FROST DAMAGE TO CROP PLANTS AND ITS CONTROL

A Thesis Submitted to the University
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By

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PREFACE

Estimates of the loss of fruit crops due to frost damage are necessarily inexact, but it is evident that this factor is a major cause of crop reduction and in exceptional years may be responsible for total failure. Grainger (unpublished) estimated the value of the fruit crop in Scotland lost, due to the severe Spring frost of 1945, to be about half a million pounds. Bush (1945) gives cropping figures for apples in the United Kingdom for 1934 to 1938 - this period includes two years of major Spring frosts, 1935 and 1938, coinciding with exceptionally low yields :

Year	Apple crop in tons
1934	527,000
1935	133,000
1936	511,000
1937	165,650
1938	126,150

The low yield in 1937 was not due to frost but probably to unfavourable weather during pollination, combined with the tendency of many varieties to crop poorly following a glut year.

The great majority of severe frosts during late April and May in this country are radiation frosts, occurring under relatively calm conditions. Severe frost accompanied by strong wind is of relatively rare occurrence in late Spring, and since the control of such 'wind frosts' presents apparently insuperable difficulties, they are not considered in this investigation. The control of radiation frosts is technically possible but it remains to be proven that any method at present under trial would prove economic in this country.

The present investigation falls into four sections :-

(1) A study of the various geographic, topographic and soil factors which determine the severity of radiation frosts

The problem was investigated firstly by an analysis of the data available in the Monthly Weather Report (1939 - 1945) on the incidence of frost at Meteorological Reporting Stations in Great Britain, in relation to their geographic location and local topography, and secondly by the intensive study of nocturnal temperature distribution and the factors influencing it, in a compact area comprising a section of the Ayr valley adjacent to Auchincruive.

In addition, preliminary studies were commenced on the effect of soil type, soil moisture content and degree of compacting, on the minimum temperature assumed by the soil surface under radiation frost conditions.

(2) Temperature relations of buds and blossoms

A study of the internal temperatures of buds and blossoms in relation to that of the air, and of the roles of transpiration and radiation in causing depression of plant temperatures below that of the air.

(3) Practical methods of frost control

a) By orchard heating.

b) By air mixing with blowers.

by means of refrigeration tests

(4) An investigation of Spring frost injury to fruit by means of refrigeration tests

The effect of the following factors on the incidence and severity of injury was studied :-

a) Temperature.

b) Time of exposure.

c) Rate of chilling and thawing.

d) Influence of stage of development on susceptibility.

e) Effect of location of the blossom truss on the plant.

f) Variation in varietal susceptibility.

g) Environmental factors affecting susceptibility.

h) Erratic supercooling as a cause of variation in response to refrigeration.

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SECTION I

A STUDY OF THE VARIOUS GEOGRAPHIC, TOPOGRAPHIC AND SOIL FACTORS WHICH DETERMINE THE SEVERITY OF RADIATION FROSTS

Introduction

The minimum night temperature at any given location under radiation frost conditions is determined by a complex of factors, chief among which are the following :-

(A) Geographic and topographic factors

- a) Latitude
- b) Altitude
- c) Relationship to the sea and to the disposition of land masses, ocean currents and prevailing winds.
- d) Ground contour.
- e) Ground aspect or slope.
- f) Relationship with the surrounding country.
- g) Distribution of shelter.

(B) Soil factors

- a) Soil type.
- b) Soil moisture.
- c) Soil cover.
- d) Cultivations.

(c) Meteorological factors

- a) Cloud amount and height.
- b) Atmospheric humidity.
- c) Wind velocity.
- d) Temperature profile.

The present investigation has approached the problem from two angles :-

A. A survey of the effects of geographic, topographic and soil factors on frost liability in England, Scotland and Wales.

B. An intensive examination of a relatively small area of characteristic conformation.

PART I. A SURVEY OF THE EFFECTS OF GEOGRAPHIC, TOPOGRAPHIC AND SOIL FACTORS ON FROST LIABILITY IN ENGLAND, SCOTLAND AND WALES

Review of the literature

Lewis (1943) investigated the seasonal distribution over the British Isles of the number of days with screen minimum temperatures of 32°F. or below. She showed that well-defined areas of high frequency generally coincide with the main upland areas, but that the flat district surrounding Cambridge constitutes a secondary area of high frequency. Low frequency areas are located in the vales of Berkshire, Gloucester and Evesham. The entire coastal seaboard was shown to have an exceptionally low frequency, that of the west falling below that of the east.

Hawke (1933) discussed the characteristics of reporting stations, showing extreme ranges of air temperature in the British Isles. Such stations also exhibit notably low minimum temperatures and are generally located in valley bottoms. Examples are cited in Rickmansworth, Attenborough, Welshpool, Halstead, Oundle and Wokingham.

Manley (1944) investigated the effect of a number of factors including relief, proximity to the coast, soil differences and urban conditions, on the incidence of frost, by reference to the data from Meteorological Reporting Stations, and estimated the mean frost-free period for (a) an enclosed urban site, (b) a favourable hill slope, (c) a normal low-lying flat, (d) a frost hollow, (e) an extensive sandy lowland. Kincer (1941) publishes statistics of the length of the frost-free period in the individual states of the U.S.A. including a series of maps showing the distribution of areas coinciding in the onset and termination of the frost-free period.

Day and Pease (1937) analysed the occurrence of May frosts during the period 1926 to 1935, in England, Wales and Scotland. They divided the country into eight districts and recorded in each year, the number of Meteorological Reporting Stations within each district at which absolute minimum temperatures of 28°F. or below occurred, and similarly the occurrence of absolute minimum temperatures within the range 29 to 31°F. They point out that this data does not in any way provide a quantitative analysis of the incidence of May frosts.

Methods

The determination of the effect of geographic, topographic and soil factors on the incidence and severity of Spring frosts is complicated by the fact that meteorological conditions are never uniform over the country on occasions of radiation frost, and variations in cloud cover, wind velocity and humidity inevitably modify the severity of frosts in different areas.

In the following investigation, the mean of the absolute minimum temperature recorded in the months of April and May, over a period of seven years, has been used as a comparative estimate of the mean frost liability of each reporting station in these months. Records of the absolute minimum temperature in each month are published in the Air Ministry's Monthly Weather Report for a wide range of meteorological reporting stations.

It was necessary for the purpose of this investigation to obtain exact information relating to the situation, local topography, soil type etc., of each reporting station. The Climatological Department of the Meteorological Office very kindly agreed to co-operate in obtaining this information, and through their agency a questionnaire (Appendix I) was circulated to reporting stations. On the basis of the replies received, stations were classified into various topographic and soil type categories.

Absolute minimum temperatures for the months of April and May relating to these stations were abstracted from the Monthly Weather Report over the period 1939 to 1945. The seven-year mean of this data was derived for each station, separately for the months of April and May. This mean was corrected to sea level on the conventional assumption that altitude imposes a depression of temperature of 1°F. per 300 ft. This extensive data was then treated in the following way :-

(a) Stations were grouped in twenty geographic areas and divided into two classes, 'coastal' (within three miles of the coast), and 'inland'.

(b) A mean absolute minimum temperature was obtained for each geographic area for both April and May, derived from inland stations only, hereafter referred to as the 'Area Mean'. The inclusion of coastal stations in the derivation of the area means, would result in an unequal weighting of the means according to the proportion of coastal stations contributing to them. Appendix II (a) lists the twenty geographic areas and their corresponding area means based on inland stations.

(c) The deviations of individual station means, both inland and coastal, from their appropriate inland area means were recorded for both months. These station deviations provide a comparative estimate of the frost liability of the individual stations within each area, when the effect of altitude has been discounted. The data is recorded in full in Appendix II (a) and (b) together with the range of the deviations within each area.

It should be noted that all inland stations for which data was available, over the seven year period, were included for the purpose of obtaining the area means. Topographic data was not available for many of these stations, which could not therefore be included in the following analysis. Those stations for which topographic data was available comprised 66 coastal and 101 inland stations. The above treatment eliminated, as far as possible, the effect of altitude and geographic location from the data. Coastal and inland stations were separately analysed.

(d) Stations were then allocated according to location to the following broad topographical classes:-

i Hill top locations.
ii Valley bottom locations.
iii Hill or valley flank locations.
iv Plain locations.
v Broad valley locations.

(e) From the records of the deviations of all stations within each topographic class, a mean deviation was calculated for each class. This allows us to compare the mean frost liability of the five topographic classes.

(f) The significance of the class differences was assessed, using t-tests throughout.

This method of treatment makes the legitimate assumption that the absolute minimum temperature for the months of April and May generally occurs under radiation frost conditions. The mean minimum temperature would obviously not provide a reliable index of intensity of frequency of radiation frosts. Monthly frequency of ground frost and air frost both provide a qualitative rather than a quantitative estimate of liability to radiation frost. In this relation it is interesting to note that the data abstracted by Lewis (1945), namely 'Mean Frequency of Spring Air Frosts', ranges stations in a sequence as regards liability to frost, closely similar to that obtained using the mean absolute minimum temperature for the months of April and May (uncorrected for height). Table 1. A highly significant inverse correlation occurs between the two criteria calculated for the twenty stations common to both investigations. (r = 0.90; p = 0.01)

Table 1. Comparison of mean frequency of Spring air frosts with mean absolute monthly minimum temperature (°F.)

