolite wind measurements were available for the day but only one balloon penetrated the inversion, earlier attempts being limited by stratus cloud. Wind changes with height are tabulated below:

MEASURED WIND (deg true/m sec⁻¹) AT 1456 GMT

HEIGHT (Metres above the surface)	WIND
680	282/3.2
690	291/2.6
700	294/1.8
710	298/2.2
720	282/2.8
730	285/3.6
740	285/3.0
750	285/2.2
760	240/0.8
770	296/0.8
780	129/0.6
790	222/0.6
800	267/3.4
810	270/4.4

These values suggest the presence of an inversion base near 760 m which agrees well with the observed base near 77 mb above ground level.

The rate equation was applied to the data (in the same way as described in Section 2(i) for 24th August), although its use on this occasion when changes of state occurred is questionable. The results were as follows:-

PERIOD (GMT)	PREDICTED RISE (mb)	MEASURED RISE (mb)
0833-093	4	9
093 -1151	17	12
11 1-1321	8	37

It may be noted that the final observed base height (1321 GMT) referred to the height of the higher "synoptic" inversion, the lower inversion having been completely eroded during this latter period. Thus only the first two periods may be regarded as a test of the application of the equation, and it is of interest to note the agreement between the measured and predicted rise of the inversion, i.e. a rise of 21 mb, over the whole period 0833 to 1151 GMT. Comparing the fluctuations in surface sensible heat flux and downward heat flux (figure 4) it is difficult to draw firm conclusions regarding the

actual ratios of the two fluxes over the period. The predicted rates of inversion rise (tabulated above) result from a straightforward application of the equation which assumes no entrainment.

iii. 12th September

An anticyclone over the Hebrides maintained a light East or SE airflow over Central and Southern England. Near cloudless conditions persisted at Cardington throughout the day; small amounts of high cloud were observed at times with one report, at 10 GMT, of one okta of shallow cumulus base 600 m. The only suspected advective change was that of increased moisture content near the surface during the late afternoon.

Figure 5 shows the sequence of potential temperature profiles based on three soundings from the surface to (near) the main capping inversion and one sounding restricted to the layer above about 100 mb (above ground level). One sounding carried out at 1356 GMT is omitted from this plot owing to a large temperature error. The absence of a 'complete' sounding from the surface upwards between 0710 and 1135 GMT rules out any consideration of the lifting and erosion of a lower induced inversion which must have occurred. Thus the $W\theta$ summation is limited to the two periods between soundings, (see figure 5 inset).

The net radiation curve and sensible heat flux values are shown in figure 6 and show a reasonably smooth change with time, the two surface $W\theta$ summation values of heat flux agreeing well with the energy balance results. Unfortunately no probe data was available for this day.

3. Conclusions

The case of 24th August is an example of the complete 'warming out' of a nocturnal inversion finally resulting in dry adiabatic conditions within the boundary layer below the main inversion. The lower inversion dispersed 'passively' with no detected entrained (downward) heat flux. On 12th September similar 'warming out' of a lower inversion must have occurred beneath a clearly defined overhead capping inversion which was not affected by the changes in heat flux below. In each of these cases a reasonable sequence of radiative and

sensible heat flux changes is shown and the summation technique whereby sensible heat flux may be derived from a series of temperature profiles is seen to be quite reliable.

The case of 7th September, although basically that of erosion of a low level inversion beneath a higher capping inversion, is made more complex by the presence of the stratus cloud layer during the morning, by evaporative and condensation processes and by probable advective changes. The simple techniques described in this paper do not allow for such changes adequately.

Difficulties and uncertainties encountered in the analysis, to some degree on each of the selected days, show that it is advisable to make a series of Balghum soundings which record data from the surface up to the capping inversion on each occasion. This would rule out the subjective estimates of some points on the temperature profiles which were made in the course of this study. The problem of advective and subsidence changes (or instrumental error) is difficult to resolve although the simple technique applied in the case of 24th August results in acceptable values of heat flux. The usual synoptic scale techniques used to produce estimates of advection, e.g. wind shear in the vertical, cannot easily be applied to the relatively small changes within the boundary layer which may appreciably affect heat flux estimates and water budget calculations. Energy balance estimates of sensible heat (the residual technique) depend largely on reliable evapotranspiration values. The data for 7th September suggests that values are suspect if quoted for short periods when evapotranspiration is taking place at a high rate. Some difficulty was encountered regarding the reliability of soil flux values: extrapolation of the 4 cm and 8 cm readings in order to arrive at a 'surface' value resulted in some high values. This may have been due to instrumental error. Sensible heat values derived (using these values) were correspondingly very low. For the purpose of this analysis, the 8 cm reading was regarded as a 'surface' value.

