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RELATIONS BETWEEN MINIMUM TEMPERATURE AND TOPOGRAPHY IN BRITAIN

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Summary

The effects of topography on two measures of temperature, the daily minimum and the diurnal range, were investigated using the conventional network of climatological stations in the UK. The effects of water and buildings were minimised by restricting the analysis to data obtained from 145 inland rural sites, while topograhic influences were considered to be mainly due to the effects of local and large scale shelter. Local shelter is associated with height above the valley and is represented by the drop in height within 3 km, while large scale shelter is associated with the area being drained of cold air, and is represented by the average height of the terrain above the valley over a radius of 10 km. The height above the valley is the most important variable and its maximum effect on diurnal range occurs in the early autumn, when the difference in soil misture deficit between valleys and summits reaches its maximum. Large scale shelter is more important in winter than in summer, and for diurnal range, for rare rather than common events. This represents the increasing importance of nocturnal drainage with the length of the night and suitable radiating conditions. For minimum temperatures in winter, however, the maximum impact of large scale shelter occurs for events with a return period around 2 years, and which are loosely associated with cold spells lasting a day or so. More extreme temperatures are usually attained at the end of cold spells lasting several days, when continued radiational cooling over level ground can produce temperatures as low as those attained through cold air drainage.

1. Introduction

Minimum temperature is one of the most important of climatological variables. A knowledge of the lowest temperature likely to be experienced in a given number of years is required by planners and designers, while information on the frequency and severity of frosts is important to both the construction and agricultural industries, with the latter being especially sensitive in the spring. Many climatological enquiries inevitably relate to locations for which no observations are available, so estimates are obtained by means of subjective interpolation. For minimum temperature this is very difficult because of its dependence on topographical (and other) features. Quantification of the relationships between minimum temperature and topography would enable minima to be 'reduced' to a standard topography; spatial interpolation from such a field would then be relatively simple.

An excellent survey of all the factors affecting minimum temperatures, and of early work in the field, is presented by Geiger (1965). A qualitative review of topographical effects on night minima, with examples from the UK, is also provided by Manley (1944). Relatively little quantitative work on general relations between minimum temperature and topography has been performed; many authors have been concerned with documenting temperature variations observed in particular frost hollows (eg Waco, 1968; Catchpole, 1963; Albright & Stoker, 1974). In the more general studies, a wide variety of techniques have been used to obtain the required temperature data. Some workers, eg Hess et al (1975) and White (1979) have relied mainly on the established network of climatological stations while others, eg Jones et al (1979), Laughlin (1982) have set up dense networks of stations in a small area for a limited period of time. Hocevar and

Martsolf (1971) have been among those who attached instruments to cars to identify spatial variations in temperature, while Mahrt and Heald (1983) used radiation thermometers on low flying aircraft for the same purposes. Finally, radiation measurements from satellites have been used in the attempt to map minimum temperatures eg Chen et al (1979), Kalma et al (1983).

This paper is concerned only with the relationships between minimum temperature and topography, although the effects of other environmental factors such as buildings, water, soil and vegetation are discussed briefly. The temperature data was obtained from the established climatological network in the UK, while a data set containing spot heights on a 0.5 km grid was used as the principal source of topographic information. Local and large scale shelter were recognised as being important factors, and the topographic data set was used in an attempt to identify parameters which would provide objective representations of these variables. The topographic parameters were then regressed against measures of minimum temperature associated with given return periods. The explicit consideration of the return period acts as a considerable aid in the quantification of the relationships, and is a factor that has been notably absent from most previous work on the subject.

2. Environmental factors affecting minimum temperature

2.1 General review

Height above valley

On a clear night, the earth's surface cools by radiation to the sky but receives compensatory heat flows from the ground below and the air above. The surface temperature cannot fall indefinitely; even in the absence of compensating heat flows the temperature cannot fall below that of the sky radiant temperature. Heat transfer through the atmosphere takes place principally through radiative and turbulent exchange, and the latter will be weakest when winds are light and the atmosphere stable. A good early account of the theory of nocturnal cooling is provided by Fleagle (1950a) and an interesting applied study is presented by Greene and Nelson (1983).

On a clear night with little wind, radiation alone will produce a distribution of temperature in which the isotherms lie parallel to the surface. This introduces horizontal temperature contrasts which are reduced by thermally induced air motions, and consequently the isopleths lie more nearly horizontal. As a result, the lowest temperatures are found where the ground is locally lowest. When a wind is blowing, the most efficient means of heat transfer through the atmosphere occurs via turbulent exchange, and on these occasions the lowest temperatures are experienced where protection from the atmosphere above is greatest; ie again where the ground is locally lowest. The principal effect of topography on minimum temperature is therefore to provide variable protection from the un-modified atmosphere above, and thereby create variations in the depth and intensity of the surface cooled layer.

Large variations in minimum temperature can occur in complex terrain in the absence of substantial cold air drainage. A bowl shaped hollow will experience lower minima than a surrounding plain, for instance, yet very little of the temperature difference between the hollow and the plain will be due to cold air drainage. The temperature in the free atmosphere above the hollow will be similar to that over the plain, and minima in the hollow will be lower simply because of the greater depth of the surface cooled layer there.

Although genuine frost hollows such as that described above are rare, well-marked topographic features may be responsible for creating areas where the depth of the surface inversion is greater than elsewhere; in this paper such features are referred to as damming points. Often, such well marked features are absent and minimum temperatures will then increase with height above a main valley. This has been demonstrated by Harrison (1971) and Hocevar and Martsolf (1971) who found temperature increases of 4.9 and 6.2°C per 100m above valley floors in Kent and the Appalachians respectively.

Area drained

Nocturnal drainage of cold air is clearly an important factor in creating variations in the depth and intensity of the surface cooled layer. The drainage occurs through the mechanism of the well known katabatic winds, but their development is still not properly understood. An early attempt at a theoretical explanation is provided by Fleagle (1960b), and the literature on the subject is reviewed by Barry (1981). A brief description of the development of katabatic winds is given below.

Air which has been cooled by contact with the surface will become denser than that at the same level in the free atmosphere, and so if the land is sloping, the surface air will sink down the slope. Once cold air has collected in a valley and a stable lapse rate established, however, the mechanism by which the surface air descends to the valley bottom is destroyed, and the katabatics no longer penetrate to the surface (see Hawke, 1944). The low temperatures experienced in locations subject to nocturnal convergence of cold air, therefore, are not caused directly by the advection of air over the surface. The movement of air results in an increased depth of the surface cooled layer, and this provides extra 'insulation' from the warmer air above; it is this which allows the temperature at the surface to fall further. The strongest katabatics are generally observed in situations where the temperature differential between the highest and lowest levels is maintained by an external heat source, usually the sea. Examples are the very strong outflows which have been reported from Greenland and Antarctica (see Streten 1963)and the Bora wind of Yugoslavia.

The area of land being drained of cold air is clearly an important factor, but is very difficult to define. It is not just a question of measuring areas defined by conventional watersheds; if that were the case, the lowest temperature would be observed near estuaries. Any damming points upstream will deprive a conventional catchment of a supply of cold air and will have to be taken into account.

Slope

The reservoir of cold air ponded up in the bottom of a valley will be very stable and the air adjacent to the lower valley slopes will be in a state of equilibrium. At higher elevations, however, where the air is less stable, the cooled air adjacent to a slope will sink down, and this continual movement and replacement of air means that the surface cooled inversion is shallow, and minimum temperatures approach those in the free atmosphere. This is the origin of the well known thermal belt of the Alps and Appalachians in which the highest minima are observed at altitudes corresponding to the top of the surface cooled air occupying the valley.

Changes of slope are important. The depth of the surface cooled layer will be greater on concave than convex surfaces, with correspondingly lower minima on the concave slopes. This phenomenon has been pointed out by Lawrence (1956), Hess et al (1975), and Mahrt and Heald (1983). Aspect is expected to be more important for maximum temperatures than for minima.

Type of surface

Slope and vegetation are strictly separate variables, but are related through land use. Conduction of heat to the surface depends mainly on the amount of air trapped in the soil, and lower temperatures occur on dry soils (eg sand) than on those with large water holding capacities (eg clay). The height of vegetation is also important because if tall vegetation grows close to the screen, the level of the radiating surface is brought nearer the height of the thermometers. Trees can act as topographic features by directing the flow of cold air and creating frost hollows in forest clearings.

The characteristics of the surface can undergo large seasonal variations. Soils are generally drier in summer than in winter, and differences in their winter holding capacities are much more important in summer than in winter (see Eden, 1982). Deciduous trees lose their leaves in winter, so that clearings in deciduous forests form much more effective frost hollows in summer than in winter. Arable land is bare for much of the winter, but is covered by tall crops in early summer. A snow cover may completely transform the thermal and aerodynamical characteristics of a surface.

Buildings

Buildings affect minimum temperatures by emitting heat and by restricting the solid angle subtended by the sky. Chandler (1967) and Oke (1981) both show that the density of buildings is more important than the size of the town. Parry (1956) found that relief and urban effects accounted for most of the variance of minimum temperatures around a medium sized town in England. The industrial character of a town, however, is also important, for the amount of smoke emitted will influence minimum temperature through the turbidity of the atmosphere.

Proximity to water

Lakes can raise minimum temperatures considerably. Lakes downstream prevent the establishment of a 'damming point' while lakes upstream reduce the area of cold air draining to a station. Distance from the sea in all directions is also important once the effects of any intervening high ground have been taken into account.

2.2 Local and large scale shelter

The influence of topography on minimum temperature may be broadly categorised into the effects of local and large scale shelter. Local shelter may be associated with a height above the valley close to zero, while large scale shelter is related to nocturnal drainage of cold air from a large area of surrounding countryside. A site with local but no large scale shelter will typically lie in a shallow valley or hollow in gently undulating country; plenty of trees will help afford protection from the ambient wind. A station with large-scale but no local shelter will generally lie in the proximity of hills, but will receive no immediate protection from the wind.

The postulated fall of temperature on a clear night with light winds at stations with local and large scale shelter is illustrated schematically in fig 1. Consider two stations A and B, the first with local but no large scale shelter, and the second with large scale but no local shelter. At station A the local shelter enables the temperature to fall rapidly during the evening. The lack of any substantial cold air drainage, however, means that any further fall of temperature during the remainder of the night is relatively modest. At station B the lack of local shelter prevents the evening fall of temperature from being as rapid as at station A. The drainage of air from the surrounding countryside, however, enables the depth of the surface cooled layer to increase throughout the night, and the minimum will be lower than at station A.

2.3 Influence of climate

The effect of topography on minimum temperatures is clearly dependent on climate, since the temperature difference between valleys and summits for a given return period will depend on the frequency of clear, calm nights. Latitude will also be a factor by affecting the length of night and the intensity of the inversions which are established. To illustrate the influence of climate in more detail, consider 3 measures of minimum temperature (obtained over a period of 30 years, say):-

(i) daily min - this is the mean of all 24 hour minimum temperatures recorded in a calendar month.

(ii) monthly min - this is the mean of the lowest temperatures recorded in a calendar month.

(iii) extreme min - this is the lowest temperature recorded in a calendar month during a period of years.

Next consider 3 types of climate - cloudy and windy, clear and calm, and an intermediate type representative of Britain. The distribuion of daily, monthly, and extreme minimum temperatures in the 3 types of climate are illustrated in fig 2 for 3 types of site - standard, and those with local or large-scale shelter.

In a cloudy, windy climate, good radiation nights are so rare that the daily min at a site with large scale shelter is scarcely any lower than that at the standard site. Even the monthly min associated with large-scale shelter will be above that obtained with local shelter. For the extreme min, however, the potential of large scale shelter in producing low minima is finally realised.

In a clear, calm climate even the daily min will be lower at the site with large scale shelter than that with local shelter. The monthly min will be nearly as low as the extreme min.

The British climate lies closer to the cloudy, windy regime than to a climate with a prevalence of clear, calm conditions. As a consequence, British frost hollows based on large-scale shelter can scarcely be identified from an examination of daily min. Their full potential is only realized in the extreme min.

In the above discussion, it has been assumed that the extreme min has been attained as the result of a large overnight drop in temperature. If this is not the case, as occasionally happens in winter, then large scale shelter will not be so crucial to the production of low temperatures. This situation is discussed further in section 6.5.

The effect of distance from the coast is also dependent on climate. In cloudy, windy weather, locations a few tens of km from the coast are strongly maritime; under calm, clear conditions, continental influences at those places are much stronger. Climate also affects the state of surface through the frequency and depth of snow cover and the dryness of soils.

2.4 Illustration of differing topographical effects

The differing topographical effects on minimum temperature cause the rank of a particular station in a 'frost hollow league table' to vary with return period and season. This is illustrated in fig 3 by comparing the departures of the daily, monthly, and extreme minimum from the long period monthly means for 4 stations - Oxford, Rickmansworth, Braemar, and Santon Downham.

Oxford is a standard site used as a reference with which to compare the other 3 frost hollow stations. The departure of the daily min from the monthly mean is merely half the average diurnal range of temperature, and this peaks in summer. The departure of the extreme min from the mean, however, is greater in winter than in summer, a consequence of the best radiating conditions being associated with cold weather in winter and warm weather in summer. The departure of the monthly min from the mean is intermediate between the other two values, and accordingly undergoes only small seasonal variations.

Rickmansworth has generally been regarded as the most extreme frost hollow recorded in Britain, and the site is described by Hawke (1944) and King (1952). It is, however, based essentially on local shelter, with no large scale drainage of cold air toward the station. Fig 3 shows that the departure of the daily min from the mean far exceeds that at Oxford, but that its performance in respect of monthly and extreme minima is far less spectacular.