Station	Mean frequency of Spring air frosts period March to May	Mean of absolute monthly minimum temperatures for April & May 1939 - 1945	Sequence of mean absolute monthly minimum temperatures
Eskdalemuir	37.8	26.1	1
Mayfield	23.1	28.3	2
Cambridge	19.7	29.5	4
Renfrew	19.4	28.5	3
Fort William	19.3	30.5	6
Shrewsbury	18.0	29.6	5
Cranwell	17.3	31.5	8
Norwich	13.1	31.1	7
Oxford	13.0	32.6	13
Stonyhurst	12.9	32.1	12
Ross on Wye	12.2	31.8	9
Southampton	11.1	33.6	17
Stornoway	10.6	32.9	14
Lympne	10.4	32.1	11
Birmingham	10.0	33.2	16
Kew	9.8	35.2	18
Southport	9.0	31.7	10
Rothesay	7.8	33.1	15
Douglas I.O.M.	5.5	35.2	18
Falmouth	3.1	37.6	20

Table 2. Analysis of inland stations

Location	No. of Stations	Mean deviation from area mean M_D °F.	Standard deviation σ °F.	Standard error E °F.	Range of 7 yr. mean
			APRIL (°F.)		
Hill top	22	+ 0.51	2.14	0.440	8.2
Hill flank	38	+ 0.28	1.96	0.309	7.5
Valley bottom	14	- 1.54	1.60	0.398	5.5
Broad valley	10	- 0.31	2.08	0.658	7.2
Plain	14	+ 0.03	1.41	0.350	5.4
			MAY		
Hill top	23	+ 1.03	1.78	0.388	5.9
Hill flank	38	+ 0.23	2.01	0.308	7.7
Valley bottom	15	- 1.68	1.47	0.406	6.0
Broad valley	10	- 0.72	2.02	0.678	7.0
Plain	15	- 0.14	1.34	0.373	4.5
		Combined data for April and May			
Hill top	23	+ 0.76	1.54	0.230	8.2
Hill flank	38	+ 0.25	1.95	0.221	8.3
Valley bottom	15	- 1.61	1.48	0.275	6.5
Broad valley	10	- 0.52	2.01	0.450	7.8
Plain	15	- 0.052	1.35	0.250	5.4

Table 3. Analysis of coastal stations

Location	No. of Stations	Mean deviation from area mean M_D °F.	Standard deviation σ °F.	Standard error E °F.	Range of 7 yr. mean
		APRIL (°F.)			
Hill top	12	+ 3.49	1.34	0.385	5.2
Hill flank	13	+ 3.22	1.93	0.536	6.2
Valley bottom	8	+ 2.56	1.24	0.437	3.3
Broad valley	9	+ 2.09	1.12	0.374	3.5
Plain	24	+ 2.02	1.54	0.314	6.0
		MAY			
Hill top	12	+ 4.52	1.01	0.290	2.9
Hill flank	13	+ 3.35	2.14	0.594	7.1
Valley bottom	8	+ 2.70	1.24	0.549	3.5
Broad valley	9	+ 2.24	1.43	0.475	4.2
Plain	24	+ 1.76	1.68	0.343	5.3
		Combined data for April and May			
Hill top	12	+ 4.01	1.27	0.259	5.2
Hill flank	13	+ 3.29	2.00	0.392	7.7
Valley bottom	8	+ 2.64	1.20	0.300	3.8
Broad valley	9	+ 2.17	1.24	0.294	4.3
Plain	24	+ 1.89	1.82	0.262	6.0

Table 4. Statistical comparison of topographic classes

Inland Stations

Topographic classes	Valley bottom	Broad valley	Plain	Valley flank
	APRIL			
Hill top	2.05 <0.01	0.32 0.3/0.4	0.43 0.4	0.23 0.6/0.7
Valley flank	1.82 <0.01	0.59 0.4/0.5	0.25 0.6/0.7	
Plain	1.57 <0.01	0.34 0.6/0.7		
Broad valley	1.23 0.1/0.2			
	MAY			
Hill top	2.71 <0.01	1.75 0.02/0.05	1.17 0.02/0.05	0.80 0.1/0.2
Valley flank	1.91 <0.01	0.95 0.2/0.3	0.37 0.4/0.5	
Plain	1.54 <0.01	0.58 0.4/0.5		
Broad valley	0.96 0.3/0.4			
	COMBINED DATA FOR APRIL and MAY			
Hill top	2.37 <0.01	1.28 0.01/0.02	0.81 0.02	0.51 0.1/0.2
Valley flank	1.86 <0.01	0.77 0.1/0.2	0.31 0.3/0.4	
Plain	1.56 <0.01	0.46 0.3/0.4		
Broad valley	1.09 0.01/0.02			

Upper figure: Difference between class mean in degrees F.
Lower figure: Value of 'p'

Table 5. Statistical comparison of topographic classes

Coastal Stations

Topographic classes	Valley bottom	Broad valley	Plain	Valley flank
	APRIL			
Hill top	1.47 < 0.01	1.40 < 0.01	0.93 0.1/0.2	0.27 0.6/0.7
Valley flank	1.20 0.05/0.1	1.13 0.05/0.1	0.66 0.3/0.4	
Valley bottom	0.54 0.3/0.4	0.47 0.4/0.5		
Broad valley	0.07 0.8/0.9			
	MAY			
Hill top	2.76 < 0.01	2.28 < 0.01	1.82 < 0.01	1.17 0.05/0.1
Valley flank	1.59 0.02/0.05	1.11 0.1/0.2	0.65 0.3/0.4	
Valley bottom	0.94 0.1	0.46 0.4/0.5		
Broad valley	0.48 0.4/0.5			
	COMBINED DATA FOR APRIL and MAY			
Hill top	2.12 < 0.01	1.84 < 0.01	1.57 < 0.01/0.02	0.72 0.1/0.2
Valley flank	1.40 < 0.01	1.12 0.02/0.05	0.65 0.1/0.2	
Valley bottom	0.75 0.05/0.1	0.47 0.2/0.3		
Broad valley	0.28 0.4/0.5			

If the seven-year mean of the absolute monthly minimum temperature is, in fact, a reliable estimate of the station's liability to frost, then the April and May mean deviations of each station from its area mean should be closely similar. The mean difference between these deviations for all stations for the two months is 0.8°F.

The correlation coefficients between April and May mean deviations of 144 inland stations and 66 coastal stations are as follows :

Inland stations $r = 0.86$
$p = 0.01$
Coastal stations $r = 0.78$
$p = 0.01$

indicating that the data does provide, in general, a good estimate of mean frost liability.

Results

Tables 2 to 5, and Fig. 1 give the results of this analysis which may be considered under several headings.

Local Topography

Topographic differences undoubtedly account for the major portion of the variation occurring between stations within each geographic area. Comparing the flat area of Norfolk, Suffolk, Essex and Cambridge with the mountainous area of Stirling, Perth and Inverness, we find the range of station's mean deviations to be 2.9 and 3.9°F. for April and May compared with 8.1 and 8.4°F. within those respective areas.

Fig. 1 and Tables 2 and 3 summarize the mean effect of location on absolute minimum temperature, due in the main, to air drainage effects. The results for inland stations, Table 2, are in accordance with expectation. Hill top stations have a significantly higher absolute minimum temperature than valley bottom stations (mean difference 2.37°F.) with flank, plain and broad valley stations occupying intermediate positions in that sequence. Tables 4 and 5 give the relative significance of the difference between any two class means.

The analysis of coastal stations, Table 3, indicates that coastal plain locations constitute the coldest class in this group. The relatively higher values of the 'valley bottom' and 'broad valley' classes may be accounted for by the fact that valleys in the neighbourhood of the coast debouche upon the sea and cold air readily drains from them.

Height above valley floor

The distribution of temperature in valleys, under radiation frost conditions, has been studied for a wide range of valley types ranging from small frost hollows to valleys over 1000 ft. in depth. The form of the temperature distribution is constant, at least as regards the lower slopes, temperature increasing with height above the valley floor. The scale of the effect is known to vary from a degree or two in the case of small frost hollows, to over 30°F. in the case of certain deep valleys in the Carolina highlands in America (Cox, 1919).

The data here under review is drawn from country where the hills rarely rise above 1000 ft. Fig. 2 plots the deviation of 49 inland stations located in the bottom and on the flanks of valleys or on hill slopes overlooking a plain, against their height above the valley floor or the level of the plain. The scatter of points at any one height is a measure of the dispersion attributable to the differing form of the valleys from which the data is drawn, ranging from narrow, deep and poorly drained, to broad, shallow and well drained, which is, in effect, indistinguishable from a frost plain.

In order to determine the mean scale of the drainage effect the 49 stations were allotted to five classes according to height above valley or plain floor. Table 6 records the mean deviation of each class from the area mean.

Table 6. Relationship between height of location above valley floor and mean absolute minimum temperature

Height above valley floor	No. of Stations	Mean deviation from area mean
25 ft.	15	- 1.61 °F.
25 - 50 ft.	9	- 1.30
50 -100 ft.	8	0.025
100 -200 ft.	11	0.88
200 -500 ft.	6	1.76

The result is represented graphically on Fig. 3. Mean deviation increases positively with increasing height above valley or plain floor to at least 150 ft. Above that height the number of available stations is insufficient to give a reliable indication.

The range of the drainage effect at the bottom of the valley may be taken to lie between the lower extreme within the valley bottom class and the mean of the broad valley class, i.e. -4.9 and -0.5°F. (Fig.2). Peripheral stations of the scatter diagram (Fig.2) are representative of extreme types of valley, i.e. (a) broad and open, and (b) deep and narrow.

The deviations here analysed incorporate the correction reducing the absolute minimum temperatures to sea level. This effect is in opposition to the drainage effect. In Fig. 3 a theoretical diagram has been constructed, based on the data of Table 6, to illustrate the combined effect of height above valley floor and height above sea level on mean absolute minimum temperature.

The series of curves represent the height/temperature relationship of a series of identical valleys, the floors of which range from 0 to 300 ft. above sea level. The relationship is probably not as simple as suggested by Fig. 3. Increased exposure to wind with increasing height, and the fall in vapour pressure and consequent increase in intensity of outgoing radiation with increasing height above sea level are factors which will undoubtedly tend to modify temperature relations in high valleys.

Proximity to the coast

The mean of the deviations of all coastal stations from their appropriate area means (based on inland stations only) is as follows:-

April + 2.60°F;

May + 2.75°F.

A comparison of stations on the East, South and West coasts shows no significant variation in this effect :

	Mean deviation (°F.)	
	April	May
East	+ 2.55	+ 2.40
South	+ 2.40	+ 2.97
West	+ 2.65	+ 2.30

These figures portray the general effect of coastal location on the absolute minimum temperature, upon which the topographic effects, summarized in Table 5, are superimposed. Manley (1944) states that any appreciable effect is confined to a zone not exceeding four miles from the coast, but in the absence of any close range of observations in coastal districts this is difficult to verify.

<u>The effect of soil type</u>

The influence of soil type on absolute minimum temperature is largely masked in Meteorological Station observations by the fact that these are made over a grass surface. Nevertheless the effect is apparent in a comparison of two extreme types, namely clay soils and sandy soils.

Table 7 gives the results of a comparison of 39 inland stations; 18 on clay, and 21 on sandy soil, and 31 coastal stations, 8 on clay, and 23 on sandy soil.

Table 7. Mean differences between station deviation and topographic class mean for stations overlying clay and sand

	Soil type	Mean difference from topographic class mean ($^{\circ}F.$)
Inland stations	Clay	+ 0.57
	Sand or sandy loam	- 0.60
Coastal stations	Clay	+ 0.21
	Sand or sandy loam	- 0.47

The mean difference of 1.17°F. between soil types is significant in the case of inland stations ($p = 0.01$) but that of 0.68°F. between coastal stations is not ($p = 0.2$)

The influence of urban conditions

Bilham (1938) has commented on the differences in temperatures recorded in large towns and in rural sites. This effect is undoubtedly a source of variation in the present data. A comparison has therefore been made between fourteen stations located in London and other large industrial towns, and twenty-eight rural stations, in order to determine the mean effect on the absolute minimum temperature attributable to this cause. In this case the proportion of stations drawn from different topographic classes were matched in the two categories 'town' and 'rural', thus:-

Town Stations	Rural Stations
8 Valley flank	16 Valley flank
4 Plain	8 Plain
2 Hill top	4 Hill top

The mean of the absolute minima for town stations exceeds that for rural stations in both months, by the following amounts. If the data for both months is combined, the difference becomes statistically significant.