The test of the rate of rise equation was not part of the original aim of this study and the result of such a limited test is inconclusive.

This study may be regarded as a 'pilot study' providing some useful guidelines for the analysis of the more extensive radio-sonde data which has resulted from experiment CABLE 74.

Acknowledgements

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LIST OF FIGURE CAPTIONS

FIGURE 1 NET RADIATION AND SENSIBLE HEAT FLUX (24 AUG 1973)


x — x Net Radiation
 0 — 0 Surface Energy Balance
 . Cardington Probe value
 | —  — | Summation technique over a period

FIGURE 2 PROFILES OF POTENTIAL TEMPERATURE (0 degC) - 24 AUG 73

$P_0 - P_1$ = height above surface (mb)

Sequence of Balthumb soundings:

. — . 0 — 0 x — x 
 0500 GMT 0838 GMT 1031 GMT 1654 GMT

FIGURE 2 (INSET) UPWARD SENSIBLE HEAT FLUX (mWcm^{-2})

Summation values for periods between successive soundings

(a) 0500-0838 GMT

(b) 0838-1031 GMT

(c) 1031-1654 GMT

FIGURE 3 PROFILES OF POTENTIAL TEMPERATURE (0 degC) - 7 SEPT 73

$P_0 - P_1$ = height above surface (mb)

Sequence of Balthumb soundings:









. — .	0715 GMT
x — x	0833 GMT
0 — 0	0928 GMT
 — 	1116 GMT
 — 	1241 GMT
 — 	1350 GMT
 — 	1650 GMT

FIGURE 3 (INSET) UPWARD SENSIBLE HEAT FLUX (mWcm^{-2})

Summation values for periods between successive soundings

(a) 0833-0928 GMT (b) 0928-1116 GMT

(c) 1116-1241 GMT (d) 1241-1350 GMT

(e) 1350-1650 GMT

FIGURE 4

NET RADIATION AND SENSIBLE HEAT FLUX (mWcm^{-2}) - 7 SEPT 73

x——x NET RADIATION
o——o Surface Energy Balance
• Cardington Probe value
|▲| Summation technique over a period
△——△ Negative (downward) flux from summation technique

FIGURE 5

PROFILES OF POTENTIAL TEMPERATURE (0 degC) - 12 SEPT 73

$P_0 - P_1$ = height above surface (mb)

Sequence of Balthem soundings:

•——•	0710 GMT
▲——▲	0941 GMT
x——x	1135 GMT
o——o	1650 GMT

FIGURE 5 (INSET) UPWARD SENSIBLE HEAT FLUX (mWcm^{-2})

Summation values for periods between successive soundings

(a) = 0710-1135 GMT

(b) = 1135-1650 GMT

FIGURE 6

NET RADIATION AND SENSIBLE HEAT FLUX (mWcm^{-2}) - 12 SEPT 73

x——x Net Radiation
o——o Surface Energy Balance
|▲| Summation technique over a period