Braemar holds the record for the lowest temperature recorded in the UK, and the site has been described by Manley (1978). The station is not located in the lowest part of the valley, and the local shelter is modest. The catchment area of cold air, however, is wide. Fig 3 shows that for daily min, no frost hollow characteristics are evident. For monthly min, however, they are becoming apparent, and in winter the departure of the extreme min from the mean exceeds that for Rickmansworth. Given perfect radiating conditions, the long nights and snow cover experienced at Braemar in winter enable its potential as a frost hollow based on cold air drainage from a wide area of central Scotland to be fully realized. The relatively cloudy and windy prevailing climate also helps to emphasize the differences between the extreme min and the daily min compared with other sites examined.

Santon Downham is renowned for its low temperatures in summer and its short frost free season. The latest site is described by Hurst (1966) and Oliver (1966), although this is not quite the same as that from which the data in fig 3 was obtained. The frost hollow characteristics are based on local shelter, and are derived from soil and vegetation rather than relief. The departure of the daily min from the mean is the highest of the currently recording stations, although it is much less than that observed at Rickmansworth. The seasonal variation in the departure of the extreme min from the mean is less than at Oxford, and in summer the values exceed those recorded at Rickmansworth. The frost hollow characteristics are more pronounced in summer because of the drier soil and longer vegetation in that season than in winter. The present site is in a clearing in a coniferous forest, with cold air draining off the forest canopy. If the forest was deciduous, the contrast in frost-hollow characteristics between summer and winter would be even more marked.

3. Data

3.1 Climatological parameters

The effects of topography on minimum temperature are best investigated when variations due to other factors, eg latitude and altitude, have been minimised. Two appropriate climatological variables to use are therefore the diurnal range of temperature (hereafter referred to simply as the diurnal range) and the departure of the minimum from the long period mean temperature for the month. Both of these parameters are compromised by topographic effects on the maximum temperature, but variations in the minimum temperature are expected to be dominant.

A disadvantage of the departure of the minimum temperature from the mean is its dependence on the overall variability of temperature at a station, which causes much larger values to occur in the interior of continents than in coastal regions. These geographical variations can be eliminated by using the diurnal range. The lowest temperatures in winter, however, are not necessarily associated with large diurnal ranges, as the surface inversion present during periods of cold weather gradually increases its strength day by day. Furthermore, the largest diurnal ranges in winter may be caused by advection rather than radiation.

There are two main practical applications of this work:-

(i) the liability to frost for construction and agricultural purposes, the latter being particularly sensitive in the spring.

(ii) the lowest winter temperatures likely to occur in a given return period for use in engineering design.

For estimating the liability to spring frosts, the diurnal range is likely to be the most appropriate variable. The largest diurnal ranges in spring will be caused by radiation rather than advection, and there will be no geographical variations caused by differences in the variability of temperature. For estimating the lowest temperatures likely to occur in winter, however, the departure of minimum temperature from the mean is likely to be the more appropriate variable. In this paper, topographic variables are related to both the diurnal range (R) and the departure of the minimum temperature from the monthly mean (T).

3.2 Climatological data

Monthly means and extremes of maximum and minimum temperature were available for all stations in the UK with less than 120 months of missing data in the period 1959-79. A few other stations with slightly less data were also included, and this brought the total number of stations available to 570. A data set containing monthly maximum values of diurnal range for a similar number of stations was created, and is described by Tabony (1984). Missing values in all these data sets were then estimated using the procedures described by Tabony (1983).

Measures of diurnal range selected for analysis were

R_A = average diurnal range

R_2 = median value of the highest diurnal range in a month.

R_{30} = diurnal range to be expected once every 30 years in a calendar month.

Similar measures of the departure of the minimum temperature from the monthly mean were also selected:-

T_A = departure from the mean of the average daily minimum.

T_2 = departure from the mean of the median value of the lowest minimum in a month.

T_{30} = departure from the mean of the lowest temperature to be expected once every 30 years in a calendar month.

There are only 5 independent variables here since $T_A = 0.5R_A$.

The average and median values (ie R_A, T_A, R_2, T_2) for each month were obtained directly from the data. The 30 year events were calculated by fitting a 2 parameter extreme value distribution to the monthly extremes using a program devised by Jenkinson (1977) which gave extra weight to the more extreme observations. An example of its application is given by Tabony (1984).

As the monthly extremes only represent the largest values drawn from a small number of independent observations there is no question of the theory of extreme values being satisfied. Neither is there any question that fitting a linear relation to the values obtained is physically realistic. The procedures were adopted merely to provide measures of R and T which exhibited less random scatter than the most extreme observations in the period 1959-79 (Rx and Tx respectively). It is therefore necessary to show that no systematic errors are introduced by such a procedure.

For 145 inland rural stations, table 1 compares the mean, standard deviation and skewness of R_{30} and Rx, T_{30} and Tx (meaned over all months), and shows that Rx and Tx exceed R_{30} and T_{30} by only 0.2 to 0.3°C.

Assigning a probability p to the mth ranking of N observations by the equation

$$p = \frac{m-0.31}{N+0.38}$$

gives the largest observation in 21 years a return period of 31 years. This indicates that Rx and Tx should exceed R_{30} and T_{30} respectively by 0.05°C so the differences in table 1 can be reduced by this amount. Hence it can be concluded that R_{30} and T_{30} form a good representation of the most extreme events in 21 years of observation.

Much of the work in this paper involves values of R_A, R_2, R_{30}, T_2 and T_{30} which have been meaned over all months. For investigating seasonal variations, however, it was found advantageous to smooth the monthly values using a 7 point binomial filter to obtain a smooth seasonal variation (see Lee, 1981).

3.3 Topographic Data

The topographic data most commonly used was derived from a data set containing spot heights on a 0.5 km grid. The spot values had been modified to enable contour lines drawn from the grid to closely resemble those on the original Ordnance Survey maps, thereby allowing the main topographic features to be retained.

In view of the possible difficulties in defining appropriate topographic parameters from a grid point data set, estimates of parameters such as height above the valley were estimated subjectively from 1:50000 Ordnance Survey maps. The strength of the relationship between these estimates and minimum temperature then forms a bench mark against which the performance of the objective estimates may be assessed.

Two types of subjective estimates were made. First values of the height above a damming point (h_d) were based on the following guidelines:-

(i) If the station was above a main valley, h_d was estimated as the drop to the main valley combined with the drop along the valley until a damming point was encountered. This could have been a bend in the valley, a junction with a larger valley, a constriction in valley width, or a sudden slackening of gradients.

(ii) If the station was above a minor valley, h_d was estimated as the drop to the minor valley combined with the drop along it to the major valley; the junction with the major valley was deemed to be the damming point.

The identification of a damming point often proved difficult, and frequently the procedure degenerated into following the main valley for an arbitrary distance. Hence a new scheme was devised in which the drop in height from the station, following the valley, was extracted at fixed distances along the valley. It was felt that this procedure combined the advantages of manual inspection of the maps with a reasonably unambiguous means of determining the drop in height along the valley. The opportunity was also taken to extract information on the proximity of the station to buildings and water. The parameters extracted were

(i) The drop in height from the station following the valley for distances of 0.1, 0.3, 1, 3, and 10 km.

(ii) For circles of radii 0.1, 0.3, 1, 3 and 10 km centred on the station, the percentage of area covered by buildings.

(iii) For the same radii, the percentage of area covered by water. An estimate of the distance from the coast was also made.

To help identify the influence of topography, the effects of water and buildings were largely eliminated by combining the analysis to inland rural sites. The following criteria were used in the selection of stations:-

(i) The station must be more than 10 km from the coast. The preliminary analysis of diurnal range by Tabony (1984) showed that maritime effects disappeared rapidly inland.

(ii) The proportion of the surroundings covered by buildings, as estimated for all 5 radii above, must be less than 25%.

(iii) The proportion of the surroundings covered by water, as estimated for all 5 radii above, must not exceed 5%.

(iv) The ability to estimate the drop in height along the valley must not be impaired by the presence of lakes.

The number of stations satisfying these requirements was 145, around one quarter of the total examined, and their distribution is shown in fig 4.

4. Statistical modelling considerations

4.1 General

The most important topographic variable is the height above the valley (h) and this is expected to have an exponential relationship with diurnal range in the form

$$R = C + Be^{-Ah}$$

This involves fitting 3 parameters A, B and C but since observations from 145 stations are available this might be considered to be straight forward. Fig 5, however, shows that this is not so. It displays a plot of R_2 (meaned over all months) against the drop in height from the station within 3 km (h_1) derived from the 0.5 km topographic data set. Two exponential fits to the data are shown corresponding to the equations

$$R_2 = 9.24 + 5.86e^{-0.0055hl}$$

and

$$R_2 = 7.09 + 7.92e^{-0.0035hl}$$

Fig 5 shows that these two equations give similar solutions over the range of observations, yet the 3 parameters fitted are all quite different. Clearly the best values of the parameters to use are not well defined; higher values of the asymptote C are associated with lower values of the scale parameter B and larger values of the curvature parameter A. A reduction in the number of unknown parameters to two by assigning a value to the third is clearly in order.

In any statistical investigation in which one variable is expressed in terms of several others, it is generally convenient to use the wealth of statistical procedures based on the general linear model. The exponential relationship between diurnal range and height above the valley is conveniently linearised by assigning a value to the asymptote C and making the independent variable ln (R-C). This procedure involves constraining the relationships involving other topographic variables, essentially those relating to large scale shelter, to be linear with ln (R-C) rather than R. This is physically realistic. The effect of adjacent high ground is expected to be large for valley sites but minimal for summit stations, and this is the non linearity introduced by making the transformation. The identification of topographic parameters in section 5 was therefore carried out using ln (R-C) as the independent variable; this required the assignment of reasonable values to the asymptote C, and this process is described in section 4.2.

A disadvantage of the above procedure is that the regressions produced are associated with RMS errors which are minimised for ln (R–C) rather than R. During the final regression analyses it became apparent that the reduction in the explained variance of R, at around 5%, was larger than expected. It was therefore decided to obtain the final relations using R and T as the independent variable, and this was achieved by assigning a value to the curvature parameter A, rather than the asymptote C, and defining a new variable $Hl = e^{-Ahl}$. The procedures used to determine A are described in section 4.3.

The assigning of a curvature parameter at first sight seem to be more of an imposition than the forcing of an asymptote, but fig 5 shows that this is not so. The two regression lines displayed show that large differences in the curvature parameters do not necessarily imply large differences in the solutions over the range of observations, and it is quite acceptable to impose a reasonable value to the curvature.

4.2 Assignment of asymptotes

The concept of the asymptote is that on an isolated mountain summit, well above the influence of most of the surface, there will still be a finite diurnal range due to the heating and cooling of the summit itself. The problems in using data from the 145 stations to define an appropriate value of C stem from the fact that they do not contain sufficient high level sites with values of R and T close enough to the asymptote to clearly indicate its true value. Manuscript data from the Ben Nevis Observatory maintained from 1884 to 1903 were therefore used to give an indication of the likely levels. R_2 and R_{30} could not be readily evaluated, but values of R_A = 3.8°C, T_2 = 6.6°C and T_{30} = 10.2°C (meaned over all months) were obtained. The values for T_2 and T_{30} are only around 0.8°C less than the lowest values obtained from the 145 stations being analysed.

Some statistics concerning the temperature parameters for the 145 stations under investigation are presented in table 2. It was found that the standard deviation of each of the parameters was around 10% of the mean and that by taking 65% of the mean value, figures were obtained which were slightly less than the lowest values observed at the 145 stations, and, for T_2 and T_{30}, similar to those observed at Ben Nevis. The asymptotes were therefore set to 65% of the mean values of the temperature parameters.

The asymptote for R_A corresponds to the diurnal range expected on an isolated mountain summit in 'average' weather and will, therefore, be a function of climate. By assigning a fixed value, this variation with climate is being ignored. For the time being, however, it is sufficient to note that it is variations in climate which account for the assigned value of the asymptote for R_A being well above the value observed at Ben Nevis.

4.3 Assignment of curvature parameters

When exponential regressions with 3 parameters were fitted to the relations between h_1 and temperature, a wide range of curvatures were obtained, with values ranging from -0.0030 for R_2 to -0.0053 for T_{30}. When asymptotes were imposed, however, the values were much closer and ranged from -0.0047 for T_{30} to -0.0060 for R_{30}. It therefore seemed reasonable to choose a mean value, around -0.0055, for use with all parameters.

The imposition of various curvatures to the relations between hl and temperature showed that the variance explained was very insensitive to the precise value used; this can be seen from fig 5. The greatest temperature variance was explained for curvatures around -0.0035, but -0.0055 was consistent with the preferred values of the asymptotes and was accordingly adopted as the chosen value.

5. Identification of topographic parameters

5.1 Height above valley

Estimates extracted manually from Ordnance Survey maps

Two types of subjective estimates were made, those based on height above a damming point (hl) and the drop in height following the valley for distances of 0.1, 0.3, 1, 3 and 10 km. The latter are denoted by h_0, h_1, h_2, h_3 and h_4 respectively, and it is with the analysis of these that this subsection is concerned.

Some of the characteristics of the h's are given in table 3, which shows that they are highly correlated with one another and positively skewed with their standard deviations almost identical to their means. Their correlations with the logarithmically transformed temperature parameters are presented in table 4. It had been expected that the correlations involving R_A would be less than those obtained from the other variables, as the effects of cloudy, windy weather, changes in climate, and distance from the coast all assume greater important for R_A than for the other variables. Despite this, however, table 4 shows that the association with the h's is stronger for R_A than for the other temperature parameters.