April	0.96°F.	('p' 0.16)
May	0.97°F.	('p' 0.15)
Combined data	0.965°F.	('p' 0.03)

APPENDIX I

Name of Station ______________

County ______________

QUESTIONNAIRE

General nature of country	Location of Meteorological Station in relation to topography	REPLY and REMARKS (In the case of 1-8 insert a,b, c or d as appropriate)
(1) Flat or gently sloping plain?		
(2) Gently undulating country?	(a) Bottom of hollow (b) Top of rise (c) Intermediate on slope*	
(3) Broad valley or plain flanked by hills?	(a) At base of hills (b) Situated some distance from base of hills (Give approx. distance)	
(4) Plain cut by deep or shallow valley?	(a) Lip of valley (b) Bottom of valley (c) Flank of valley*	
(5) Hilly country, alternation of hill and valley with little or no flat ground?	(a) Hill top (b) Exposed hillside* (c) Valley flank* (d) Valley bottom	
(6) Mountainous country?	(a) Hill top (b) Exposed hillside* (c) Valley flank* (d) Valley bottom	
(7) Escarpment overlooking a plain or broad valley?	(a) Top of escarpment (b) Flank of escarpment* (c) Base of escarpment	
(8) Comparatively isolated ridge or hill overlooking a plain?	(a) Hill top (b) Hill side* (c) Base of hill	
(9) * If situated on a hillside or valley flank, (a) Give if possible the approximate height above the valley floor or plain. (b) Indicate whether it lies :- (1) On an exposed convex ridge or spur (2) In a concave declevity or gully (3) On the comparatively flat face of the hill or valley flank.		
(10) If situated on sloping ground : (a) Give aspect of slope, N, NW, W, SW, S, SE, E, NE. (b) Indicate the nature of the slope, slight, moderate, steep.		
(11) Nature of surrounding country? (a) Open country, pasture or arable land. (b) Well wooded country. (c) Built up area. (1) Completely built up. (2) Sparcely built up.		
(12) Nature of soil : (a) Light sandy. (b) Loam. (c) Clay (d) Chalk (e) Peat.		
(13) Distance from sea coast. (If less than 30 miles)		
(14) Is the station situated near a lake, estuary or river? If so, give its location in relation to this.		
(15) Is the location prone to radiation fogs developing on clear nights?		
(16) Is there any obstacle (embankment, thick hedge) downslope from the station, in such a position as to impede the free drainage of cold air? It has been observed that such obstacles exist at several stations which report unusually low minima.		

If the location of your station will not fit into the above classification, please supplement with a brief description of its peculiarities. Any additional information which in your opinion, may have a bearing on the frost conditions at your station would be welcomed.

Signed ______________

Date:

Appendix II. Area and Station means of the absolute minimum temperature in the months of April and May over the period 1939 - 1945

(a) Inland Stations

Counties comprising area	Area mean Degrees F		Standard error of mean		Station	Classification and height above plain or valley floor in feet	Altitude	Mean absolute minimum temperature of Station		Mean absolute minimum temperature corrected to sea level		Deviation from area mean		Range of deviations °F.	
	April	May	April	May			feet	April	May	April	May	April	May	April	May
Caithness Sutherland Ross & Cromarty	-	-	-	-	Achnashellach	F	225	26.3	29.4	27.0	30.2	-	-	-	-
Argyll Bute Dumbarton Renfrew	28.1	30.3	1.1	1.4	Dunoon Benmore	B	46	27.7	28.4	27.9	28.6	-0.2	-1.7	4.9	6.3
					Glenbranter	B	120	26.4	27.4	26.8	27.8	-1.3	-2.5		
					Paisley	-	106	31.0	33.7	31.4	34.1	3.3	3.8		
					Renfrew	-	19	26.5	30.6	26.5	30.6	-1.6	0.3		
Stirling Perth Inverness	27.0	30.3	1.5	1.5	Balfron	-	342	27.3	30.0	28.4	31.1	1.4	0.8	8.1	8.4
					Stirling	F 151	151	30.6	34.7	31.1	35.2	4.1	4.9		
					Perth	-	76	26.5	30.0	26.8	30.3	-0.2	0.0		
					Dalwhinnie	B	1176	19.6	23.4	23.0	26.8	-4.0	-3.5		
					Fort Augustus	-	68	26.3	28.6	26.7	29.1	-0.3	-1.2		
Fife Nairn Moray Banff Angus Kincardine Aberdeen	28.5	31.5	0.8	0.6	Gordon Castle	-	104	29.3	32.8	29.6	33.1	1.1	1.6	6.5	4.7
					Balmoral	F 50	927	22.4	26.6	25.5	29.7	-3.0	-1.8		
					Braemar	-	1111	20.7	25.5	24.3	29.1	-4.2	-2.4		
					Dunfermline	-	237	30.0	33.0	30.8	33.8	2.3	2.3		
					Kettins	B	218	26.6	29.3	27.3	30.0	-1.2	-1.5		
					Dundee	F 147	147	29.3	31.7	29.8	32.2	1.3	0.7		
					Cupar	-	210	29.6	31.9	30.3	32.6	1.8	1.1		
					Craibstone	F 50	300	29.1	31.0	30.1	32.0	0.6	0.5		
Berwick Selkirk East Lothian Roxburgh Peebles Midlothian	28.8	32.6	0.9	0.7	Balerno	F 150	750	28.7	31.4	31.2	33.9	2.4	1.3	8.0	6.5
					Edinburgh										
					Blackford	F 300	441	31.1	34.4	32.6	35.9	5.8	3.3		
					Boghall	BV	639	29.0	31.6	31.4	34.0	2.2	1.4		
					Botanic Gdns.	-	74	28.4	32.9	28.7	33.1	-0.1	0.5		
					Liberton	-	190	27.0	31.6	27.6	32.2	-1.2	-0.4		
					Marchmont	-	498	28.0	31.4	29.7	33.1	0.9	0.5		
					West Linton	-	820	23.3	27.6	26.0	30.3	-2.8	-2.3		
					Kelso	F	193	27.6	31.1	28.2	31.8	-0.6	-0.8		
					Wolfee	-	537	22.9	27.6	24.6	29.4	-4.2	-3.2		

Counties comprising area	Area mean Degrees F.		Standard error of mean		Station	Classification and height above plain or valley floor in feet	Altitude	Mean absolute minimum temperature of Station		Mean absolute minimum temperature corrected to sea level		Deviation from area mean		Range of deviations °F.	
	April	May	April	May			Feet	April	May	April	May	April	May	April	May
Ayr Wigton Lanark Dumfries Kirkcudbright	28.0	31.4	0.9	0.5	Auchincruive	B	89	27.1	31.0	27.4	31.3	-0.6	-0.1	6.3	4.2
					Colmonell	-	170	29.6	30.1	30.1	30.7	2.1	-0.7		
					Kilmarnock	-	130	26.0	30.7	26.4	31.1	-1.6	-0.3		
					Dumfries	-	140	27.4	32.6	27.9	33.0	-0.1	1.6		
					Eskdalemuir	-	794	24.7	27.4	27.4	30.1	-0.6	-1.3		
					Carluke	-	534	28.3	31.6	30.1	33.4	2.1	2.0		
					Dungavel	F 125	798	22.3	27.9	24.9	30.5	-3.1	-0.9		
					Glasgow Speke Park	T	351	30.9	31.9	32.0	33.0	4.0	1.6		
					Glenlee	B	181	25.1	28.6	25.7	29.2	-2.3	-2.5		
Yorks N.Riding Durham Northumberland	29.1	32.0	0.9	1.0	Berwick	F 60	76	31.0	34.0	31.3	34.3	2.2	2.3	7.9	7.9
					Bellingham	-	849	25.3	29.7	28.7	32.5	-1.0	0.5		
					Cockle Park	T	325	28.9	-	29.9	-	0.8	-		
					Durham	T	336	24.7	29.3	25.8	30.4	-3.3	-1.6		
					Houghall	BV	160	23.6	25.9	24.1	26.4	-5.0	-5.6		
					Ushaw College	T	594	30.0	32.3	32.0	34.3	2.9	2.3		
					Ampleford	F 180	313	29.7	31.4	30.8	32.5	1.7	0.5		
					York	-	57	31.0	33.7	31.2	33.9	2.1	1.9		
Cumberland Westmorland	27.8	31.7	0.2	0.7	Keswick	B	254	27.6	32.3	28.4	33.1	0.6	1.6	1.0	3.0
					Newton Rigg	T	560	25.9	30.1	27.7	32.0	-0.1	0.3		
					Ambleside	B	145	27.0	29.6	27.4	30.1	-0.4	-1.6		
					Appleby	F 50	440	26.3	30.0	27.9	31.5	-0.1	-0.2		
Yorks West Riding	30.4	33.1	0.3	0.4	Askham Bryan	P	90	27.9	30.1	28.1	30.4	-2.3	-2.7	4.5	6.0
					Bingley	F 350	610	29.3	31.7	31.3	33.7	0.9	0.6		
					Bradford	F 100	439	30.0	32.3	31.5	33.8	1.1	0.7		
					Harrogate	F 300	478	29.4	31.9	31.0	33.5	0.6	0.4		
					Huddersfield	F 125	325	27.9	30.4	28.9	31.5	-1.5	-1.6		
					" Oakes	F 500	761	28.7	32.4	31.2	35.0	0.8	1.9		
					Ilkley	B	315	27.7	30.9	28.8	31.9	-1.6	-1.2		
					Pontefract	T	255	31.1	33.4	32.0	34.3	1.6	1.2		
					Rotherham	F 110	284	29.9	31.0	30.8	31.9	0.4	-1.2		
					Sheffield	F 127	428	31.1	35.0	32.6	36.4	2.2	3.3		
					Wakefield	F	124	27.9	31.0	28.3	31.4	2.1	1.7		