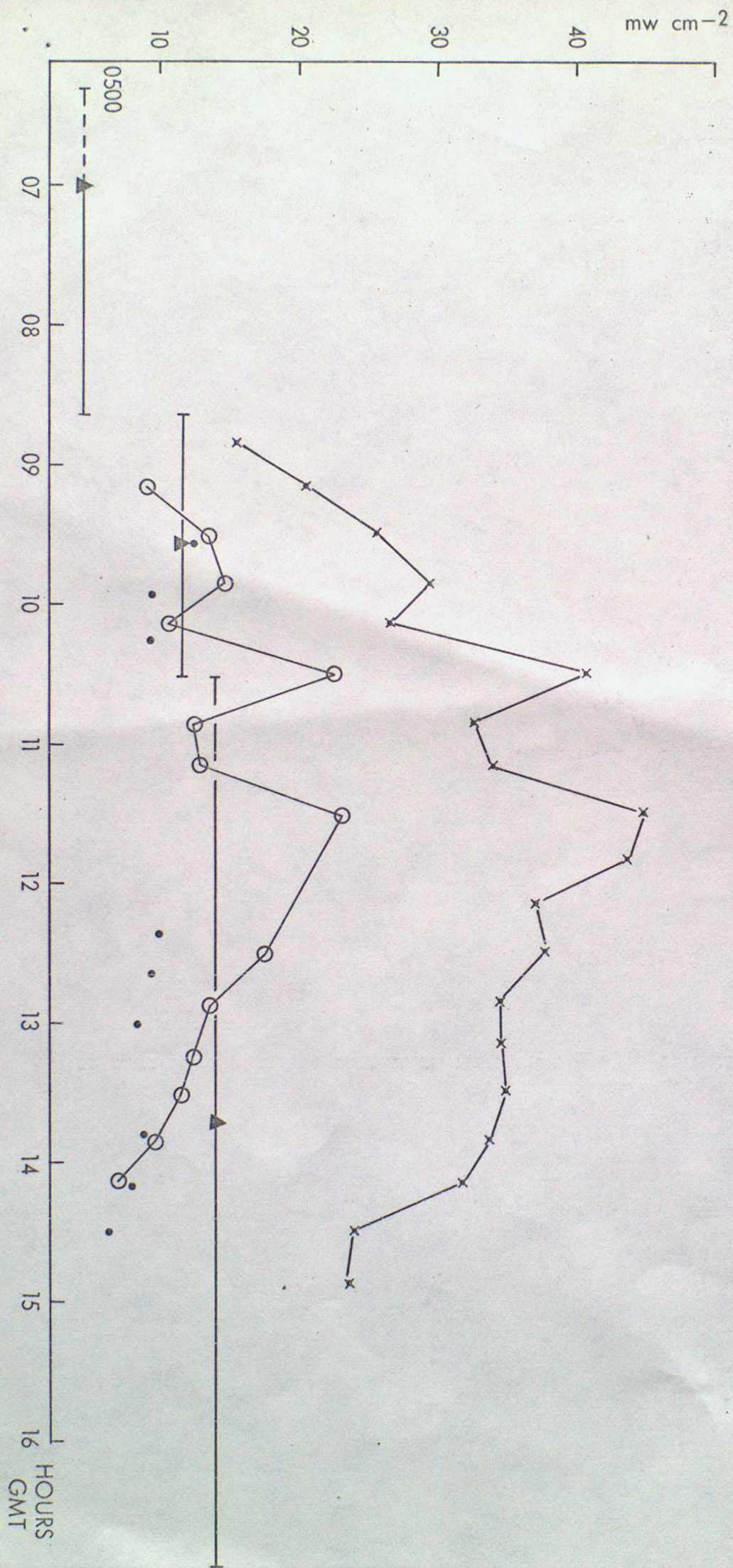


Figure 1