A point of interest is that the highest correlation is acheived with the drop in 10 km for R_A, the drop in 3 km for R_2 and R_{30}, and the drop in around 2 km for T_2 and T_{30}. The high correlation between R_A and the drop in 10 km reflects the deterioration of climate (and hence the decrease of R_A) with altitude.

It had been expected that a linear combination of all the drops would yield a higher correlation with temperature than any individual drop, but this was not found to be so. Multiple regressions involving various combinations of the h's failed to improve on the correlations (averaged over all parameters) obtained with the drop in 3 km (h_3), which was accordingly chosen as the best estimate of height above the valley.

Estimates obtained from the 0.5 km topographic data set

During the manual extraction of the drop along the valley there was sometimes ambiguity about which valley to follow. The impression was formed that the height of the station above the lowest point within a given distance of the station would secure an equally good correlation with the temperature parameters. Accordingly the 0.5 km topographic data set was used to obtain this height difference (h_1) for a square array of 2 K_1 x 2 K_1 gird points; h_1 then represented the height of the station above the lowest point within K_1 grid points.

Correlations between h_1 and the logarithmically transformed temperature parameters were evaluated for a range of values of K_1 and the findings were similar to those obtained using the manually extracted data. The correlations change only slowly with k_1 and the highest values were associated with a value of K_1 = 6, corresponding to the drop in height from the station within about 3 km.

Since the 0.5 km topographic data set enables valleys to be followed, the drop in height along the valley was obtained as follows. The deepest nearby valley was located by finding the point with the lowest height within a square of dimension X grid points. This valley was then followed by selecting the point with the lowest height from a square containing the 8 neighbouring points. If this procedure failed to provide a single point with a lower height than the previous value then the size of the square being searched was increased until all ambiguities were removed. This procedure was follows for various values of X and k_1, but no improvements over the simple relations with h_1 were obtained.

Comparison of estimates

A comparison of the 3 estimates of height above the valley, ie h_d, h_3 and h_1 is presented in table 5. It shows that they are highly correlated with one another and have very similar mean values, indicating that they all represent the drop in height from the station within about 3 km. The height above the damming point h_d is the least similar of the three, and this is reflected by its larger variance. Differences between h_d and the other two estimates arose when there were well defined damming points close to the station (when h_d would represent the drop over a distance shorter than 3 km), or when a station was located above a long, uninterrupted slope (when h_d would represent the drop over a distance greater than 3 km).

The performance of the three estimates was assessed by fitting 3 parameter exponential regressions, and averaging the variance accounted for over the 5 temperature parameters. The values of the asymptotes obtained (averaged over the temperature parameters) are shown in table 5.

Estimates of h_d were assigned with a prior knowledge of the values of R_2 and R_{30}. The 50% of the variance explained by h_d therefore probably represents an upper limit to that which can be obtained by a measure of the height above the valley. In this context the performance of the objective h_1 in accounting for 42% of the variance is most encouraging, and this is the parameter which is used in subsequent analyses as a measure of local shelter.

5.2 Mean height of terrain above valley

Measures of large scale shelter in general, and of the area of land being drained of cold air in particular, are difficult to define. The mean height of the terrain above the valley (h_a) is a variable which is expected to be closely associated with large scale shelter and which can be readily evaluated. It is clearly relevant to the protection of the valley from the free atmosphere and is also proportional to the area of land being drained.

The mean height of land was calculated over a square array of K_a x K_a grid points obtained from the 0.5 km topographic data set and the value of h_a obtained by subtracting the height of the lowest point within 6 grid lengths of the station. Values of h_a were evaluated for a range of K_a, and the most appropriate ~~to~~ value of K_a to use obtained by regressing h_a against the residuals of the relations between h_1 and the logarithmically transformed temperature parameters. It had been expected that the best relations would be obtained by centring the area on the lowest point, but it was found that correlations with areas centred on the station were almost as high, and these are the values presented in table 6. It can be seen that, as expected, R_A is essentially unrelated to h_a, but that for the other temperature variables the correlations increase steadily with k_a until about $k_a = 40$, when they become fairly constant.

The best value of k_a to use was chosen as 40, corresponding to a square of dimensions 20 km or 'radius' of 10 km. Since the data include stations as close to the coast as 10 km, squares larger than this may include an area of sea. The decision to include stations as close to the coast as 10 km therefore effectively limits the investigation of the most appropriate value of k_a to a value not exceeding 40.

The height of the terrain averaged over all points in an area may not be the best measure of large scale shelter. It may depend on the presence of some high ground which may not need to be extensive. Accordingly the mean height was calculated not from all grid points in a square, but from the highest X% of them. Another modification was to require that the highest X% be selected equally from the 4 quarters of the square. Neither of those variations yielded any improvement over the relations obtained using simple measures of h_a.

5.3 Quadratic fit to terrain

The degree of nocturnal cooling may be expected to be related to the large-scale curvature of the land - a concave surface is likely to produce lower minima than convex terrain. This possibility was investigated by fitting 3 types of quadratic surface to topography:-

(i) A full quadratic of the form

$$Z = a_1 + a_2x + a_3y + a_4x^2 + a_5y^2 + a_6xy + a_7x^2y + a_8xy^2 + a_9x^2y^2.$$

where x and y are horizontal distances in perpendicular directions and Z is the height of the surface.

(ii) A shorter equation in which some of the cross-products of x and y were omitted, ie.

$z = a_1 + a_2x + a_3y + a_4x^2 + a_5y^2 + a_6xy$

(iii) A simple type of the form

$z = a_1 + a_1x^2 + a_5y^2$

The surfaces were calculated over a square of dimensions kq points and the degree of curvature estimated by evaluating the height of the surface at the centre of the square and subtracting this from the mean height of the square (hq).

Values of hq were computed for a range of kq for squares centred on the station and the lowest point, and were regressed against the residuals of the relations between the logarithmically transformed temperature variables and h_1 and h_a. All three equations yielded similar results and so the simplest, representing a bowl or dome, was preferred. None of the permutations tried, however, yielded correlations which much exceeded 0.2.

Another relevant variable to minimum temperature is the goodness of fit of a concave quadratic surface. For concave surfaces with the same values of hq, the area of nocturnal drainage of cold air is likely to be greater for a smooth land surface in the shape of a bowl rather than rough terrain with many hills and valleys in the kq x kq grid point square. A simple measure of the goodness of fit is how closely the quadratic surface, evaluated at the site of the lowest point, approaches the altitude of that point. Because of the relatively modest degree of curvature, however, this height difference was highly correlated with h_a, and so little additional variance could be explained.

5.4 Slope and aspect

Slope and aspect are clearly variables which may be expected to exert a secondary influence on minimum temperature and diurnal range. The effect of slope may already have been largely accounted for by h1, but the effect of north and south facing slopes remains to be assessed.

The components of slope to the north and east were calculated from the 0.5 km topographic data set for a rectangle of K_E points in the east-west direction and K_N points in the north-south direction. These were combined to form a measure of overall gradient and regressed against the residuals of the relations between the logarithmically transformed temperature parameters and h1 and h_a (h_1 only for R_A). As expected, no relations were found with the overall slope or the gradient to the east, but for R_A, a weak relation with the component of slope to the north was found for gradients calculated over a rectangle elongated in the east-west direction (10 x 4 points). This presumably represents the fact that the raising of maximum temperatures on south-facing slopes is greatest where the slope has a reasonable east-west extent.

Correlations were obtained between the component of slope to the North and the residuals of the relations with R_2, R_{30}, T_2 and T_{30} which were not anticipated. For R_{30}, the results are displayed in table 8. South-facing slopes are credited with positive gradients and so the negative correlations indicate that diurnal ranges are largest, and minimum temperatures lowest, on north facing slopes, with the largest effects associated with gradients evaluated over rectangles elongated in the north-south direction (16 x 4 points). Possible reaosns for this are discussed in section 6.3.

6. Regression of topographic parameters on temperature

6.1 Variables considered

The topographic parameters considered were

h_l - the height of the station above the lowest point within 6 grid lengths

h_a - the average height of the ground over a square of 40 x 40 grid points, centred on the station, above the lowest point within 6 grid lengths of the station.

h_q - the average height of the ground above that of a 3 term quadratic surface, evaluated at the station, both calculated over a square of 40 x 40 grid points centred on the station.

G_N - component of gradient to north (south facing slopes positive) calculated over a rectangle of 16 points in the north-south direction and 4 points in the east-west direction.

G_S - component of gradient to north (south facing slopes positive) calculated over a rectangle of 4 points in the north-south direction and 10 points in the east-west direction.

G_O - overall gradient measured over 4 x 4 grid points around station

The heights were expressed in metres and the gradients in metres per km. The parameters h_l, h_a, G_N and G_S are those which were found to be important in section 5. G_O and h_a were included because, although they did not feature strongly in the preliminary analysis of residuals, they might yet emerge as important in the final regression analysis.

Two further variables were chosen to represent the effects of climate:-

$N^1 = 0.001\ (N - 0.22E)$ (units = 100 km)

where E and N represent national grid eastings and northings respectively, and S = average number of days with snow lying in a year.

N^1 measures the distance along the length of Britain and is used to represent the deterioration of climte to the NNW. This was preferred to the direct use of climatological variables such as wind and sun since they were not observed at many of the stations used and it was not clear how they should be combined to form an overall measure of the nocturnal radiation climate. Distances measured along other axes were also tried, but the relations obtained were insensitive to the precise orientation of the axes used.

The average annual duration of snow cover was deduced from the work of Jackson (1978). His map of the number of days with snow lying at sea level formed the basis of an exponential relation with distance to the north east,

ie $$S_L = \exp[0.5 + 2.25 \times 10^{-4}(E+N)]$$

which was used to estimate the number of days with snow cover at sea level at inland locations (S_L). The number of mornings with snow lying at station height hs was then estimated using the relation given by Jackson for altitudes up to 400m,

ie. $$s = S_L \exp\ (hs/300)$$

The effects of large scale shelter, represented by the variabels h_a and h_q, are not expected to be independent of hl. The impact of h_a and h_q

is expected to be large in valleys but small on summits, and this was taken into account by forming new variables

$$H_L = e^{-0.0055hl}$$

$$H_A = e^{-0.0055hl}.h_a$$

and

$$H_Q = e^{-0.0055hl}.h_q$$

which were used as dependent variables in the regression analysis. H_A and H_Q are equal to ha and hq respectively when hl = 0 but approach 0 as h_l approaches ∞. The sample of data available could have been used to indicate the form of interaction between h_l, h_a, and h_q, but the confidence limits would have been very wide. It was considered better to use the a priori physical knowledge to impose reasonable relations between them. The regression equation set up therefore took the form

$$T = a_o + a_1 H_L + a_2 H_A + a_3 H_Q + a_4 G_N + a_5 G_S + a_6 G_o + a_7 N^1 + a_8 S$$

A whole range of cross products of these variables, representing the interactions between them, was also supplied, but because they were highly correlated with one or other of the original variables they failed to account for much additional variance, and were omitted. The interaction most worthy of discussion is that between H_L and N^1.

The term in N^1 represents the effects of overall climate by making the asymptote a function of N^1, but climate also affects the strength of the relations between temperature and height above the valley (and other topographic parameters). The sample of data could be used to obtain an estimate of the interactions between H_L and N^1, but in the interests of simplicity, it was decided to ignore this term. It is not expected to be important for the 2 year and 30 year events and comparisons between the equations are facilitated when the regression for R_A takes the same form as those for the remaining temperature parameters.

6.2 Survey of parameters

The mean, standard deviation, and skewness of the topographic parameters are presented in table 8. It shows that a typical inland rural station is 46 metres above the lowest point within 3 km but 36 m below the average height over a 20 km x 20 km square. The average gradient over approximately 2 km x 2 km is 24 metres per km or 2.4%, and all 3 of these parameters are positively skewed. The topographic parameters are reasonably uncorrelated among themselves, and the correlation between the most important, H_1 and H_A is only 0.06. N^1, however, has correlations of 0.68 with H_A and 0.76 with S.

The temperature parameters R_2, R_{30}, T_2 and T_{30} are closely related to one another, and when measured over all months, have correlations ranging between 0.92 and 0.97. R_A is less well related to the 2 year and 30 year events, with correlations ranging from 0.88 for R_2 to 0.72 for T_{30}.

6.3 Preliminary analyses leading to rejection of certain variables

The regression analyses were carried out using the all possible subsets program of the BMDP suite of statistical software. This is similar to stepwise regression except that in that technique, the combination of variables examined depends on the order in which the variables are included, and there is no guarantee that the best permutation will ever be found. The all possible subsets program uses an algorithm devised by Furnival and Wilson (1974) to identify the best combinations or subsets of independent variables, and so needs to compute only a small fraction of the possible regressions in order to find the best. The aim of the program is not to produce a single regression which is indisputably the best, but to provide a choice of equations from which the user can take his pick.

The regression analyses were first performed using as dependent variables the temperature parameters which had been meaned over all months. They suggested that the terms in G_o, G_n and S should be dropped and that, as expected, Gs and N^1 should only be retained in the equation for R_A.