Counties comprising area	Area mean Degrees F		Standard error of mean		Station	Classification and height above plain or valley floor in feet	Altitude	Mean absolute minimum temperature of Station		Mean absolute minimum temperature corrected to sea level		Deviation from area mean		Range of deviations °F.	
	April	May	April	May			Feet	April	May	April	May	April	May	April	May
Lincoln Yorks East Riding	30.8	33.7	0.6	0.5	Boston	P	16	29.8	32.9	29.8	32.9	-1.0	-0.8	1.9	1.8
					Cranwell	-	203	30.3	32.7	31.0	33.4	0.2	-0.3		
					Hull	P	8	31.7	34.7	31.7	34.7	0.9	1.0		
Stafford Derby Shropshire Leicester Nottingham	29.9	31.6	0.5	0.6	Belper School	B	198	29.1	30.3	29.8	30.9	-0.1	-0.7	5.3	6.7
					Buxton	F 54	1008	28.0	29.1	31.4	32.5	1.5	0.9		
					Mansfield	T	357	30.1	32.9	31.3	34.0	1.4	2.4		
					Nottingham	T	192	32.1	34.9	32.7	35.5	2.8	3.9		
					Sutton Bonnington	-	157	28.7	29.9	29.2	30.4	-0.7	-1.2		
					Newport	F	211	26.7	28.1	27.4	28.8	-2.5	-2.8		
					Shrewsbury	BV	184	29.0	30.1	29.6	30.8	-0.3	-0.8		
					Market Drayton	F 350	581	27.4	28.4	29.4	30.4	-0.5	-1.2		
					Mayfield	-	374	27.4	29.1	28.7	30.4	-1.2	-1.2		
					Leicester	-	325	28.7	30.7	29.8	31.8	-0.1	0.2		
Cheshire Lancashire	30.9	33.6	0.7	0.6	Bolton	P	342	30.4	33.0	31.6	34.1	0.7	0.5	4.1	3.7
					Burley	F 100	458	28.0	30.4	29.5	32.0	-1.4	-1.6		
					Darwin	F 224	724	-	32.9	-	35.3	-	1.7		
					Hulton	-	82	29.4	31.4	29.7	31.7	-1.2	-1.9		
					Leyland	-	125	28.3	31.6	28.7	32.0	-2.2	-1.6		
					Manchester Whitworth Park	P	125	32.4	35.0	32.8	35.4	1.9	1.8		
					Stonyhurst	-	377	30.4	33.9	31.7	35.1	0.8	1.5		
					West Kirby	-	25	31.0	33.6	31.1	33.7	0.4	0.1		
					Macclesfield	BV	500	30.3	31.9	32.0	33.5	1.1	-0.1		
Anglesea Carnarvon Brecknock Montgomery Merionith Denbigh Flint Radnor Cardigan	31.1	32.8	0.9	1.2	Aberystwyth Lety-evan-hen	T	930	30.3	33.4	33.4	36.5	2.3	3.7	4.7	6.3
					Rhayader	F 80	757	27.0	27.7	29.7	30.2	-1.4	-2.6		
					Cantreff	T	1080	29.6	31.0	32.2	34.6	2.3	1.8		
					Crickhowell	B	230	29.6	30.7	30.3	31.5	-0.8	-1.3		
					Welshpool	BV	254	27.9	30.1	28.7	31.0	-2.4	-1.8		
Glamorgan Carmarthan Pembroke	-	-	-	-	Haverfordwest	T	233	31.7	32.1	32.5	32.9	-	-	-	-

Counties comprising area	Area Mean Degrees F		Standard error of mean		Station	Classification and height above plain or valley floor in feet	Altitude	Mean absolute minimum temperature of Station		Mean absolute minimum temperature corrected to sea level		Deviation from area mean		Range of deviations °F.	
	April	May	April	May			Feet	April	May	April	May	April	May	April	May
Hereford Worcester Gloucester Monmouth Warwick Oxford	30.6	32.8	0.5	0.5	Oxford	P	208	31.3	33.9	32.0	34.6	1.4	1.8	7.2	6.4
					Hereford	-	292	29.9	31.7	30.8	32.7	0.2	-0.1		
					Ross-on-Wye	F 120	223	31.1	32.4	31.9	33.2	1.3	0.5		
					Birmingham	-	535	31.9	34.6	33.6	36.4	3.0	3.6		
					Sparkhill	F 50	425	29.9	30.1	31.3	31.6	0.7	-1.2		
					Coventry	F 45	241	26.1	29.7	28.8	30.5	-1.8	-2.3		
					Leamington Spa	BV	163	31.1	33.1	31.7	33.7	1.1	0.9		
					Rugby	T	390	29.3	30.7	30.6	32.0	0.0	-0.8		
					Cheltenham	BV	214	30.9	33.0	31.6	33.7	1.0	0.9		
					Parkend	F 200	325	29.3	31.3	30.4	32.4	-0.2	-0.4		
					Droitwich	T?	380	26.0	30.7	26.4	31.1	-4.2	-1.7		
					Malvern	F 300	380	32.0	35.3	33.3	36.6	2.7	3.8		
					Stonehouse	-	150	29.3	30.7	29.8	31.2	-0.8	-1.6		
					Worcester	-	94	28.1	29.9	28.5	30.2	-2.1	-2.6		
					Usk	B	70	28.9	-	29.1	-	-0.6	-		
Suffolk Norfolk Essex Cambridge	29.7	31.2	0.3	0.4	Norwich	T	110	29.3	32.9	29.6	33.2	-0.1	2.0	2.9	3.9
					Sprowston	P	93	30.1	30.4	30.5	30.7	0.8	-0.5		
					Terrington	(P?)	13	29.9	31.1	30.2	31.5	0.5	0.5		
					Cambridge Botanic Garden	P	41	28.9	30.1	29.0	30.3	-0.7	-0.9		
					Bungay	-	79	30.9	31.3	31.1	31.6	1.4	0.4		
					Mildenhall	P	15	28.1	29.2	28.2	29.3	-1.5	-1.9		
					Earls Coln	-	160	29.3	30.9	29.8	31.4	0.1	0.2		
					Halsted	-	140	28.7	30.1	29.2	30.6	-0.5	-0.6		
					Maldon	P	14	30.0	32.1	30.0	32.2	0.3	1.0		
Berks Bedford Middlesex Bucks Northampton Herts Huntingdon	30.4	32.9	0.8	0.6	Luton	F	381	25.7	31.3	27.0	32.6	-3.4	-0.3	6.1	5.0
					Woburn	B	291	27.9	29.4	28.8	30.4	-2.6	-2.5		
					Rothamstead	T	420	29.9	31.7	31.3	33.1	0.9	0.2		
					St Albans	P	272	28.9	31.6	29.8	32.5	-0.6	-0.4		
					Reading	P	152	32.6	33.6	33.1	34.1	2.7	1.2		
					Shinfield	-	200	30.4	31.7	31.1	32.4	0.7	-0.5		
					Kew	-	18	(34.0	36.3)	(34.1	36.3)	3.7	3.4		
					Hampstead	-	450	30.6	33.9	32.1	35.4	1.7	2.5		
					Regents Park	-	129	(33.7	36.1)	(34.1	36.6)	(3.7	3.7)		
					Greenwich	F 120	149	(32.1	34.6)	(32.6	35.1)	(2.2	2.2)		
					Kensington	P	80	(34.0	36.4)	(34.3	36.7)	(3.9	3.8)		

[redacted]

APPENDIX II

(a)

Counties comprising area	Area Mean Degrees F		Standard error of mean		Station	Classification and height above plain or valley floor in feet	Altitude	Mean absolute minimum temperature of Station		Mean absolute minimum temperature corrected to sea level		Deviation from area mean		Range of deviation °F.	
	April	May	April	May			Feet	April	May	April	May	April	May	April	May
Surrey Sussex Kent	31.5	32.4	0.5	0.3	Croydon	P	217	31.0	32.9	31.7	33.6	0.2	1.2	5.3	5.9
					Wisley	T	150	30.3	31.3	30.8	31.8	-0.7	-0.6		
					Bromley	T	213	31.7	33.1	32.4	33.9	0.9	1.5		
					Canterbury	-	135	31.6	31.9	32.0	32.3	0.5	-0.1		
					East Malling	F 100	132	30.0	29.6	30.4	30.0	-1.1	-2.4		
					Goudhurst	T	290	28.6	29.4	29.5	30.4	-2.0	-2.0		
					Lympe	-	346	31.9	32.3	33.0	33.4	1.5	1.0		
					Manston	-	154	34.3	35.4	34.8	35.9	3.3	3.5		
					Tunbridge Wells	F 35	351	29.0	29.9	30.2	31.0	-1.3	-1.4		
					Wye	BV	164	30.0	31.6	30.5	32.1	-1.0	-0.3		
Somerset Wilts Dorset Hampshire	31.4	32.7	0.3	0.5	Boscombe Down	-	417	29.3	31.9	30.7	33.2	-0.7	0.5	3.2	6.1
					Larkhill	T	440	29.6	32.6	31.0	34.0	-0.4	1.3		
					Marlborough	B	424	27.9	28.0	29.3	29.4	-2.1	-3.3		
					Porton	T	363	28.7	30.4	29.9	31.6	-1.5	-1.1		
					Shaftsbury	T	722	29.9	33.1	32.3	35.5	0.9	2.8		
					Bath	B	67	31.3	31.7	31.5	31.8	0.1	-0.9		
					Bristol	-	209	31.1	31.7	31.8	32.3	0.4	-0.4		
					Cannington	BV	95	32.1	32.6	32.5	32.9	1.1	0.2		
					Long Ashton	F 50	162	31.7	31.7	32.3	32.3	0.9	-0.4		
					Holton Heath	-	64	30.7	32.3	30.9	32.5	-0.5	-0.2		
					Leckford	F 85	385	30.0	33.0	31.3	34.3	-0.1	1.6		
					Long Sutton	T	479	28.6	30.6	30.2	32.2	-1.2	0.5		
					Southampton	T	64	32.1	35.0	32.4	35.2	1.0	2.5		
					South Farnborough	-	226	29.4	29.6	30.2	30.3	-1.2	-2.4		
Devon Cornwall	32.8	34.3	0.5	0.9	Barnstable	BV	25	32.3	32.6	32.4	32.7	-0.4	-1.6		
					Cullompton	F 50	202	31.1	31.7	31.8	32.4	-1.0	-1.9		
					Killerton	-	159	30.7	31.9	31.2	32.4	-1.6	-1.9		
					Newton Abbot	-	375	33.0	35.1	34.2	36.3	1.4	2.0		
					Princetown	F 200	1359	29.9	32.9	34.4	37.4	1.6	3.1		
					Ellbridge	F 80	200	32.1	34.3	32.8	35.0	0.0	0.7		