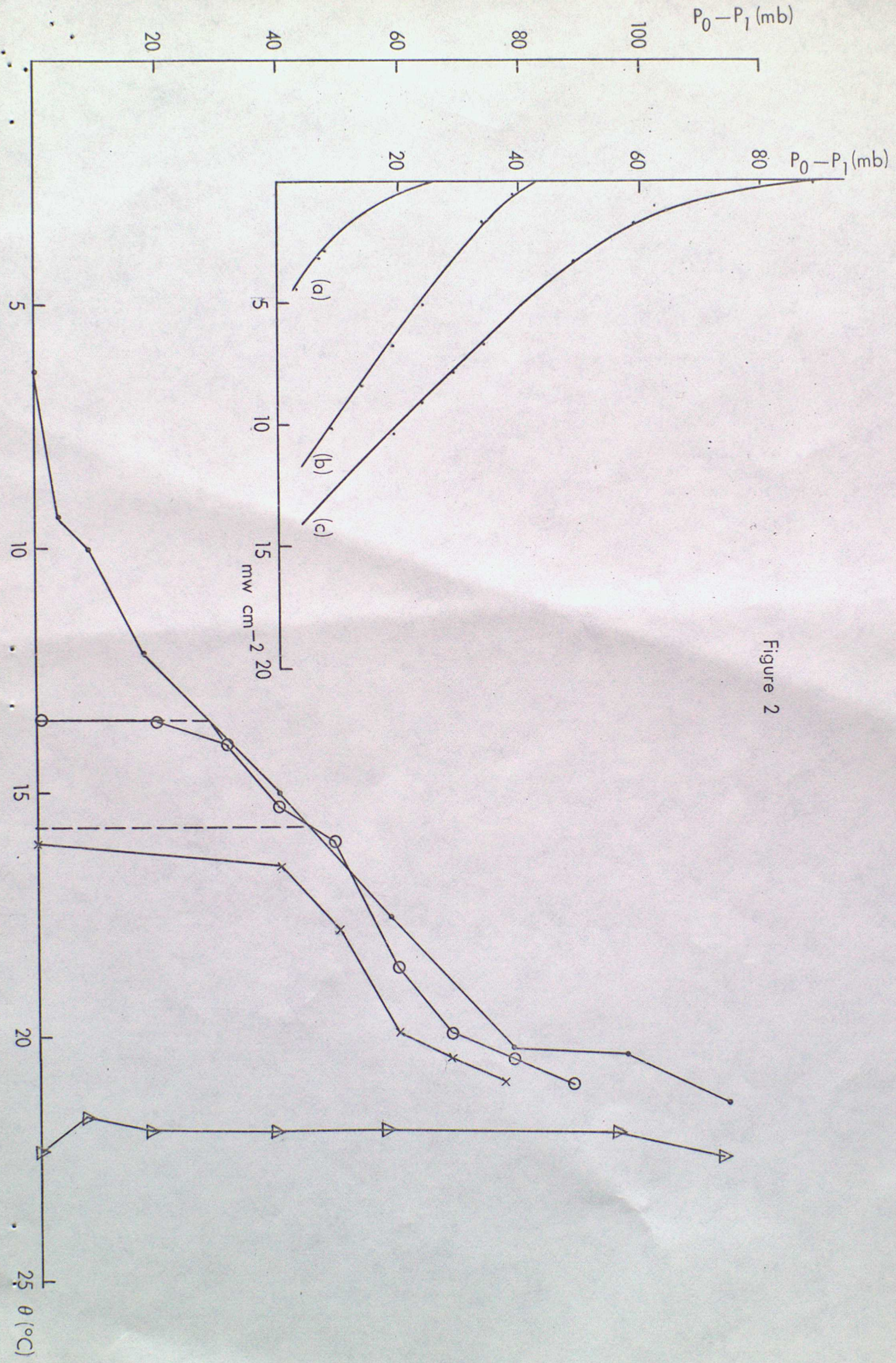


Figure 2