It is not surprising that the simple attempt to represent the effects of snow cover through the use of the average annual duration should prove unsuccessful. Common events (represented by R_A) are not expected to be much influenced by snow cover because of the generally unfavourable radiating conditions. In winter minimum temperatures with a return period of 30 years are likely to be accompanied by a snow cover in most places, and in summer, of course, there will be no snow anywhere in Britain. The largest effects of snow cover on minimum temperature are likely to occur for 2 year events in winter and 2 year and 30 year events in spring, but the differences in the frequency of snow cover at stations on these occasions will vary with month and will not be the same as the differences in the average duration of snow cover over the whole year. Thus, although differences in the frequency of snow cover are expected to have some impact on minimum temperatures, they are not easily identified and the effects on diurnal range are uncertain. Much of the effect will have been taken into account explicitly through the separate treatment of events of different return period, and implicitly through the high correlations with H_A and N^1.

The impact of slope, as measured either by G_o or the drops within 0.1 and 0.3 km (h_o and h_1) is not large because associated changes in temperature are largely accommodated by variations in h_l. Consider, for example, the distribution of h_l on and around a long, uniform slope separating a plain from a plateau. On the plain and interior of the plateau (ie more than 3 km from its edge), $h_1 = 0$ (say). On the upper slopes, more than a horizontal distance of 3 km from the plain, h_1 is constant at a large value. On the lower slopes and plateau periphery (within 3 km of the plain and plateau edge respectively), h_1 changes steadily between these two values. It can be seen that these changes in h_1 incorporate many changes in minimum temperature associated with changes of slope; indeed h_1 is a more appropriate parameter than slope in that minimum temperatures corrected for altitude are expected to be higher on level surfaces near the plateau edge than on slopes just above the plain.

A lack of generality in the use of h_1 is caused by its interpretation as a 'height above the valley' rather than a 'drop over the plateau'. In the present formulation temperture changes most rapidly with h_1 when it is near zero, which on a plateau will occur around 3 km from its edge; this is clearly unrealistic. In Britain, however, the 'plateau edge' type of topography is uncommon and the lack of high level stations prevents its effects from being properly represented.

Minimum temperatures can be expected to be lower on north facing than south facing slopes for 3 reasons:-

(i) Less heat flux through the ground due to less heat having been absorbed during the day. This factor cannot account for the higher diurnal ranges on north facing slopes (as observed).

(ii) Wind shift of the profile of minimum temperature with respect to relief. On a radiation night, the profiles of minimum temperature and topography are very similar, with the lowest values in valleys. Mahrt and Heald (1983) show that when there is a wind, the temperature profile is shifted so that temperatures are lower on the downwind than on the upwind slope. The coldest situations are likely to be associated with northerly winds when the lowest temperatures will be observed on north facing slopes. This phenomenon is likely to be best developed, however, on slopes with a large east-west extent rather than the long north-south extent indicated by the data.

(iii) More persistent snow cover. This would account for the observed tendency for temperatures to be lowest where there was a long slope in the north-south direction since this would enable the air sinking down the slope to remain in contact with the snow for a long time. This explanation, however, cannot account for lower minima and higher diurnal ranges in the summer, as is observed.

As no physical reason could be advanced to account for the observed tendency for minimum temperatures to be lower and diurnal ranges higher on north facing slopes evaluated over a rectangle elongated in the north-south direction, the effect was ascribed to the trawling of the data, and the term in G_N excluded from the regressions; the loss of variance incurred by this exclusion was only around 2%.

G_N represents the slope averaged over a large rectangle 8 km in the north-south direction by 2 km in the east-west direction, and table 7 shows that typical values of G_N (as indicated by its standard deviation) are only 1.3%, ie very slight. The conclusion is that the resolution of the 0.5 km topographica data aset is too coarse to enable the full effects of slope and aspect to be properly assessed.

6.4 Analyses based on temperature meaned over all months

The final regression equations for the temperature parameters are based only on H_L, H_A and H_Q with the addition of Gs and N^1 for R_A. The statistical significance of each of these variables when meaned over all months is included in table 9, which displays values of the 't' statistics defined as

$$t = \frac{\text{slope of regression}}{\text{standard error of slope}}$$

Table 9 also shows the percent of variance accounted for by the regressions which is around 60% for diurnal range but closer to 50% for minimum temperature. It can be seen that the most important variable is H_L with H_A second (except for R_A). The surprising feature is the importance of H_Q for R_A compared to the remaining temperature variables. It had been expected that the quadratic fit to terrain would be more important for extreme rather than common events, but table 9 shows that this is not so. The importance of H_Q for R_A is attributed to the ease with which cold air drainage is established in a bowl; it occurs so readily that it has an impact on R_A. Under progressively better radiating conditions, cold air drainage takes place in the presence of more complicated relief, and the advantages of a simple bowl shape are lost.

The full equations for temperature parameters meaned over all months are

$$R_A = 5.55 + 2.95\ H_L + 0.00124\ H_A + 0.0088\ H_Q + 0.00390\ G_S - 0.0832\ N^1.$$

$$R_2 = 9.32 + 5.19\ H_L + 0.00565 H_A + 0.0128\ H_Q$$

$$R_{30} = 11.98 + 6.81\ H_L + 0.00935\ H_A + 0.0128\ H_Q$$

$$T_2 = 6.89 + 3.64\ H_L + 0.00510\ H_A + 0.0066\ H_Q$$

$$T_{30} = 10.02 + 5.04\ H_L + 0.00670\ H_A + 0.0098\ H_Q$$

The intercepts are close to the asymptotes fitted to the exponential relations with h_1 and approximate to the values of the parameters to be expected on isolated mountain summits. The term in N^1 can be regarded as giving rise to a geographical variation in the asymptote for R_A.

The coefficient in H_L is expressed in degrees Celsius and indicates the temperature difference to be expected between valleys and summits. About half this variation is accomplished between the valley floor and h_1 = 125m. H_A and H_Q take on values equal to h_a and h_q respectively in valleys (ie when $h_1 = 0$), but zero on summits (as h_1 approaches ∞). The coefficients of H_A and H_Q are expressed in units of deg C per m so that at valley sites R_2, for example, increases by 0.56°C for every 100m increase of h_a. Note that the coefficients of the topographic parameters are greater for R than T; radiating conditions will generally be more favourable on the occasion of the largest diurnal range in a month than the lowest temperature.

Harrison (1971) and Hocevar and Martsolf (1971) found changes of minimum temperature with height above the valley of 4.9 and 6.2 deg C per 100m respectively, and these are greater than the changes given by the above equations. Harrison's figure, for instance, is derived from observations on 28 nights in 15 months in Kent, and therefore corresponds approximately to radiative conditions represented by R_2, when the above equations predict an increase of only 2.2 deg C per 100m. The discrepancy between the figures is caused mainly by the fact that in Harrison's work, the effects of large scale shelter and soil type have been incorporated into the regression on height above the valley. Although large scale shelter is included in the above equations, its effects are underestimated in general, and particularly in places like the Weald where the well defined relief promotes more organised nocturnal drainage than usual. Soil type also contributes to the differences, and the relatively dry and sunny climate in Kent will help in this respect.

6.5 Seasonal variations

The seasonal variation in the coefficients of the regressions are displayed in fig 6, where the smoothness of the seasonal transitions is due to the previous filtering of the temperature parameters. An idea of the reliability of the coefficients, however is provided by the standard errors shown, although these are based on the assumption that the errors associated with the 145 stations are uncorrelated.

For diurnal range the asymptotes display a fairly uncomplicated sinusoidal variation with a maximum in summer. This is also observed in the curve for T_A, since this is merely 0.5 R_A. For T_2 and T_{30}, however, the skewness of the overall distribution of temperature (negative in winter, positive in summer) becomes progressively more important, and for T_{30} gives rise to values which are slightly larger in winter than summer.

The standard deviation is a measure of the spread of the 145 values of the temperature parameters which have been obtained, ie the difference in R_2 (say) between valleys and summits, and is therefore an expression of the variance to be explained. A point of interest is the larger variance of T_{30} in winter than summer, and the small difference between T_2 and T_{30} in summer.

An outstanding feature of the coefficient of H_L is the pronounced September maximum for diurnal range. This is attributed to the large difference in soil moisture deficit between valleys and summits at that time of year. The diurnal range will increase with soil moisture deficit because the increasing proportion of air in the soil will reduce the conductance of heat. In winter both upland and valley soils will be at field capacity, but whereas upland soils experiencing high rainfalls will be driest in June, at drier valley sites soil moisture will decrease throughout the summer. The biggest difference in soil moisture between valleys and summits will occur around September, when upland soils are approaching field capacity but valley soils are still dry.

This hypothesis is supported by fig 7, which compares the largest diurnal ranges (represented by R_{30}) observed at the stations with the 5 highest and the 5 lowest values of h_1. The curve for the upland stations is similar to the asymptote and undergoes a reasonably sinusoidal variation with a maximum in June; this is the kind of curve one would expect if radiation were the determining factor. For the lowland stations, however, the curve is asymmetric, with the slow increase through the summer suggesting that increasing dryness of the soil is an additional factor. The coefficient of H_L will be proportional to the difference between these two curves, and this reaches a maximum around September.

The subsidiary peak in R_{30} in March evident in fig 6 can also be accounted for. The seasonal variation of diurnal range is clear, calm weather at summit and valley sites, and in the absence of variations in soil moisture, is illustrated schematically in fig 8. In a valley, the diurnal range will depend mainly upon the length of the night, which affects the minimum temperature, and the maximum solar elevation, which affects the maximum temperature through the magnitude of the lapse rates which can be maintained. In winter the sun is unable to break down the nocturnal inversion, and so the seasonal variation in diurnal range is characterized by a broad summer peak and a sharp winter trough. On a summit, on the other hand, the length of the night is unimportant as the cold air drains away, and in winter there is no nocturnal inversion to be destroyed. Consequently, the seasonal variation in diurnal range is reasonably sinusoidal. Fig 8 shows that the difference between these curves is a maximum in March and September. In reality, the September maximum is dominant because of the effect of the drier soils in the valley.

The coefficients of H_A for diurnal range and minimum temperature shown in fig 6 are broadly similar and display a marked maximum in winter, especially at large return periods. This agrees with the pre-conceived notion that large scale shelter would be most effective on long nights with ideal radiating conditions. The relative behaviour of the coefficients of H_L and H_A for 2 year and 30 year events, however, are very different for minimum temperature than for diurnal range. In summer the variance of T_{30} is scarcely greater than that for T_2, and consequently the coefficients of H_L and H_A for T_2 and T_{30} are very similar. In winter, however, the additional variance of 30 year events is not accounted for by H_A, as it is for diurnal range, but by H_L. In other words, as the return period of minimum temperature increases beyond 2 years, the importance of large scale shelter diminishes in favour of height above the valley.

A fundamental difference between diurnal range and minimum temperature in winter is that the latter can represent the culmination of a period of cold weather lasting several days while the former has to be achieved in a single day. The minimum temperature reached during a cold spell lasting a day or so may loosely be associated with T_2, while T_{30} is more likely to represent minima attained at the end of a cold spell lasting several days. The fall of temperature induced by large scale shelter on a single radiation night may be much larger than elsewhere, but the very magnitude of the fall reduces the radiation loss to such an extent that it is difficult for the temperature to drop much lower on subsequent nights. In lowland areas, on the other hand, provided conditions are favourable, temperatures can fall steadily by radiation over several days, and the advantages offered by large scale shelter are nullified. The changes in the relative importance of large scale shelter with return period are illustrated by the fact that the lowest temperatures recorded in lowland England are almost as low as those observed in central Scotland, but that these extremes are approached much more frequently in Scotland than in England.

A very good investigation into large diurnal ranges in Scottish glens is provided by Dight (1967). He shows that large diurnal ranges in winter are associated with high maxima as well as low minima, with temperatures rising above freezing point even in the presence of a snow cover. Dight ascribes this to the turbulence set up by the mountains breaking down the nocturnal inversion which would persist over lowlands.

Low minimum temperatures in Scottish glens are not always associated with large diurnal ranges. Following the minima of −27.2°C at Braemar on 10th January 1982, for example, the day maximum (09-21Z) was only −19.1°C (Graham, 1982). Nevertheless, it is evident that large diurnal ranges do occur in Scottish glens in winter, and on those occasions the presence of high ground, although responsible for low minima on the first radiation night, may hinder the development of very low temperatures by destroying the nocturnal inversion, and preventing the establishment of intense surface inversions developed over several days.

The coefficients of H_{Ω} are not shown in fig 6. They are subject to large errors, but appear to undergo little in the way of seasonal variations.

The proportion of the temperature variance explained by the topographic parameters is displayed in fig 9. The percentages quoted correspond to the reduction in the explained variance which would follow from the exclusion of the parameter from the regression equation. The pre-eminence of H_L, with its peak performance in autumn for diurnal range, and the relative importance of H_A in winter, especially for R_{30} and T_2, are clearly displayed. The insignificance of H_Q (except for R_A) and Gs is also apparent.

The seasonal variation in the impct of N^1 is of some interest. The deterioration of climate to the northwest is least in spring and greatest in autumn, and while the contribution of N^1 does reach a maximum in autumn, fig 9 shows that it reaches its minimum in winter rather than spring. This is caused by the influence of advection. The difference between the average daily maxima and minima is not caused solely by radiation; advection also plays a part, and this is greatest in winter and in the North. In winter, therefore, the fall in the radiative component of R_A to the northwest is balanced by an increase in the advective component, and this results in a very small gradient of R_A across Britain.

The net result of all these changes is a pronounced seasonal variation in the proportion of the variance of diurnal range which can be explained, and fig 10 shows that this ranges from around 50% in May to 65% in November. For minimum temperature, the proportion remains closer to 50% throughout the year.