(b) Coastal Stations

Counties comprising area	Station	Classification	Altitude	Mean absolute minimum temperature of Station		Mean absolute minimum temperature corrected to sea level		Deviation from inland area mean		Range of deviation °F.	
			feet	April	May	April	May	April	May	April	May
Caithness Sutherland Ross & Cromarty	Stornoway	P	79	31.9	33.9	32.1	34.1	5.0	3.9	2.8	1.2
	Fortrose	P	69	30.0	34.4	30.2	34.7	3.2	4.5		
	Duntulm	T	294	32.0	34.3	33.0	35.3	6.0	5.1		
Argyll Bute Dumbarton Renfrew	Cardross	F	130	28.1	30.0	28.6	30.4	0.5	0.1	4.6	5.4
	Dunoon	F	132	30.7	32.7	31.2	33.2	3.1	2.9		
	Rothesay	F	200	32.1	34.1	32.8	34.8	4.7	4.5		
	Helensburgh	BV	293	28.6	31.0	29.6	32.0	1.5	1.7		
	Greenock	F	199	32.6	35.1	33.2	35.8	5.1	5.5		
Stirling, Perth, Inverness	Fort William	P	34	29.6	31.4	29.7	31.6	2.7	1.3	-	-
Fife, Angus, Nairn, Kincardine, Moray, Aberdeen, Banff	Nairn	P	20	28.6	32.3	28.6	32.4	0.1	0.9	1.2	1.2
	Arbroath	P	93	29.1	0.9	29.5	31.2	1.6	-0.5		
	Dundee	BV	147	29.3	31.7	29.8	32.2	1.3	0.7		
	St Andrews	P	13	29.4	31.9	29.5	31.9	1.0	0.4		
Ayr, Dumfries, Kirkcudbright, Wigton, Lanark	Prestwick	P	17	29.7	32.4	29.8	32.5	1.8	1.1	2.9	1.7
	Turnberry	P	30	32.6	34.1	32.7	34.2	4.7	2.8		
Yorks N.Riding, Durham Northumberland	Scarborough	F	118	35.3	37.6	35.7	38.0	6.6	6.0	4.9	5.2
	Redcar	P	25	30.7	32.7	30.8	32.8	1.7	0.8		
Isle of Man	Douglas	F	284	34.4	36.0	35.4	36.9	-	-	-	-
	Point of Ayr	P	30	33.7	36.6	33.8	36.7	-	-		
Lincoln Yorks E.Riding	Skegness	P	15	32.4	35.3	32.5	35.3	1.7	1.6	0.3	0.2
	Cleethorpes	B	23	32.1	35.0	32.2	35.1	1.4	1.4		
Cheshire Lancashire	Blackpool	P	65	31.6	33.4	31.8	33.6	0.9	0.0	4.6	4.6
	Fleetwood	P	21	32.6	35.0	32.6	35.1	1.7	1.5		
	Morecambe	P	23	33.3	34.0	33.4	34.1	2.5	0.5		
	Southport Bed.Rd.Park	P	35	30.7	32.7	30.8	32.8	-0.1	-0.8		
	Bidston Observatory	T	198	34.7	36.7	35.4	37.4	4.5	3.8		
	Hoylake	P	23	31.1	32.8	31.2	32.9	0.3	-0.7		

APPENDIX II

(b)

Counties comprising area	Station	Classification	Altitude	Mean absolute minimum temperature of Station		Mean absolute minimum temperature corrected to sea level		Deviation from inland area mean		Range of deviation °F.	
			feet	April	May	April	May	April	May	April	May
Anglesea, Denbigh, Caernarvon, Flint, Brecknock, Radnor, Montgomery, Cardigan, Merionth	Prestatyn	P	18	34.0	35.4	34.1	35.5	3.0	2.7	3.6	3.0
	Rhyl	BV	31	32.9	33.7	33.0	33.8	1.9	1.0		
	Colwyn Bay	F	118	31.6	35.4	32.0	35.8	0.9	3.1		
	Aber	B	60	34.7	36.7	34.9	36.8	3.8	4.0		
	Aberystwyth, P.B.S.	T	452	33.0	34.3	34.5	35.9	3.4	3.1		
	Aberystwyth	P	12	35.6	36.6	35.6	36.6	4.5	3.8		
Glamorgan Carmarthen Pembroke	St Ann's Head	T	142	34.6	38.0	35.0	38.5	2.5	5.6	3.0	2.3
	Tenby	F	64	34.7	35.0	34.9	35.2	2.4	2.3		
	Cardiff	T	203	32.6	35.9	33.3	36.5	0.8	3.6		
	Swansea	BV	33	36.1	37.4	36.3	37.5	3.8	4.6		
Suffolk Norfolk Essex Cambridge	Cromer	T	178	32.4	35.1	33.1	35.7	3.4	4.5	1.3	3.6
	Hunstanton	T	105	33.0	36.9	33.3	37.2	3.6	6.0		
	Lowestoft	P	82	32.3	33.3	32.6	33.6	2.9	2.4		
	Dovercourt	P	47	33.7	35.1	33.9	35.3	4.2	4.1		
Surrey Sussex Kent	Beachy Head	T	502	33.1	36.1	34.8	37.8	3.3	5.4	4.3	6.0
	Bexhill	P	12	33.3	35.9	33.3	35.9	1.8	3.5		
	Littlehampton	P	15	32.4	35.0	32.5	35.1	1.0	2.7		
	Seaford	B	45	32.7	34.0	32.9	34.2	1.4	1.8		
	Dover	P	19	33.0	34.5	33.1	34.6	1.6	2.2		
	Dungeness	P	20	30.4	31.7	30.5	31.8	-1.0	-0.6		
	Whitstable	BV	9	33.3	34.7	33.3	34.7	1.8	2.3		
Somerset Dorset Wilts Hampshire	Newport	BV	48	33.0	35.1	33.2	35.3	1.8	2.6	2.9	3.0
	Ventnor (H)	F	60	35.9	38.1	36.1	38.3	4.7	5.6		
	St Cathrine's Point	P	150	34.4	36.6	34.9	37.1	3.5	4.4		
	Sandown	P	13	35.1	37.1	35.2	37.2	3.8	4.5		
	Totland Bay	B	140	34.4	35.1	34.9	35.6	3.5	2.9		
	Weston-Super-Mare	P	28	34.0	36.0	34.1	36.1	2.7	3.4		
	Swanage	BV	14	34.2	36.0	34.2	36.0	2.8	3.3		
Devon Cornwall	Exmouth	F	195	34.1	35.7	34.8	36.4	2.0	2.1	4.5	6.6
	Ilfracombe	B	25	37.1	39.1	37.2	39.2	4.4	4.9		
	Plymouth Hoe	T	117	35.7	37.1	36.1	37.5	3.3	3.2		
	Seaton	BV	43	33.0	34.6	33.1	34.7	0.3	0.4		
	Sidmouth	B	25	33.9	35.7	33.9	35.8	1.1	1.5		
	Teignmouth	B	20	35.0	37.1	35.1	37.2	2.3	2.9		
	Torquay	B	27	35.3	36.4	35.4	36.5	2.6	2.2		
	Bude	F	50	33.0	33.0	33.2	33.2	0.4	-1.1		
	Falmouth	T	167	36.7	38.4	37.3	39.0	4.5	4.7		
	Gulval	BV	20	36.3	37.4	36.4	37.9	3.6	3.6		
	Lizard	T	240	34.1	39.0	34.9	39.8	2.1	5.5		
	Newquay	F	182	35.7	36.9	36.3	37.5	3.5	3.2		
	Penzance	F	55	37.4	39.0	37.6	39.2	4.8	4.9		

PART II. MINIMUM TEMPERATURE DISTRIBUTION AND KATABATIC WINDS IN THE AYR VALLEY UNDER RADIATION FROST CONDITIONS

Introduction and Review of Literature

The factors determining nocturnal vertical temperature structure and temperature distribution over ground of irregular contour, are many and complex. In the following paragraphs an attempt is made to analyse, from a theoretical standpoint, the main factors involved and to relate them to observed temperature structure and distribution.

The fall of air temperature under radiation conditions is determined, primarily, by the fall of soil surface temperature. Consider first, a flat site at the approach of sunset, under calm radiation conditions. The temperature lapse rate first approximates to the dry adiabatic (Fig.4 $T_0A'A$). The ground surface cools from T_0 to T_1 by net radiation loss. The overlying air cools by contact and the temperature fall tends to be propagated upwards by (a) eddy diffusion or turbulence, and to a much smaller extent by (b) radiation diffusion and (c) molecular diffusion. Eddy diffusion is rapid when the atmosphere is unstable, i.e. when the lapse rate is large, approximating to the dry adiabatic, but becomes progressively damped out as we pass to stable, temperature inversion conditions, e.g. $T_1B'B$. Fig. 4. Cowling and White (1941) and Longley (1944) have derived mathematically the relationship between lapse rate and transfer of heat by eddy diffusion. It will be seen that the cycle reinforces itself. Inversion conditions slow down the upward propagation of cooling and this in turn increases the rate of growth of the inversion. Under such conditions the flow of heat propagated downwards from air to soil surface, F_a, is small compared with the flow arriving from the lower soil horizons, F_s, under the influence of the soil temperature gradient. The two are approximately equated with the net loss by radiation from the surface, R_n.

$$R_n = F_a + F_s.$$

Suppose now that a wind develops. Turbulence causes forced mixing in the inversion zone and the vertical temperature structure tends to approach the dry adiabatic; how closely, depends on the wind velocity. Heat is rapidly propagated downwards and a much smaller fall of temperature is spread through a much greater vertical depth of air, the temperature in the inversion zone rising sharply. ($C\ C'\ T_1$ Fig.4). A strongly condensed temperature gradient between the soil surface and the air immediately above it results ($T_1\ C'$ Fig. 4). Heat transfer from air to soil across this gradient is rapid, and in soils and soil cover of low heat capacity, such as peat or matted grass, this may result in a considerable rise in the temperature of the surface (T_1 to T_2 Fig. 4). Ultimately, equilibrium is established again and with R_n constant,

$$R_n = F_{a1} + F_{s1} \qquad \text{where } F_{a1} > F_a$$
$$\text{and } \quad F_{s1} < F_s$$

Katabatic flow

The above considerations may now be applied to a hill slope showing katabatic drainage of cold air. Temperature inversions develop in the zone near the ground in exactly the same way. This results in unstable conditions and the cold air in the inversion zone tends to flow downwards. The velocity and depth of the flow will depend on the size of the inversion, the slope of the ground, the length of the slope traversed, and also the contour of the ground whether concave, tending to concentrate the flow, or convex, tending to disperse it. Brunt (1938) mentions that katabatic winds of considerable strength develop over long snow slopes, a surface over which extremely large inversions develop. The flow continues until the cold air reaches a horizon in the valley bottom of approximately identical temperature. Hawke (1933; 1944) in his investigation of the notable frost hollow at Rickmansworth, demonstrated by means of smoke trails this spreading out of the katabatic stream on the surface of the cold lake which formed in the valley bottom. Both he and Heywood (1933), who investigated katabatic winds in a valley below Leafield in Oxfordshire, observed that the katabatic flow tends to cease in the valley bottom early in the night, due to the formation of this cold lake into which the katabatic flow does not penetrate.