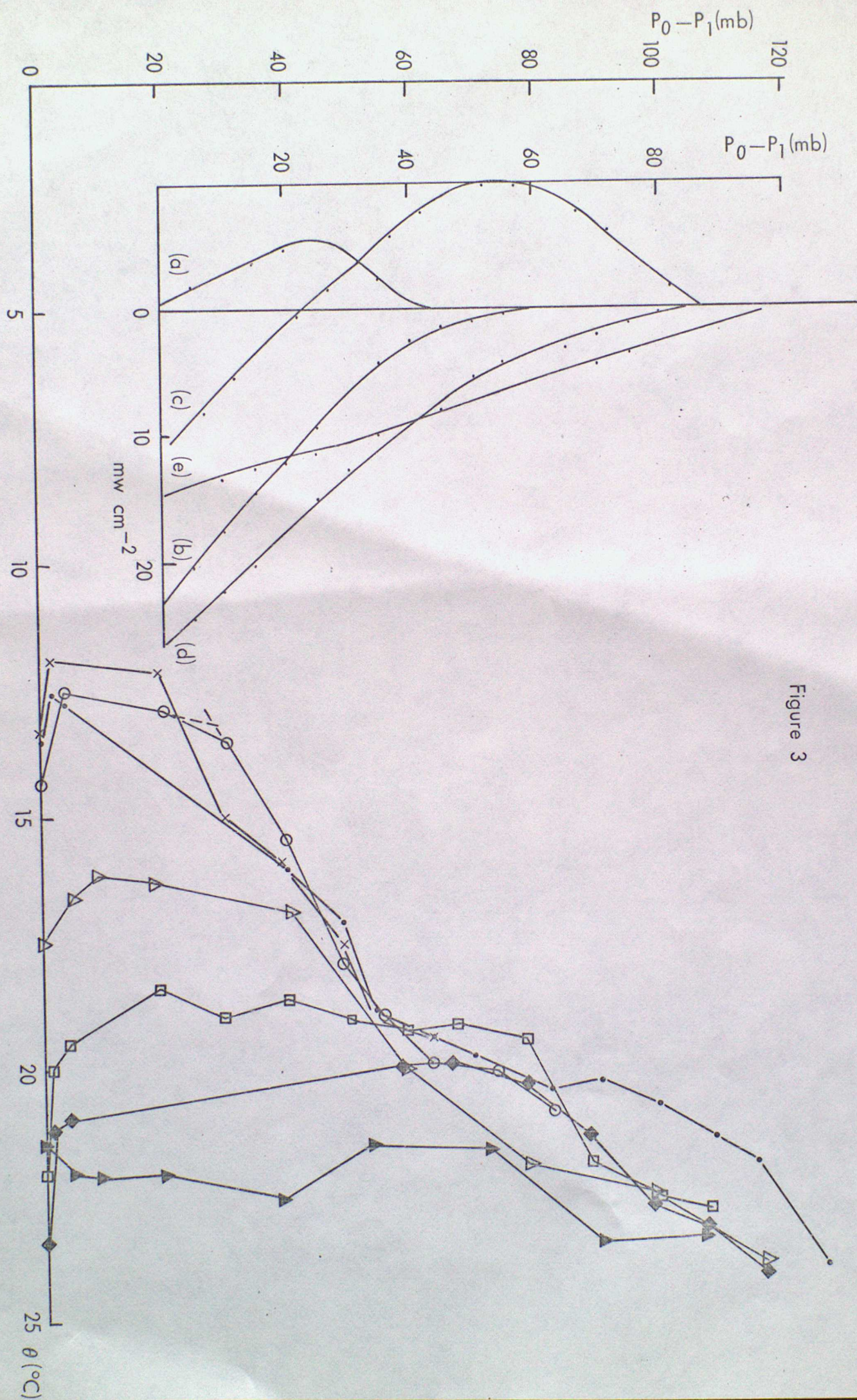


Figure 3

Figure 4

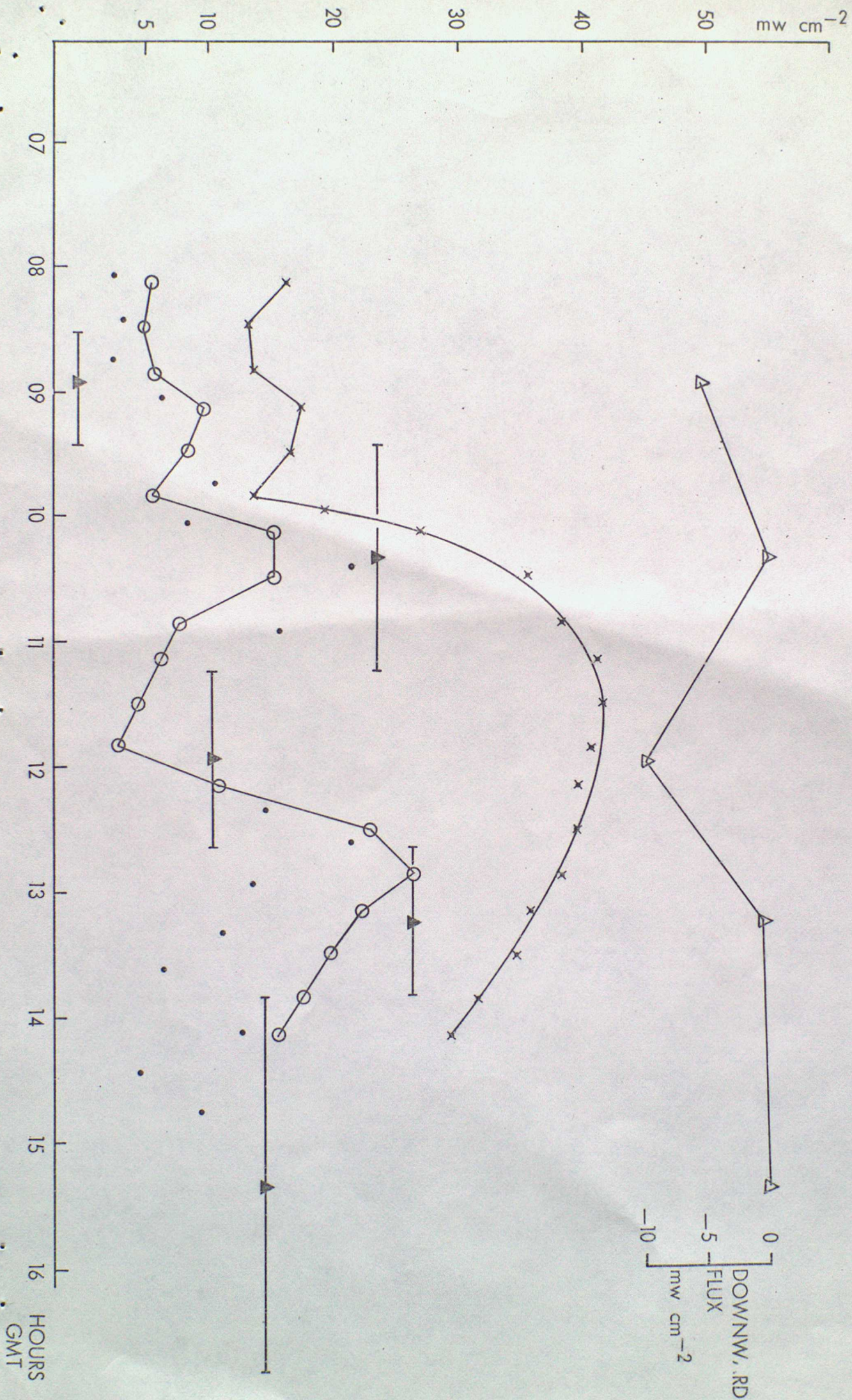