6.6 Confidence Limits

The standard errors of the regression coefficients in fig 6 were calculated on the assumption that the 145 stations contribute independent items of information. This, of course, is not true. Sampling errors in the estimates of the temperature parameters will be correlated, and although the station values of h_1 may be reasonably independent, the parameters relating to large scale shelter will not be. An estimate of the reliability of the regression coefficients can be obtained by dividing the data into halves with similar geographical distributions of stations, and comparing the coefficients. The results of such a comparison are presented in fig 11, which shows that the differences between the analyses are indeed larger than might have been deduced from the standard errors. The seasonal variations, however, seem well established.

To investigate possible geographical variations, the analyses were repeated using stations from only the North or South of Britain, with the dividing line running from the Mersey to the Wash. The differences in the predominantly highland and lowland characteristics of the two regions are reflected in a reduced range of h_a in the south; the distributions of h_1 were reasonably similar. A comparison of the coefficients for diurnal range is presented in fig 12, which shows that the differences between the regions, although marked, are not large in comparison with those between the uniformly distributed sets of stations. Such differences as there are stem from variations in the standard deviation, which reaches a maximum in the summer in the south but in the winter in the North.

The explanation of the September peak in the coefficient of H_1 for diurnal range depended upon diurnal ranges reaching a maximum in June on summits and in August in valleys. Geographical variations could have been partly responsible, with the highest stations being located in the north west where the weather is finer earlier in the summer than in the southeast. Fig 12, however, shows that the September peak is well established in both the North and South of Britain.

A comparison of the regressions coefficients of minimum temperature in the north and south of Britain is presented in fig 13. The main difference is the much larger variance of T_{30} in winter in the North, and this can be related to the effects of topography, principally large scale shelter. The large variance of T_{30} in the north, however, is accommodated by an increase in the coefficient of H_1, rather than H_A. In northern Britain, stations with low values of h_1 are much more likely to be surrounded by high ground than those in the South. In the North, therefore, there is a correlation between h_1 and large scale shelter, and it is evident that important aspects of the latter are not being captured by either h_a or h_a. For 30 year events, the radius of land which influences minimum temperature is likely to be much larger than 10 km. Before the differences between the north and south of Britain are exagerrated, however, it should be borne in mind that the two sets of uniformly distributed stations produced quite large differences in the regression coefficients for minimum temperature.

Errors in the estimation of minimum temperature may be introduced by any geographical differences in the variability of 1000-850 mb thickness across Britain. Hopkins and Whyte (1975) produced a generalised map of the minimum temperature to be expected once in 50 years anywhere in the UK, and this shows less extreme temperatures in northern England than in Scotland or the English midlands. This could be because the lowest temperatures in Scotland are associated with Arctic air, and in the southern half of England with continental air, with less extreme temperatures in northern England in either case. Such a state of affairs would be expected to reveal itself in the pattern of the residuals of minimum temperature from regression equations developed for the whole of Britain. Maps of the residuals for all the temperature parameters, however, were found to be fairly similar, and those for T_{30}, meaned over all months, are shown in fig 14. Although the residuals are spatially coherent (some smoothing was employed in drawing the maps), no major geographical variations are evident.

7. Conclusion

The main effects of topography on minimum temperature can be categorised into those of local and large scale shelter. Local shelter may be interpreted in terms of a height above the valley while large scale shelter may be associated with the area of land being drained of cold air. Their relative importance varies with climate, season, and return period.

Local shelter is the most important aspect of topography and can be represented by the drop in height from the station within 3 km. The negative exponential relationship between minimum temperature and h_1 reflects the bias in the data sample used towards h_1 representing a height above the valley rather than a drop over a plateau edge. In topography in which plateau edges or ravines with restricted views of the sky are common, the role of h_1 woudl have to be revised. Regarded as a measure of height above the valley, the optimum horizontal distance over which the drop is measured will depend on the scale of the most common topographhic features, but the lack of sensitivity to the precise horizontal distance used in this work suggests that the drop in 3 km may be of fairly general application.

The most scatter in the relations between minimum temperature and h_1 occurs for low values of h_1. This is because the effects of large scale shelter (which are poorly represented), small scale topography (10 to 100m), and soil and vegetation are more important for small than large values of h_1 (the latter are often associated with wet soils). The change in temperature with height above the valley undergoes a seasonal variation, with the maximum vertical gradients of extreme minimum temperatures occurring in winter when the strongest inversions are established, and the largest changes in diurnal range occurring in autumn, when the biggest differences in soil moisture deficit between valleys and summits are found.

Large scale shelter is difficult to represent by objective or subjective means, and in this work a simple estimate, the mean height of the terrain above the valley over a radius of 10 km, was used. Unlike local shelter, no general values for the most appropriate radius is likely to emerge; it will depend on the scale of the main topographic features, climate, and return period.

The importance of nocturnal drainage on long nights with ideal radiating conditions is illustrated by the effect of h_a on diurnal range, which is greater in winter than summer, and increases with return period. For minimum temperatures in winter, however, the maximum impact of h_a is associated with events of return period around 2 years, and which may be loosely associated with cold spells lasting a day or so. More extreme temperatures are recorded during cold spells lasting several days and on these occasions the fall in temperature induced by large scale shelter on the first radiation night can be so great that the temperature cannot drop much further on subsequent nights. In the lowlands, however, provided synoptic conditions are favourable, the temperature can fall by radiation over several days and the advantages of large scale shelter are overcome.

The decrease in importance of large scale shelter for minimum temperatures as the return period increases beyond 2 years in exagerrated by the relations with h_a. Firstly, h_a serves only as an approximation to the area of land being drained; efforts to improve on this through a quadratic fit to topography failed. Secondly the radius of terrain which is relevant to the development of minimum temperature is expected to increase with return period and to be greater than 10 km for T_{30}. The decrease in importance of h_a from T_2 to T_{30} is therefore partly caused by the fact that 10 km is a more appropriate radius for 2 year than 30 year events. That this is not obvious from the data analysed can be ascribed to the fact that it includes stations as close as 10 km to the sea, and that for these stations, increasing the radius on which h_a was based would have involved including an area of sea.

The variance of the temperature parameters accounted for lies between 50 and 60 per cent, but this figure cannot be regarded as the sole measure of the success or failure of the study. The greater the range of h_1 in the sample of stations, for instance, the greater the proportion of variance which that variable can explain. In view of the well known lack of high level stations in Britain, it may be inferred that the proportion of temperature variance accounted for by the regressions will be greater for a representative distribution of points in Britain than for the current observing network. Even so, the present relations only predict an increase of 1.2°C in R_2 as h_1 is decreased from the mean value of 46m to zero. This modest change serves to emphasize the contribution of small scale (10 to 100m) topography and soil and vegetation in determining the distribution of minimum temperature. It must also be borne in mind that the effects of buildings and lakes have been deliberately excluded from the data, and coastal effects minimised. This study therefore represents only a first step towards the overall aim of successfully estimating the spatial distribution of minimum temperature in Britain.

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The data set containing spot heights on a 0.5 km grid, and adjusted to retain the main topographic features, was created by PMA Consultants, and access to this high quality data set is gratefully acknowledged. Without it, the findings of this study would have been far less convincing. The work also owes much to the powerful and economical 'all possible subsets' regression program provided by BMDP statistical software.

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Table 1.- Comparison of temperatures with return period of 30 years with most extreme events observed in period 1959-79.

	R_{30}	R_x	T_{30}	T_x
Mean	18·1	12·4	14·5	14·7
SD	1·79	1·84	1·39	1·44
Skewness	−0·2	−0·2	−0·1	0·0

Table 2 - Determination of asymptotic value C for temperature parameters

	Mean °C	SD °C	Skew	SD / Mean	Lowest Value (°C)	65% Mean (°C)
R_A	7·79	0·73	−0·44	0·094	5·4	5·06
R_2	13·94	1·38	−0·32	0·099	9·8	9·06
R_{30}	18·10	1·79	−0·17	0·099	12·9	11·76
T_2	10·20	1·05	−0·09	0·103	7·4	6·63
T_{30}	14·53	1·39	−0·07	0·096	10·9	9·44

Table 3 - Characteristics of subjectively assessed drop in height following valley.

		h_0	h_1	h_2	h_3	h_4
Horizontal distance (Km)		0·1	0·3	1	3	10
Vertical drop (m)	Mean	3·9	9·8	23·6	32·6	62·1
	S.D.	4·1	9·0	23·8	37·2	59·7
Correlation with h_4		0·57	0·65	0·77	0·92	1·00

Table 4 – Correlations between subjectively assessed drop along valley and logarithmically transformed temperature parameters					
Temperature Variable	h_0	h_1	h_2	h_3	h_4
$\ln(R_A - 5.06)$	0.55	0.59	0.71	0.77	0.80
$\ln(R_2 - 9.06)$	0.38	0.50	0.70	0.74	0.69
$\ln(R_{30} - 11.76)$	0.35	0.50	0.70	0.74	0.68
$\ln(T_2 - 6.63)$	0.33	0.49	0.68	0.69	0.61
$\ln(T_{30} - 9.44)$	0.30	0.49	0.67	0.69	0.61

Table 5 – Comparison of estimates of height above valley					
	Mean (m)	SD (m)	Correlation with h_ℓ	% Variance Explained	Asymptote as % of Mean.
h_d	40.0	55.0	0.92	49.7	77
h_3	38.7	37.4	0.96	40.4	44
h_ℓ	45.6	45.5	1.00	42.1	52

Table 6 – Correlation between h_a and residuals of relations between temperature and h_ℓ							
Temperature	Dimensions of square (K_a grid points) over which height is averaged.						
Variable	20	30	40	50	60	70	80
$\ln(R_A - 5.06)$	−0.07	0.00	0.06	0.09	0.12	0.15	0.18
$\ln(R_2 - 9.06)$	0.33	0.40	0.43	0.45	0.46	0.47	0.48
$\ln(R_{30} - 11.76)$	0.38	0.44	0.47	0.48	0.48	0.48	0.47
$\ln(T_2 - 6.63)$	0.33	0.39	0.39	0.43	0.43	0.44	0.44
$\ln(T_{30} - 9.44)$	0.33	0.39	0.39	0.43	0.43	0.44	0.44

Table 7 – Correlations between component of slope to North and residuals of relations between R_{30} and h_ℓ and h_a						
		No of grid points in E-W direction (K_E)				
		4	8	12	16	20
No of grid points in N-S direction (K_N)	4	−0.08	−0.03	−0.02	−0.02	−0.08
	8	−0.11	−0.10	−0.09	−0.09	−0.10
	12	−0.23	−0.19	−0.15	−0.12	−0.13
	16	−0.25	−0.21	−0.19	−0.17	−0.15
	20	−0.24	−0.22	−0.21	−0.19	−0.16
	24	−0.22	−0.20	−0.20	−0.19	−0.16

Table 8 - Characteristics of topographic parameters						
	h_{ℓ} (m)	h_a (m)	$h_{a,q}$ (m)	G_N (m/km)	G_S (m/km)	G_O (m/km)
Mean	45·6	36·4	6·4	0·6	−1·2	23·6
SD	45·5	83·9	31·5	13·0	209	22·0
skewness	2·54	0·93	0·04	−0·27	−0·23	1·46

Table 9 - Statistical t values of topographic variables obtained when they are regressed against temperature parameters which have been meaned over all months.						
	H_L	H_A	H_Q	G_S	N'	% Variance explained.
R_A	11·1	1·4	4·6	2·1	−3·7	61·4
R_2	10·5	4·3	3·5			59·1
R_{30}	10·5	5·5	2·7			59·7
T_2	8·7	4·6	2·1			50·4
T_{30}	9·4	4·7	2·5			53·9

Fig 1 - Fall of temperature on a radiation night for different topographical sites.

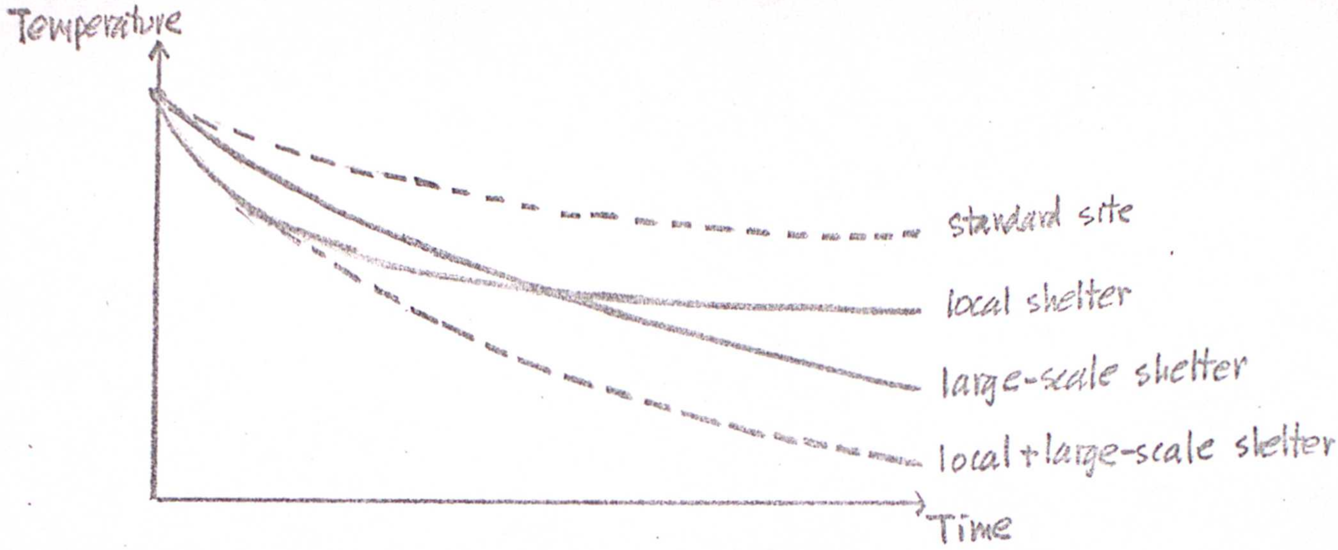

Fig 2 - Daily, monthly, and extreme minimum temperatures for different topographic sites and climates.

x Mean daily minimum

⊙ Mean monthly minimum

△ Extreme minimum.