The down-flow must be replaced by an inflow from the free atmosphere at some level towards the top of the slope, as, for instance, in the 'neutral zone' referred to by Cornford (1938), which divides the normal hilltop, gradient wind from the upper limit of the katabatic flow, when these two oppose each other in direction. The build up of a temperature inversion in this inflow proceeds as the air flows downslope. The flow is relatively non-turbulent, at least at low velocities. Heywood (1933) observed a marked absence of gustiness in the anemometer traces of the katabatic winds which he recorded. The temperature fall within the katabatic flow will be determined by the height above ground level, the nature of the ground surface, and the time during which the stream is subjected to cooling from below, i.e. it will be a function of the velocity of the flow and the length of the slope traversed. The fall in temperature with distance down the slope is apparent in Cornford's records (1938) over both grass and bare soil slopes. We should expect low temperatures and large inversions to develop on gentle slopes where the katabatic flow is sluggish, and also over the lower portions of long slopes over which the flow has a long track. Heywood (1933) noted that the flow originated as a very shallow current on the upper slopes of the valley flank and increases to a depth exceeding 15 ft. lower down. The extensive observations of Day and Peace (1937) on the distribution of frost damage in forest plantations, in diverse types of country, confirm in many ways these suggestions. The following examples are of particular interest. The flank of Glenshiel, which rises to 3,000 ft. carried a stand of Sitka spruce extending from the bottom of the glen to a height of 1,300 - 1,500 ft. Severe damage was recorded in the bottom of the glen, but the remainder of the stand showed a uniform degree of frosting up to the upper limit of the stand. Here, the long slopes above the forest must have generated a katabatic flow which cooled in sufficient depth to cause frosting throughout the remainder of its track. Newcastleton Forest on the Border, covers a series of rounded hills rising from 650 ft. at the base to a maximum height of 1,200 ft. Plantations of Sitka spruce showed frost damage increasing in severity from 1,200 ft. down to 650 ft. at the base, and in addition, where the slopes tended to flatten out, frosting was severe at whatever height these shelves occurred. Such evidence, though suggestive, is not wholely trustworthy, since altitude and also exposure, determine to some extent the stage of advancement of growth in the Spring, and therefore susceptibility to frost.

The katabatic wind velocities reported by Heywood (1933) and Hawke (1944) were in both cases of the order of less than 1 metre per second, but in both locations the drainage of cold air was impeded. Newnham (1918) on the other hand, refers to a flow of 9 metres per second near Benson, at the foot of a long slope of the Chilterns, with a fall of 500 feet. In mountainous country and over snow, katabatic winds of considerable velocity are known to develop, but actual determinations are not available. Cornford (1938) found that katabatic winds tend to flow over obstacles, such as walls, lying across their path; nor were they seriously obstructed by a wood of fairly dense scrub lying in their track. Day and Peace (1937) on the other hand, suggest that a belt of trees lying across a slope does seriously retard the flow, particularly when the ground carries a high cover of rough growth, such as is usual on afforsted slopes, and an accumulation of cold air occurs along the top border of the belt. Brunt (1945) suggests that katabatic flows might be diverted by running a thick hedge diagonally across a slope, thereby canalizing it and affording protection to the area below the hedge.

Exposure to wind

The preceding paragraphs have dealt, essentially, with calm conditions. Over high ground such conditions rarely exist, and the gradient wind is frequently sufficiently strong to prevent the development of katabatic flows. Heywood (1933) found that no katabatic flow developed in the valley below Leafield when the wind on the exposed hill top exceeded 5 metres per second at 13.4 metres. Cornford (1938) observed that katabatic flows could be observed over the lower, but not the upper slopes of the Medway valley when the surface wind on an adjacent 600 ft hill, was of the order of 5 to 10 m.p.h. (2.5 to 5 metres per sec.).

Best (1935) investigated the influence of wind velocity upon the size of the temperature inversion between the limits 2.5 cms. to 30 cms., and 2.5 cms. to

1.2 metres above ground level. The site was level and well exposed, with a cover of short turf. He shows that inversion size falls rapidly as the wind velocity, measured at 13.4 metres above ground level, increases from 0 to 2 metres per second. Above this limit, inversions are reduced to small dimensions. We may reasonably conclude that the upper limit of 2 metres per second virtually determines the upper limit of the gradient wind above which katabatic winds cannot develop.

Conditions favourable to the development of katabatic winds more frequently prevail over the lower, sheltered slopes of a valley than on the higher, more exposed hill sides. The gradient wind velocity is therefore of great importance in determining the effective size of the catchment area which contributes to the katabatic pooling of cold air in a valley bottom, as well as in determining the size of temperature inversion itself.

Young (1923) cites a remarkable example of the relationship between wind speed and minimum temperature on level ground. He shows that the wind which blows through the Cajon Pass may continue as a stream across the fruit growing plain to the East of Los Angeles, and create a lane of high minimum temperature in its path on clear, calm, radiation nights. During the severe freeze of 1922 the mean minimum temperature inside the lane was -2.4°C. while outside it fell to -4.4 to -6.7°C.

Geiger (1927) notes that large forest clearings behave as frost hollows, presumably due to the protection from wind afforded by the surrounding forest which permits the development of large inversions in stagnant air.

Magnitude of the cold air drainage effect

The following observations indicate the scale of temperature difference which may develop between hill top, or hill flank, and valley bottom locations, attributable to air drainage.

Hawke (1933; 1944) made a most thorough examination of temperature variation in the notable frost hollow at Rickmansworth in Hertfordshire, 182 ft. above mean sea level. The site is a narrow valley dammed by a railway embankment, the soil, sandy gravel overlying chalk, and therefore perfectly drained. Under severe radiation frost conditions the minimum temperature at the bottom of this valley may fall 14^{O}F. below that of Croydon. Comparison with Rothamsted Station, 420 ft. above M.S.L., located 14 miles to the North on an exposed, flattened ridge of the Chilterns and lying on heavy loam, shows that the absolute monthly minimum temperature falls below that of Rothamsted by an average of 9.7^{O}F. Bilham (1938) comments that the night climate of this hollow is almost exactly comparable with that of Braemar, lying at an altitude of 1,111 ft. above M.S.L., on the Aberdeenshire plateau, which is about the coldest inhabited region in the British Isles.

The observations of Schmidt (1934) of minimum temperatures at the bottom of a 500 ft deep 'doline' or hollow, at Gstettneralm in Austria, are even more remarkable. The hollow is completely enclosed, the lowest point on the rim being 160 ft. above the bottom. Minimum temperatures recorded in the hollow were as much as 25°C. (45°F.) lower than those observed at a neighbouring exposed site at approximately the same altitude. An extraordinary winter minimum of -51°C. (-60°F.) was recorded when the minimum at Sonnblick, 1,830 m. higher, was -19°C. (-2°F.). Further large scale differences are reported by Cox (1919); 31°F. between hillside and valley bottom locations in the Carolina Highlands, differing in altitude by 1,000 ft., and by Young (1921); 23°F. between a corresponding pair of stations in the Pomona valley, California, differing in altitude by 225 ft. The very low humidities experienced in these latter areas contributes to these large differences. Young (1920) studied the vertical extent of pooling of cold air, and of the temperature inversion in the Medway valley in Oregon, making use of a radio tower 100 metres high, located on the valley floor, to obtain records of the vertical temperature profile.

In England, Manley (1944) compares the average extreme monthly minimum temperatures of three stations in the Durham area, Ushaw College, 594 ft. and Durham Observatory, 336 ft., on ridges above the Wear Valley, and Houghall, 160 ft., on the broad floor of the valley.

The mean difference between Ushaw College and Houghall was 6°F., and that between Durham Observatory and Houghall, 3.3°F.; no seasonal fluctuation was apparent. He notes a similar mean difference of 6°F. between Malvern and Perdiswell, 333 ft. and 50 ft. respectively, above the floor of the Severn Valley. Tinn (1938) analysed the minimum temperature records of eight stations in the Nottingham district and noted the frequent occurrence of differences of the order of 4 to 7°F. between Castle, 215 ft., on a spur overlooking the Trent Valley, and Attenborough, 89 ft., in the valley bottom. The maximum recorded difference was 10°F. Further examples are given by Cornford (1938) and Geiger (1927).

Day and Peace (1937) draw attention to the fact that quite small hollows and undulations exhibit the effects of air drainage. They observed differences of up to 5°F. at a height of 1 ft above ground level, between the lip and the bottom of a hollow only 2 ft. 9 in. in depth. The type of ground cover, which may contribute largely to the effect, is not mentioned however.

The above examples indicate the range of the effect under the conditions prevailing in this country, though more extreme examples doubtless occur in the more mountainous regions.

Soil cover

The passage of air masses over continental land masses and oceans imposes characteristic temperature profiles on them. Similarly, in miniature, the flow of air over land surfaces of differing surface temperature, such as bare soil and grassland, impose corresponding changes in temperature profile of the lowest few feet. Cornford (1938) has shown that the type of soil cover markedly affects the minimum temperature of the air above it. He records temperatures as much as 6.5°F. lower over grass than over bare soils, at a height of 3 ft., and he also shows that, where the air is moving slowly over the grassland, the effect is translated some considerable distance to the leeward of the grass. He made a study of the temperatures at a height of 3 ft., in a variety of crops, including woodland with a complete canopy, tree fruits over bare soil and over grass, and meadow grass. Conditions within tree fruit plantations over bare soil differed little from those over bare soil itself. Grassed down orchards were, however, considerably colder in Spring when the leaf canopy was not complete. He suggests that the effects of soil cover are at least as important as those of topography.

MacDonald (1940) refers to differences of 5 to 6°F. in minimum temperature between areas with and without vegetation cover in the New Orleans district. Geiger (1927) noted the effect of vegetation in inducing low minimum temperatures and in modifying the temperature gradient in the soil beneath. Manley (1944) suggests that soil differences may be responsible for the large differences in minimum temperature, amounting on occasion to 13°F. between Lynfield, lying on dry sandy soil, and Cambridge. Both reporting stations at Cambridge are on light soil, however; Botanic Gardens on light sandy loam and University Farm on gravel, and it seems probable that other reasons must be sought. The fact that the difference is eliminated under snow cover indicates that topographic differences cannot be the cause.