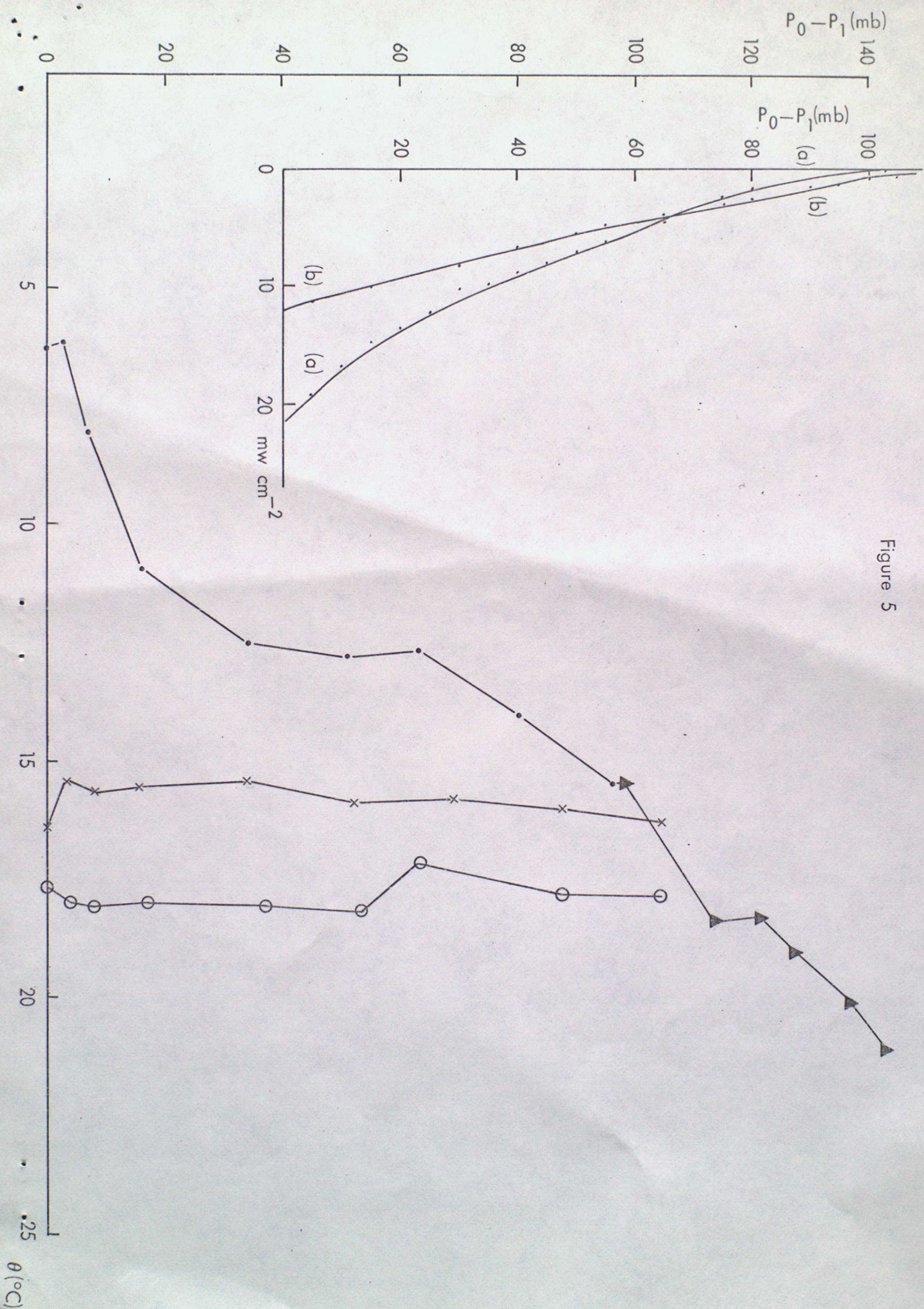