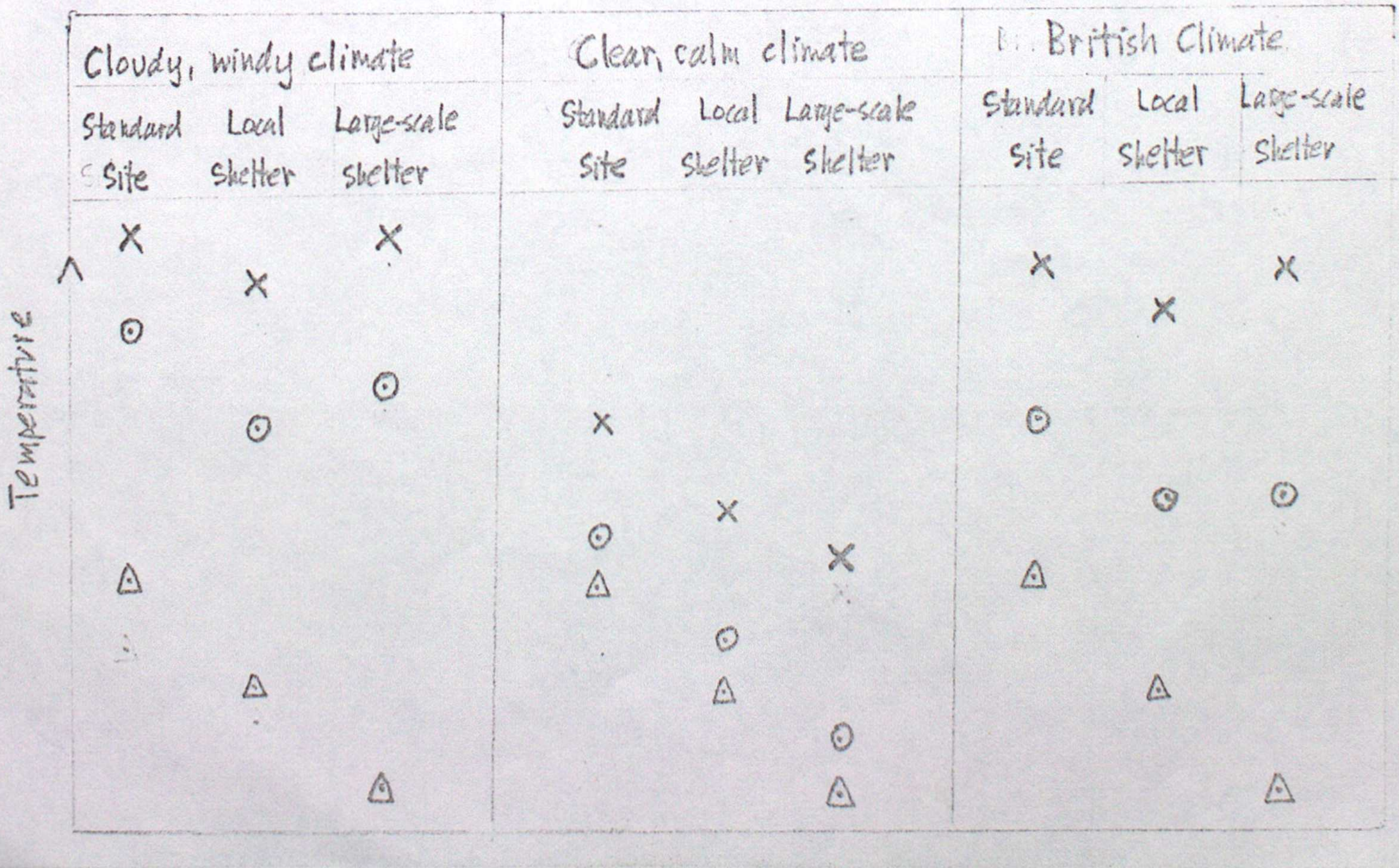

FIG 3 - DEPARTURE OF MINIMUM TEMPERATURES FROM THE MONTHLY MEAN

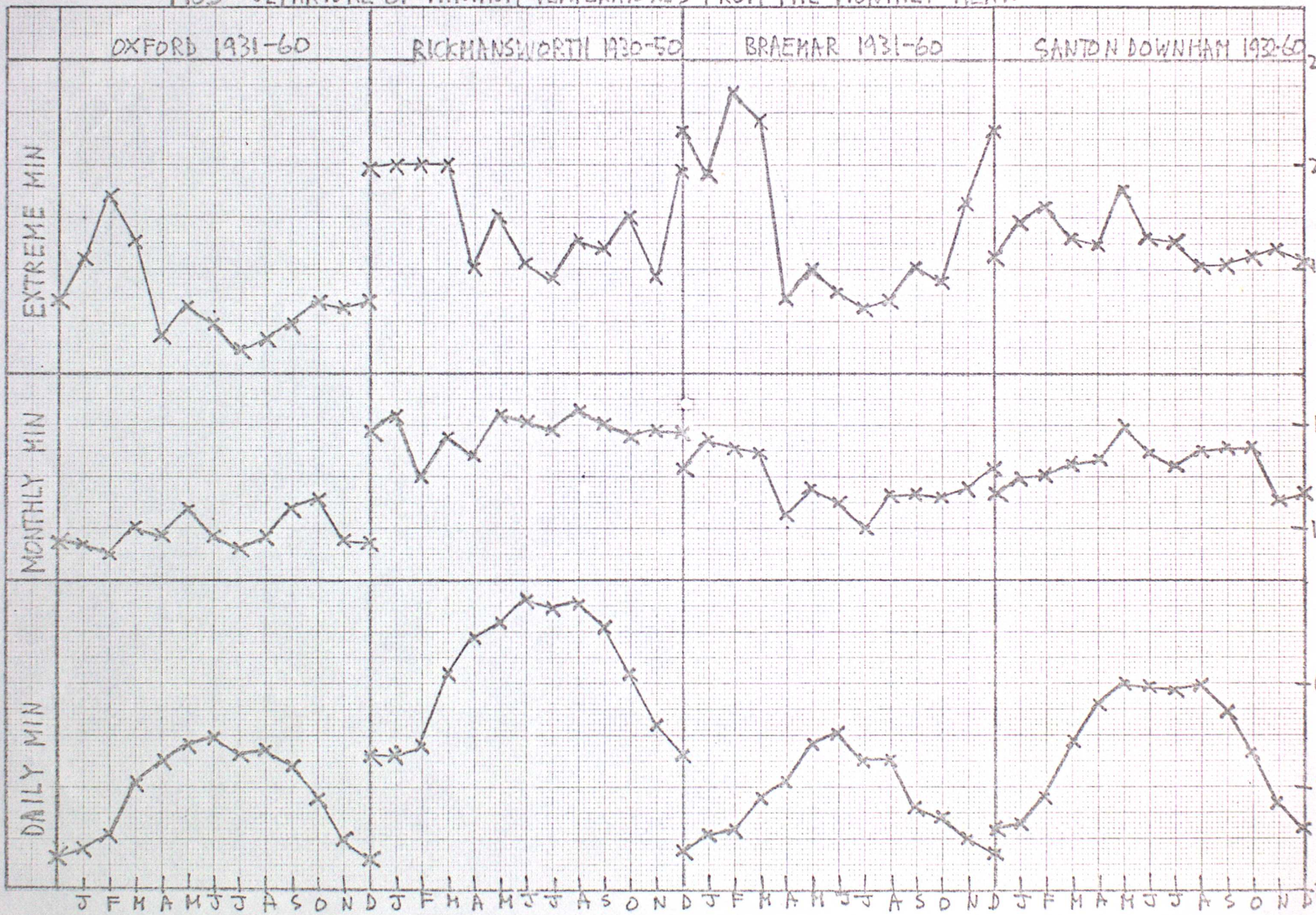

Fig 4 - Distribution of inland rural stations.

FIG 5 · DIURNAL RANGE WITH RETURN PERIOD OF 2 YEARS (R_2) PLOTTED AGAINST HEIGHT ABOVE VALLEY (h_e)

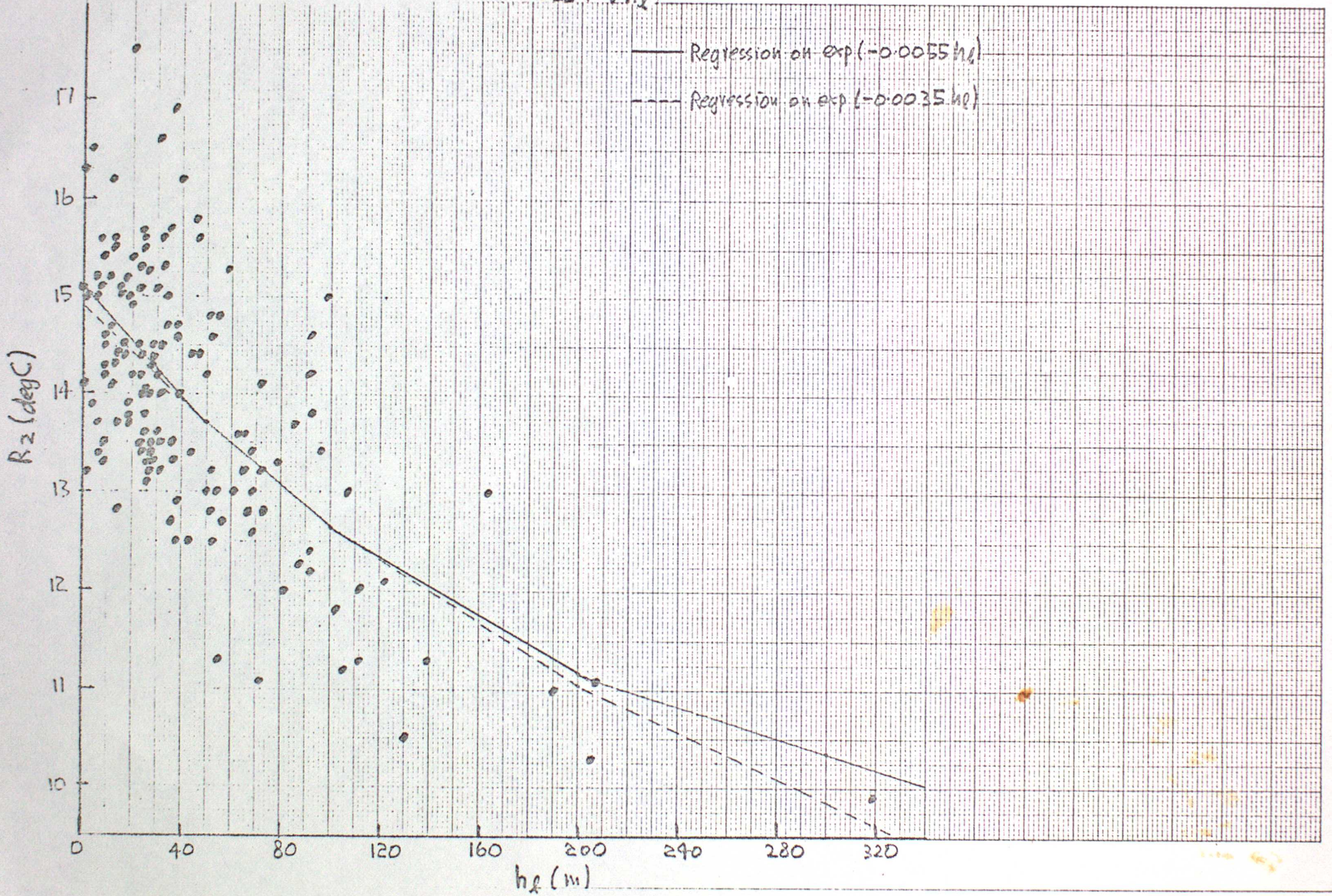

FIG 6 - SEASONAL VARIATION OF RELATIONS BETWEEN TOPOGRAPHY AND TEMPERATURE.

△ R_{30}, T_{30} ⊙ R_2, T_2 × R_A, T_A

ERROR BARS REPRESENT ± 1 STANDARD ERROR.