Methods

In the following investigation of minimum temperature distribution in the Ayr valley, temperatures were recorded at three heights, 4 ft., 1 ft and ground surface. At the first two heights, Standard Meteorological Office pattern minimum thermometers, screened with double cylindrical screens of polished aluminium, adequately ventilated, were employed. Minimum thermometers at ground level were unscreened, and recorded approximately the temperature of the surface over which they lie. Highly polished metal is chosen as a screening material on account of its very low emissivity, which ensures that cooling of the screen below air temperature by radiation is minimised. McDonald (1940) states that lack of shielding introduces errors ranging from 3 to 8°F., under the nocturnal radiation conditions prevailing in the southern states of U.S.A. Thermographs and hygrographs were also employed to obtain continuous comparative records. The latter were checked frequently against wet and dry bulb determinations of relative humidity.

Wind velocity was measured at 4 ft. above ground level by means of sensitive cup anemometers, Meteorological Office Pattern, Meteor 4. These instruments are capable of recording wind velocities as low as one to two ft. per second.

The vertical temperature structure was, on occasions, measured to a height of 60 ft. by a thermo-electric method. A fine copper-constantan thermocouple element of 36 gauge wire was employed. The air junction was unscreened while the cold junction was maintained in a small tube of crushed melting ice and water, well insulated with cotton wool. The couple was carried by three 60 in. hydrogen filled balloons and a 60 ft. length of light-weight flex acted as cable and conductor. Temperatures were recorded by a direct reading Cambridge micro-voltmeter, previously calibrated with the thermocouple and flex.

Records

The accompanying sketch map (Fig.8) shows the contours of the section of the Ayr Valley in which records were taken. The valley is of the incised type about half a mile wide between the 100 ft. contours, running through an undulating coastal plain with no marked hills in the immediate neighbourhood. The high ground at 'A', 163 ft., slopes down gently in all directions except to the S.E., where it falls away in a sharp escarpment to the flat alluvial valley bottom, PQRS, which slopes very gently to the river with a total fall of less than 20 ft. from the base of the escarpment to the river bank. The total fall from 'A' to the alluvial river flats is 100 ft. To the north of 'A' lies a small enclosed frost hollow C falling at its lowest point to 105 ft.

'F' is an isolated rise similar to 'A', altitude 168 ft. above M.S.L.

The distribution of ploughland, grass, woodland etc. is indicated.

Observations : First series

Observations were made at the following points indicated on the map:-

D 140 ft.	On the crest of a slight ridge, fully exposed to wind.
B 135 ft.	On the slope half-way down the frost hollow, N.W. exposure.
C 105 ft.	At the bottom of the frost hollow.

The above stations were over bare soil.

K 130 ft.	Over short turf 30 ft. below the edge of the escarpment. S.E. exposure.
M 55 ft.	Over stubble, with thin grass and clover, on the valley floor.
N 55 ft.	Over bare soil on the valley floor.

Apart from the shelter afforded by the valley flanks, M and N are fully exposed on flat ground.

Observations: Second series

A 165 ft. At the crest of the hill over bare soil.

F 168 ft. At the crest of an adjacent hill over short meadow grass.

Both have excellent exposure to wind from all quarters, but F is slightly protected from the west by a small wood.

H 135 ft. On a flat shelf covered with coarse matted grass and planted with small spruce.

Open to the east but protected from wind on the south by a belt of rhododendrons and on the north and west by the hill F.

O 110 ft. Over similar cover to 'H' in a 'V' shaped hollow, exit for cold air impeded by woods. Sheltered from wind from all aspects.

M }
N } As in first series.

Appendix III records the observations made at the above locations between December 3rd and March 9th, 1946-47.

Temperature differences due to soil cover

Table 8 and Fig. 11 show the differences recorded on relatively calm, radiation nights between minimum temperature recorded at three levels, over grass and over bare soil at the hill top locations A and F. It will be seen that at one inch the grassland has markedly lower minima than has the bare soil. The difference has practically disappeared at one ft, and is not detectable at 4 ft., at which level the variations between sites is small and apparently random.

Table 8. Temperature differences between hill top locations A and F, over bare soil and over grass

Height	Maximum difference. Grassland colder than bare soil. (°F.)	50% of the observed differences lie between the following limits. (°F.)
4 ft.	0.9	- 0.5 to 0.5
1 ft	1.5	- 0.4 to 0.4
1 in.	4.8	3.5 to 4.4

Table 9 and Fig. 9 show corresponding differences for bare soil and grassland in comparable sites M and N, located on the floor of the Ayr valley. Greater differences are observed than in the exposed hill top locations, but again the difference falls off rapidly with height above ground and is generally less than 2°F. at 4 ft.

Table 9. Temperature differences between comparable valley floor locations M and N, over bare soil and over grass

Height	Maximum difference. Grassland colder than bare soil. (°F.)	50% of the observed differences lie between the following limits. (°F.)
4 ft.	2.4	0.7 to 1.5
1 ft	5.7	2.2 to 3.1
1 in.	9.1	2.4 to 6.6

In comparing the hill top locations (Table 8), the lack of appreciable differences at 1 ft and 4 ft. must be attributed to exposure to wind, which tends to reduce the size of the temperature inversion to small proportions in all but a very shallow ground layer. Again the predominance of grassland in the area tends to impose a temperature profile, characteristic of grassland over the whole area, which the relatively small islands of ploughland modify only in a shallow ground zone. This is more clearly shown when temperature inversions over bare soil and grassland in the area are studied (Fig. 15 and 16).

The differences observed in the valley bottom are probably smaller than would occur between large flat tracts of grassland and ploughland, for the temperature structure of the air overlying the valley bottom is not merely the product of cooling from below by either grass or bare soil, but of such cooling (or warming) imposed on a body of cold air which has accumulated over the floor of the valley by katabatic pooling. Such pooling will materially reduce differences imposed by the type of soil or soil cover. An examination of the temperature profiles at M and N in the valley bottom shows this to be the case (Fig. 15 a, b & d).

Table 10 and Fig. 15 record the differences occuring between locations A and H, hill top location over bare soil, and a flat shelf over matted grass respectively. The latter location is rather more sheltered and may receive slight cold air drainage from the slopes of 'F'.

Table 10. Temperature differences between locations A and H, over bare soil and matted grass respectively

Height	Maximum difference. Matted grass colder than bare soil (°F.)	50% of observed differences lie between the following limits (°F.)
4 ft.	3.7	1.7 to 2.4
1 ft	4.7	2.6 to 3.5
1 in.	10.5	8.0 to 9.7

Cold air drainage effect

Fig. 10 and Table 11 record the differences arising between hill top A and valley bottom N on relatively calm nights over bare soil.

Table 11. Temperature difference between locations A and N, hill top and valley floor respectively, both over bare soil

Height	Maximum difference. Valley floor cooler (°F.)	50% of observed differences lie between the following limits (°F.)
4 ft.	7.0	2.1 to 4.5
1 ft	7.2	2.6 to 4.8
1 in.	4.2	2.5 to 3.4

The effect is most strongly marked at 1 and 4 ft. The readings at 1 in. more closely reflect the influence of the soil surface temperature. The air between 1 and 4 ft. over the floor of the valley clearly owes its low temperature to its origin over the grass flanks of the valley, and may be appreciably colder than the soil surface over which it subsequently collects, as the temperature profiles indicate (Fig. 15 a, b & d).

Maximum differences between hill top and valley bottom are recorded between hill top location A over bare soil, and valley bottom location M over grass, Fig. 12 and Table 12, where the effects of air drainage are added to those due to soil cover.

Table 12. Temperature differences between locations A and M, hill top bare soil and valley bottom grass respectively

Height	Maximum difference. Valley bottom colder (°F.)	50% of observed differences lie between the following limits (°F.)
4 ft.	8.0	2.3 to 4.5
1 ft	9.4	4.3 to 6.5
1 in.	9.2	4.9 to 6.4

Locations H and O over matted grass separated in height by only 25 ft., show clearly, the relatively important effect of air drainage on a small scale, over ground cover which favours the development of low minima and large inversions.

Table 13. Temperature differences between lip H, and base O, of frost hollow over matted grass

Height	Maximum difference. Base of hollow colder (°F.)	50% of observed differences lie between the following limits (°F.)
4 ft.	6.9	2.4 to 5.0
1 ft	8.1	4.8 to 6.8
1 in.	10.0	2.6 to 5.0

Between the locations B and C, on a ridge and at the base of an enclosed hollow over bare soil, differing in height by 30 ft., the differences are of much smaller scale, though the hollow is rather more exposed to wind.

Table 14. Temperature differences between the lip B, and the base C, of a frost hollow over bare soil

Height	Maximum difference. Base of hollow colder (°F.)	50% of observed differences lie between the following limits (°F.)
4 ft.	3.8	1.3 to 2.0
1 ft	2.4	0.8 to 1.3
1 in.	2.0	0.4 to 2.0

The nature of the ground cover on the slopes contributing to cold air drainage is obviously of major importance in determining the magnitude of the temperature differences developing in such frost hollows.

Temperature inversion between 1 in. and 4 ft.

The nature of the ground surface largely determines the magnitude of the temperature inversion under calm radiation conditions. Fig. 14 records the size of temperature inversions in the locations previously specified on selected radiation frost nights. It is presumed that the minimum temperature coincides approximately in time at both 1 in. and 4 ft. and that their difference is, therefore, the true value of temperature inversion at the time of minimum temperature. This is not necessarily the maximum value assumed by the inversion during the night which may occur at any hour, as Johnson (1929) and Johnson and Heywood (1938) have observed.

Table 15 summarizes the mean and extreme values of the inversion between 1 in. and 1 ft and between 1 ft and 4 ft. in specified locations during a series of 13 radiation frosts.

Table 15. Mean and extreme inversion values between 1 in. and 4 ft. and between 1 ft and 4 ft. at the time of minimum temperature occurrence during thirteen radiation frosts

Location and ground cover	Height interval 1 in. - 4 ft.		Height interval 1 ft - 4 ft.	
	Mean inversion	Maximum inversion	Mean inversion	Maximum inversion
A Bare soil, hill top	1.8	3.5	0.95	1.5
F Meadow grass, hill top	5.0	7.7	1.85	2.6
N Bare soil, valley bottom	1.65	3.5	1.65	2.7
M Grass and stubble, valley bottom	4.0	8.6	3.1	4.7
H Matted grass, flat shelf	8.4	9.8	2.35	3.0
O Matted grass, frost hollow	9.05	11.7	4.45	5.7

It will be observed that over bare soil and grass, the mean inversion between 1 in. and 4 ft. is larger on the hill top than in the sheltered valley bottom. This is contrary to expectation if exposure to the wind alone determines the magnitude of the inversion. If, however, the inversion value between 1 ft and

4 ft. are considered they do conform to expectation, the larger inversion invariably occurring in the valley bottom. Inspection of the temperature difference between 1 in. and 1 ft over bare soil in the valley floor on 19 occasions of radiation frost actually show a preponderance of lapse rates (temperature decrease with height) over inversions, as follows:-

4 inversions greater than 1°F.
5 inversions less than 1°F.
10 lapse rates ranging up to 1.4°F.