Figure 5



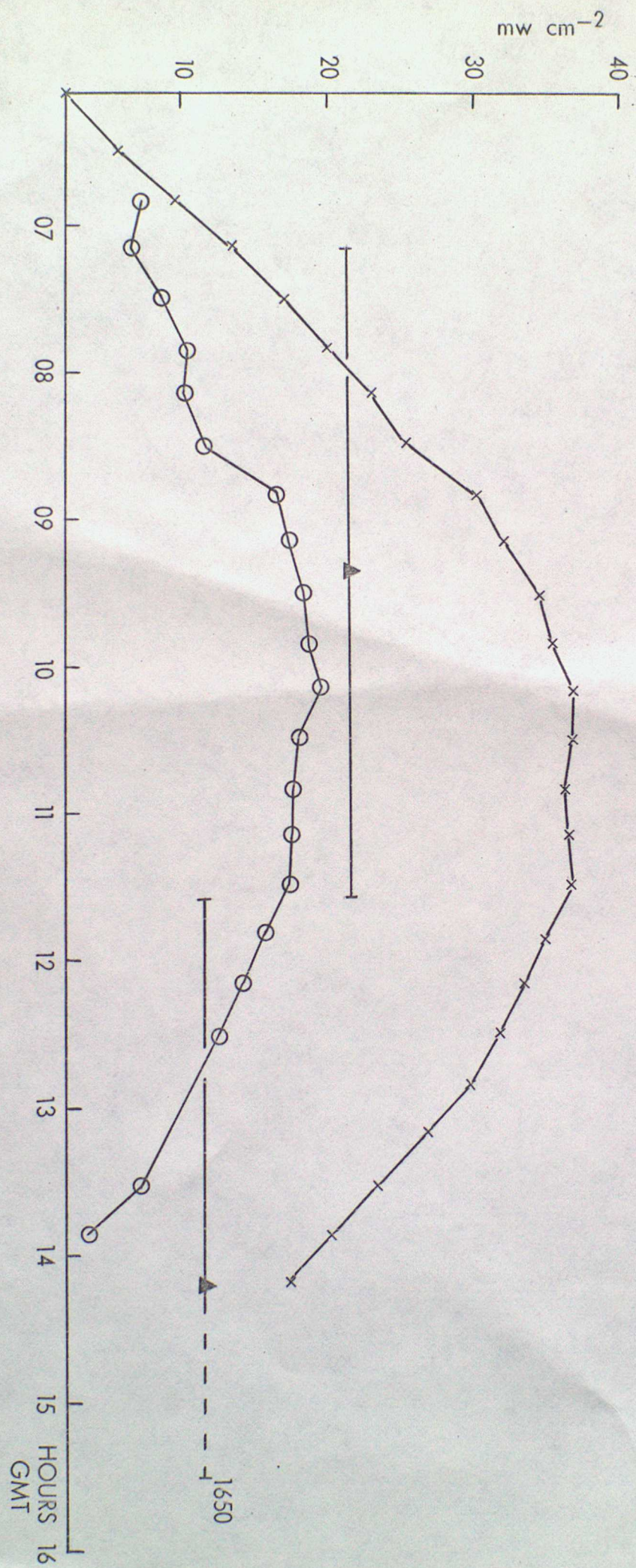


Figure 6