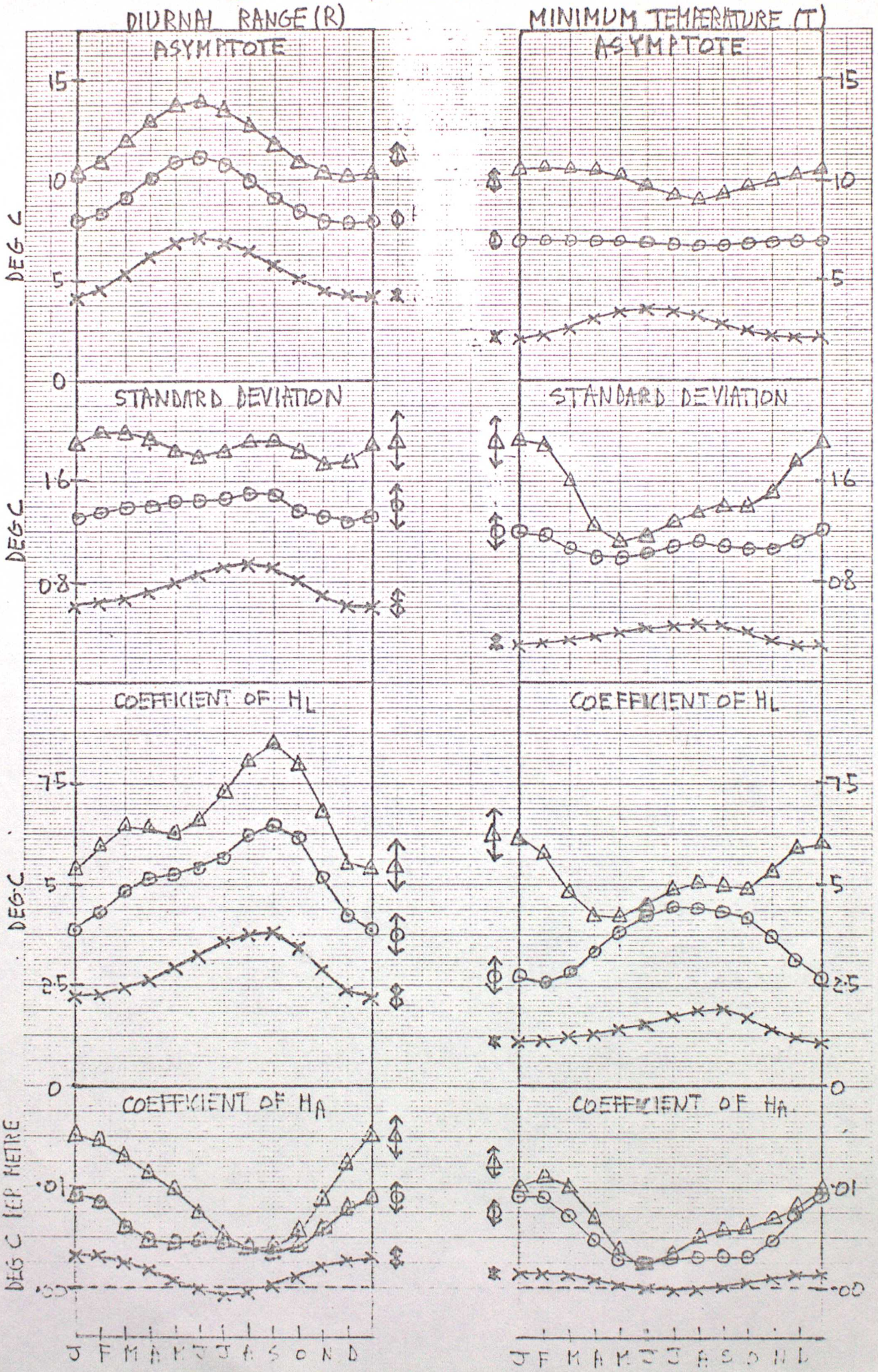

FIG 7 · LARGE DIURNAL RANGES (R_{30}) OBSERVED AT VALLEY AND SUMMIT SITES

x–x Mean of the 5 stations with the lowest values of H_L

o–o Mean of the 5 stations with the highest values of H_L

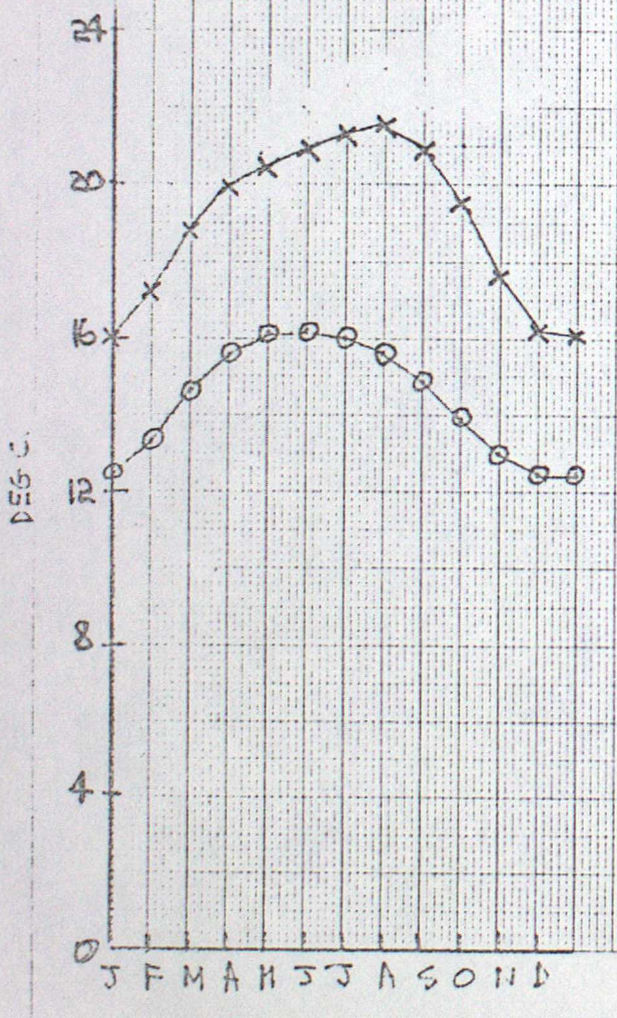

FIG 8 – LARGE DIURNAL RANGES EXPECTED AT VALLEY AND SUMMIT SITES FROM A CONSIDERATION OF RADIATION AND LANDFORM ONLY.

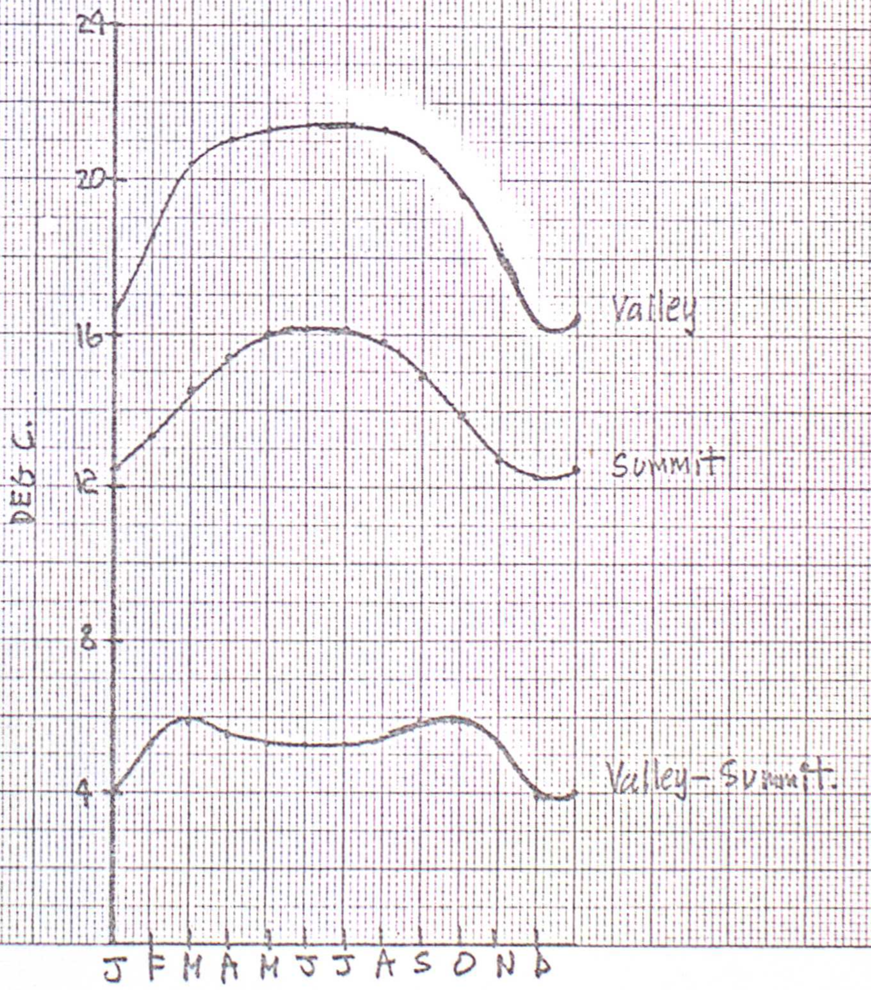

FIG 9 - PROPORTION OF VARIANCE OF TEMPERATURE ACCOUNTED FOR BY TOPOGRAPHIC PARAMETERS.

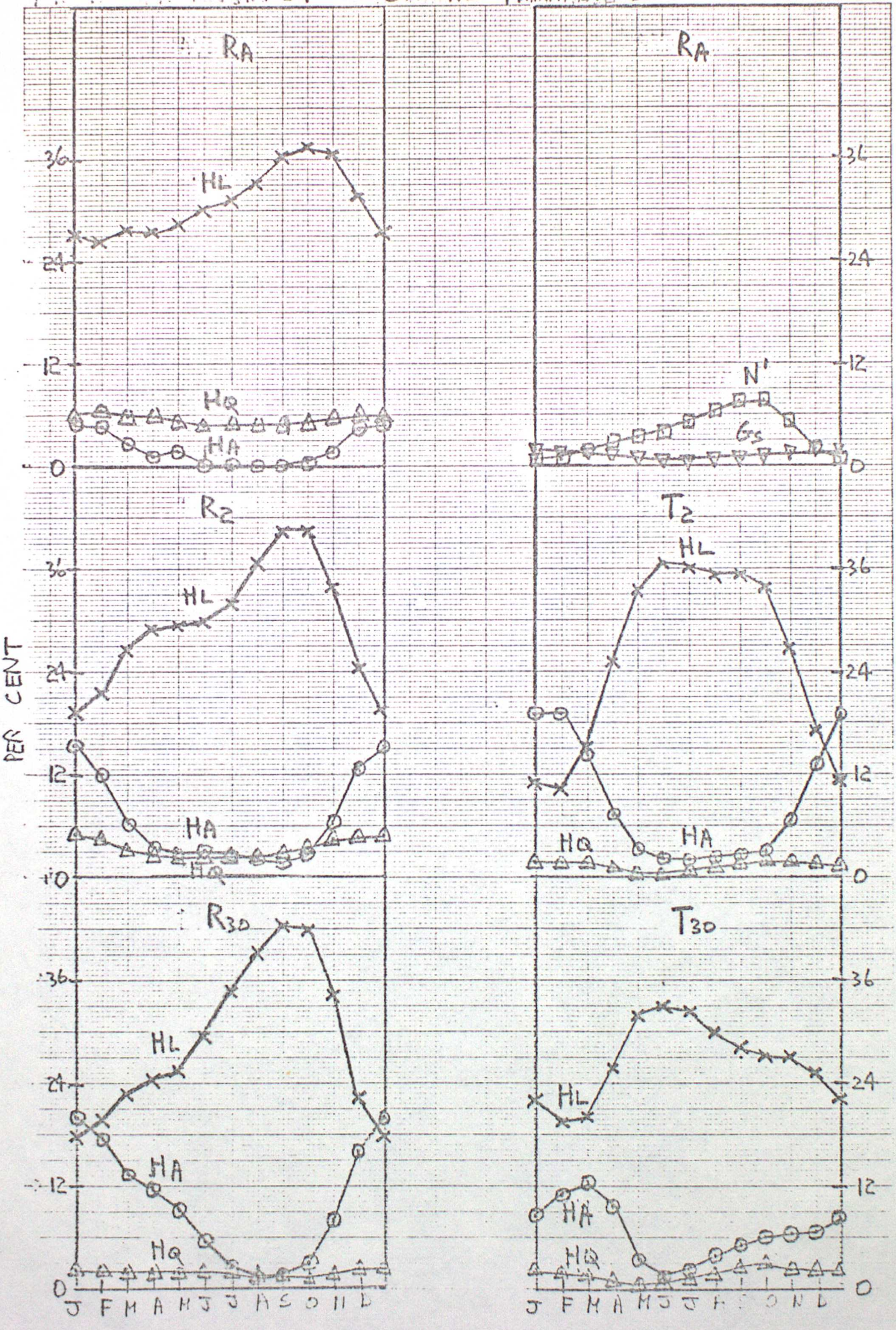

FIG 10 - PROPORTION OF VARIANCE OF TEMPERATURE ACCOUNTED FOR BY TOPOGRAPHY

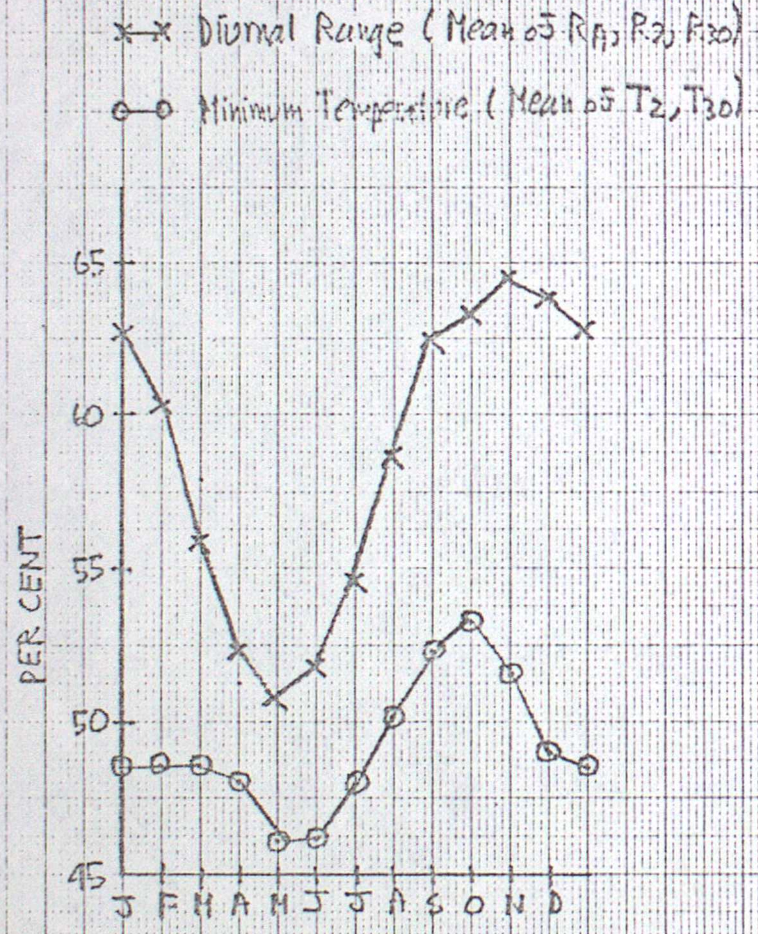

FIG 11 - COMPARISON OF RELATIONS BETWEEN TOPOGRAPHY AND TEMPERATURE OBTAINED FROM TWO HALVES OF DATA.

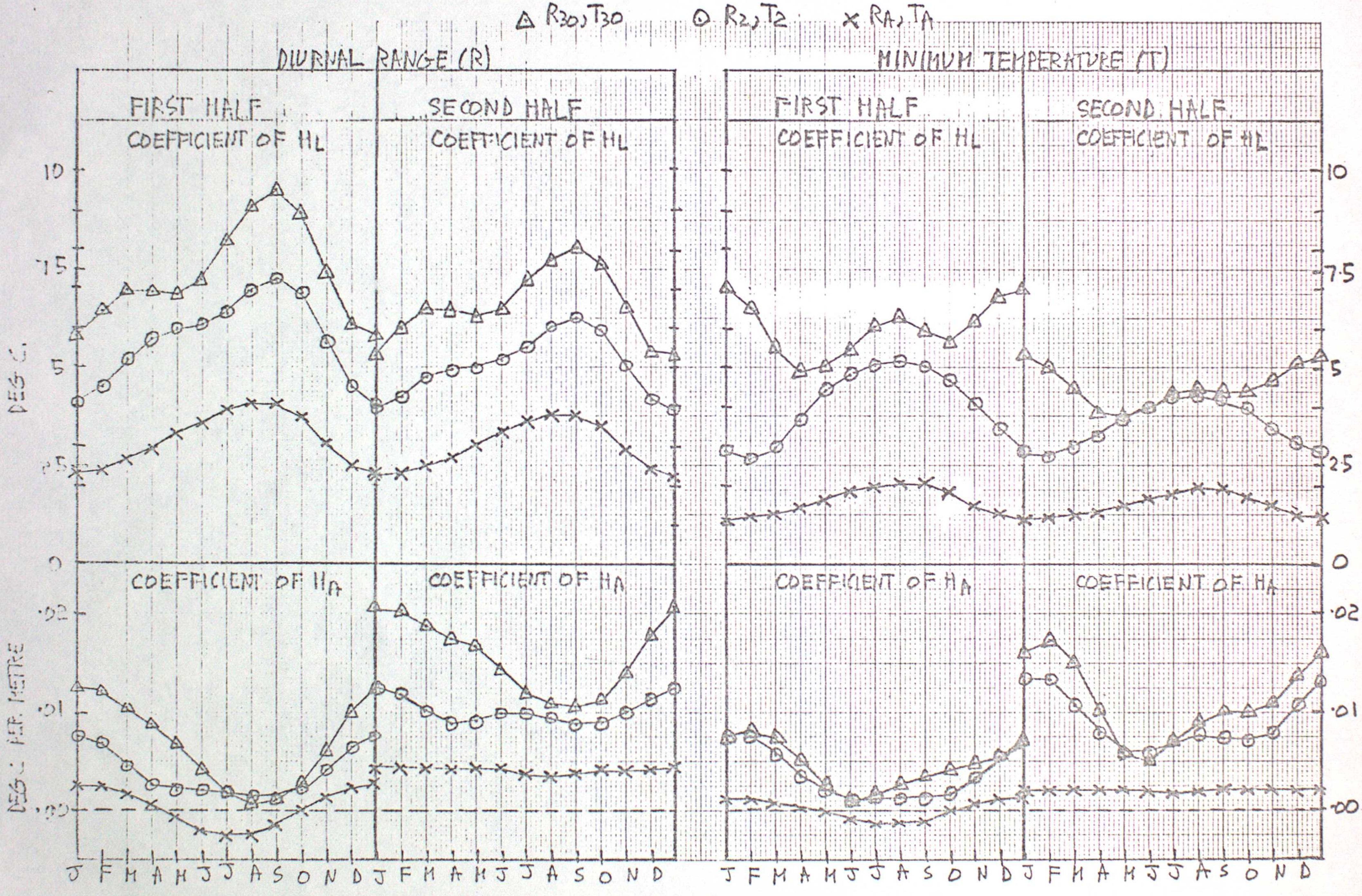

FIG 12 - COMPARISON OF RELATIONS BETWEEN TOPOGRAPHY AND DIURNAL RANGE OBTAINED FROM STATIONS IN THE SOUTH AND NORTH OF BRITAIN

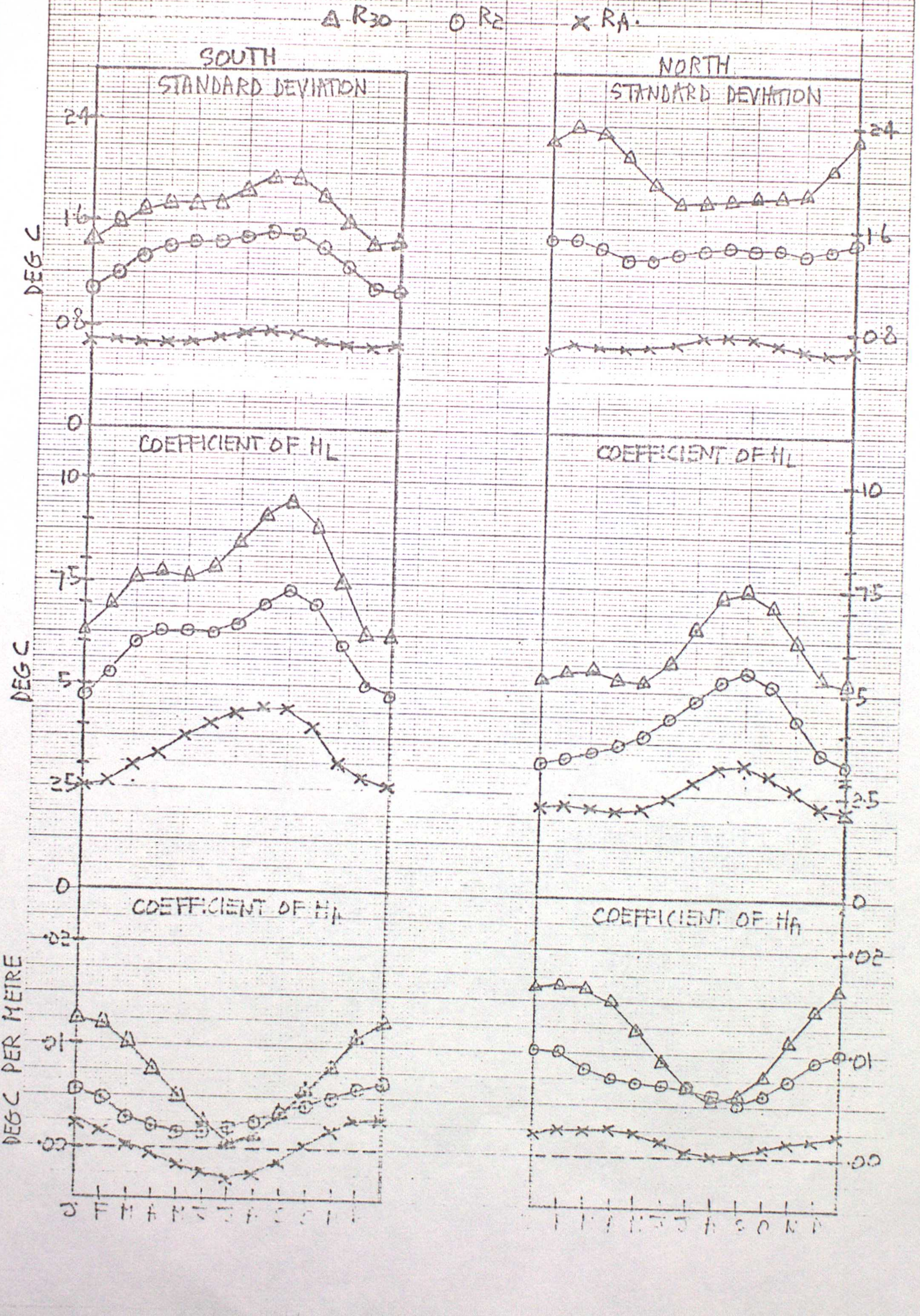

FIG 13 - COMPARISON OF RELATIONS BETWEEN TOPOGRAPHY AND MINIMUM TEMPERATURE OBTAINED FROM STATIONS IN THE SOUTH AND NORTH OF BRITAIN

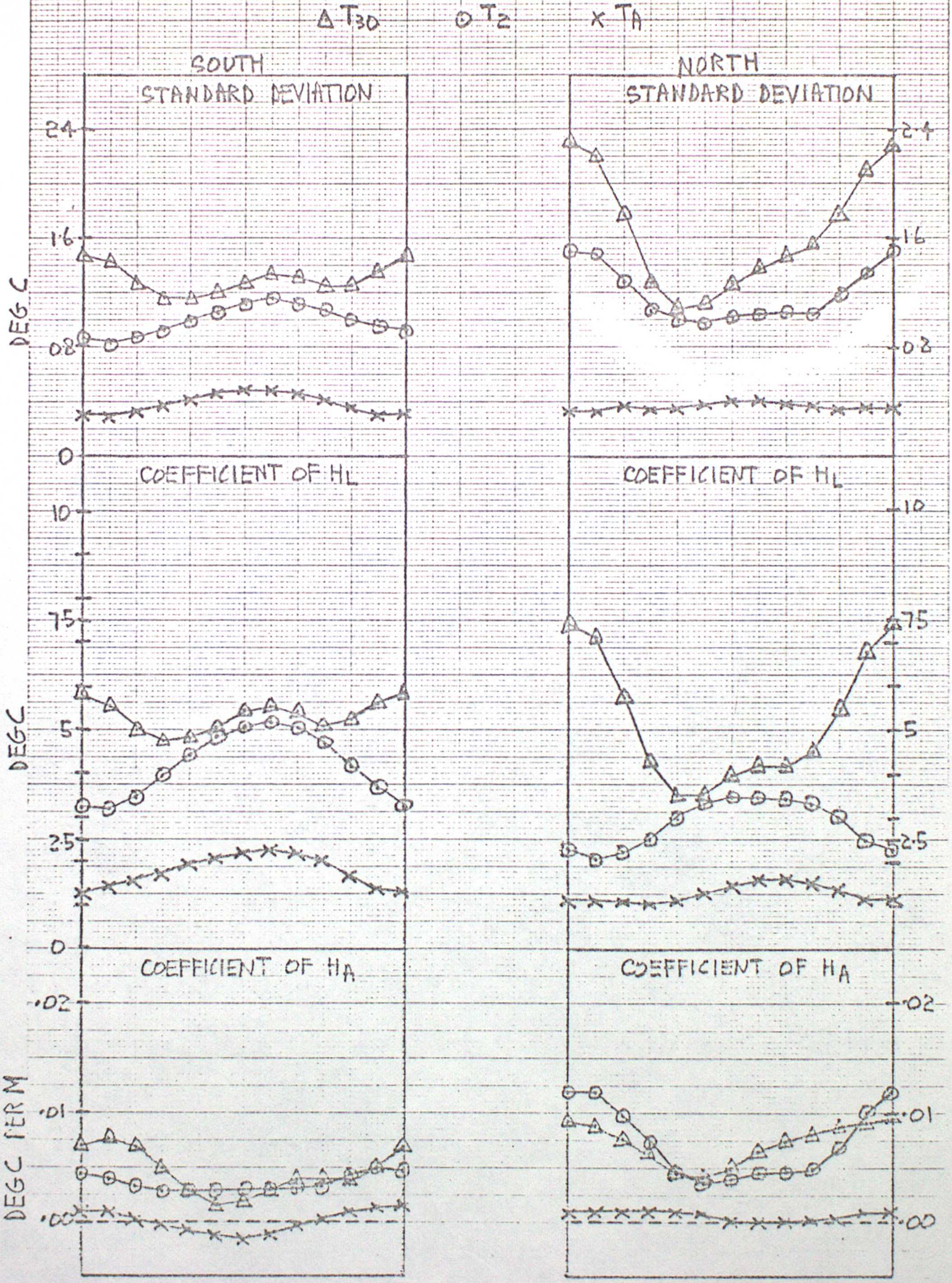

Fig 14 - Residuals of T_{30} (meaned over all months).