This reduction or elimination of the temperature inversion in the immediate ground zone must be attributed to the pooling of air, which originated over the cold, grass covered flanks of the valley, over the relatively warmer surface of the bare soil of the valley floor. The soil surface in many cases subjects the pooled air to slight warming from below, resulting in the production of the characteristic temperature profiles shown in Fig. 15 a, b & d. Over the thin grass and stubble at 'M' the effect is still evident, but less marked, though it is no doubt responsible for the small size of inversion between 1 in. and 1 ft in the valley floor as compared with the much larger values observed at 'F' on the hill top.

Temperature profiles over the frost hollow B C D (Fig. 16) indicates the same type of effect. The ground is bare, but to the S.W., and higher on the slope lies an area of grassland which is probably the source of the cold air in this case.

Even in the frost hollow 'O' over matted grass, the inversion frequently tends to be smaller than over the flat shelf 'H', over the same cover.

Katabatic winds in the Ayr valley

The development of katabatic winds on the flank and over the floor of the Ayr valley and their relationship to the gradient wind observed on the hill top, were investigated. Observations were chiefly confined to a steep portion of the escarpment on the line (A') - (M) Fig. 8.

Fig. 17 shows the profile of the slope which has a fall of 1 in 5.5 over the steepest portion. The ground cover was coarse grass on the slope and rather thin meadow grass over the valley floor. The only obstruction to a katabatic flow was a low, thin hedge at the base of the escarpment, running parallel to it. The position of anemometer and thermometer stations set up on the line of fall from (A') to (E), are also indicated. The sixth station was located at (M), on the floor of the valley, and additional records were taken at thermometer station (j), on the valley floor between (E) and (M), on the night of March 3rd.

Records - March 5th, 1947

The following observations were recorded throughout the period 2000 - 2300 hr.

(a) Wind speed and direction at stations (A') to (M).

(b) Air temperature at 4 ft. at stations (A') to (M).

(c) Temperature inversion between 1 in. and 4 ft. at stations (A') and (M) over grass cover.

The anemometers were read at intervals of approximately 20 - 25 min. and the mean wind speed determined for each period, at each of the six locations. Wind direction was determined by smoke drift and reliance had to be placed on snap readings at each location. These, however, gave fairly consistent results except in the transition zones.

Fig. 17 summarizes the wind records diagrammatically. Each horizontal line represents the direction of the line of fall of the slope (A') - (E). The direction of the wind arrows is orientated with respect to this line. True north is also indicated. Wind speed in feet per second is shown within the circles. The approximate period is indicated at the end of the line; a fluctuation of plus or minus a few minutes in the limits of the period occurs in individual records, due to the inability of two observers to take simultaneous records at all locations.

Fig. 18 shows the fall of temperature at stations (a) to (m), and the magnitude of the temperature inversions at stations (a) and (m).

A gradient wind, blowing up-slope, of approximately 6 to 7 f.p.s. persisted throughout the period at (A') at the crest of the escarpment. At stations (B) and (C), below the crest, the velocity falls off rapidly, and at (D) light variable conditions are apparent with an intermittent tendency for a katabatic down-flow to establish itself. In this location a fairly steady katabatic wind was noticeable at 1 ft above ground level. At (E) the katabatic is clearly established at 4 ft. and shows some sign of being deviated in a direction down the valley, while 'M' obviously lies in the main katabatic flow travelling approximately down the axis of the valley.

Temperature fall is fairly steady throughout the period. A mean difference of less than 2°F. at 4 ft. is apparent between the hill top and the valley bottom.

The mean inversions between 1 in. and 4 ft. are respectively 4.6°F. and 6.3°F. on the hill top and in the valley floor and reflect the difference in exposure to wind. The fluctuation in the inversions are tabled below.

Table 16. Temperature inversion in hill top and valley floor locations, March 5th, 1947

Location	Time	Height interval		
		1 in.-4 ft.	1 ft-4 ft.	1 in.-1ft
			(°F.)	
Hill top A	2023	4.9	1.3	3.6
	2107	4.9	1.4	3.5
	2127	4.8	1.2	3.6
	2152	4.3	1.2	3.1
	2217	4.0	1.0	3.0
Valley floor M	2032	6.8	3.7	3.1
	2051	6.7	2.5	4.2
	2135	7.0	2.1	4.9
	2200	6.2	1.5	4.7
	2225	4.8	1.6	3.2

This effect of reduction of the temperature inversion in exposed locations contributes substantially to the temperature difference between hill top and valley floor quite apart from cold air drainage.

The steady fall in the size of the inversion between 1 ft and 4 ft. at (M) on the valley floor may reflect the tendency for the pooling of cold air to produce an isothermal structure to replace the original inversion, but later records do not altogether support this view.

The gradient wind of 6 to 7 f.p.s. at 4 ft. on the hill top is apparently the limiting value above which katabatic flow will fail to develop over any portion of the slope under comparable radiation conditions.

<u>Records - March 3rd, 1947</u>

This occasion is of particular interest since a reversal of the gradient wind occurred during the observations. Between 1700 and 1840 the gradient wind blew down-slope, the velocity at the hill top lying between 1.9 and 3.7 ft. per sec. The reversal of direction took place between 1840 and 1930 hr. It may represent the onset of a light land breeze from the S.E. Its velocity increased from 3.8 to 6.9 f.p.s. between 1930 and 2010 hr. (Fig. 19).

During the first period a slight acceleration of the downward slope wind is apparent at locations (C) and (D); the deviation of the wind down the valley is again apparent at (M).

After reversal of the gradient wind, a katabatic flow established itself over the lower portion of the slope (C) to (E), the velocity varying from 1 f.p.s. to 2.4 f.p.s. The fall of temperature is fairly regular throughout most of the period (Fig.20) and reflects, one may suppose, the absence of any major fluctuations in wind velocity. The increase in velocity between 1930 and 2010 hr. is reflected, however, in rising temperature or at least a check in the fall, at all stations.

The pooling of cold air in the valley bottom is evident in the records of stations (e), (j) and (m). A maximum difference of 6.5°F. built up between hill top and valley floor by 1920 hr. which was reduced to approximately 4°F. by the effect of increasing wind velocity by 2000 hr.

Inversion conditions are notable and do not parallel those of March 5th. They are tabled below.

Table 17. Temperature inversions in hill top and valley bottom locations, March 3rd, 1947 (°F.)

Location	Time	Height interval		
		1 in.-4 ft.	1 ft-4 ft.	1 in.-1 ft
Hill top A'	1801	9.4	1.1	8.3
	1832	8.2	0.7	7.5
	1940	11.4	1.9	9.5
	1955	8.7	1.8	6.9
	2010	5.0	1.2	3.8
Valley floor M	1810	4.6	3.9	0.7
	1825	4.7	3.1	1.6
	1925	4.6	3.6	1.0
	1940	4.7	3.7	1.0
	1955	5.5	4.0	1.5
	2013	5.8	2.7	3.1

The total inversion is much larger on the hill top than on the valley floor, at least to a height of 4 ft. At the upper location, however, the steep gradient between 1 in. and 1 ft accounts for about 90% of the total inversion and the difference between 1 ft and 4 ft. is small, always <2°F. Exactly the reverse is true of the valley bottom inversion. The temperature increase from 1 in. to 1 ft never exceeds 1.6°F., while that between 1 ft and 4 ft. is of the order 3 to 4°F.

Conditions at (A') result from the thick turf cover which produces a low surface temperature, while exposure to the relatively turbulent gradient wind confines the steep gradient to a very shallow ground layer. At (M), the pooling of cold air reduces the total inversion. The large difference between 1 ft and 4 ft. can only be preserved in the absence of turbulence, a condition characteristic of a katabatic flow, but not of a gradient wind of equivalent velocity.

Records - February 24th - 25th, 1947

On this occasion a persistent easterly wind was recorded at (A') which increased from 5 f.p.s. to a maximum of 10 f.p.s., later in the period. No katabatic wind developed over the slope up which the gradient wind blew transversely, though at (E), at the base of the slope, the wind was mainly light variable and showed indications of eddy formation. Fig. 21 indicates the fluctuation of temperature at thermometer stations (a) to (m), the mean wind velocity at (A') on the hill top, and the variation in the size of the temperature inversion between 1 and 4 ft., on the hill top and valley floor. The correlation between wind speed and temperature at 4 ft. is marked. Temperature fluctuation is greatest at (a), on the hill top, fully exposed to the wind. The breakdown of the inversion and rapid rise in temperature between 2040 and 2130 hrs., is probably the result of a brief period of gustiness rather than the increase in mean wind speed. The effect is much less marked at stations (b) - (m) below the hill top. The further increase in wind speed from 6 to 10 f.p.s., is reflected in a second period of rising temperature. This is particularly marked at (m), on the floor of the valley. There is little evidence of pooling of cold air, (compare with Fig.20) and the temperature differences must be attributed to the effect of exposure on inversion development. The fluctuation in inversion size at (A') and (M) tabled below, also reflects the variation in wind velocity.

Table 18. Temperature inversions in hill top and valley bottom locations, February 24th - 25th (°F.)

Location	Time	Height interval		
		Ground - 4 ft.	1 ft - 4 ft.	Ground - 1 ft
Hill top	2005	5.1	2.6	2.5
	2050	5.1	1.4	3.7
	2145	4.5	0.9	3.6
	2230	4.5	1.0	3.5
	2315	2.1	0.6	1.5
	2400	2.0	0.3	1.7
	0050	2.5	0.8	1.7
Valley bottom	2029	7.0	6.0	1.0
	2113	7.4	5.0	2.4
	2140	6.7	3.2	3.5
	2252	5.5	3.5	2.0
	2340	4.0	1.2	2.8
	0024	2.0	1.0	1.0

Inversion conditions parallel those of March 5th, in which pooling of cold air is not evident. The fall in the size of the inversion with increasing wind velocity is very obvious.

Records - February 19th - 20th, 1947

On this occasion exceptionally calm conditions prevailed throughout the night. The hill top wind lay between E and S.S.E. and was generally less than 3 f.p.s. A difference of 7.0°F. between the hill top and valley bottom minima at a height of 4 ft. occurred, the highest recorded. Katabatic winds of the order of 2 - 4 f.p.s. were observed early in the period between (B) and (D), but winds were variable over the lower slopes. The main katabatic flow down the valley was well marked and of the order of 2 - 3.5 f.p.s.

Fig.22 shows the vertical temperature structure to a height of 60 ft. at the hill top (A') and over the valley floor (M). In the hill top location the vertical temperature structure above 15 ft. is practically isothermal and changes little between 2300 and 0130 hr. In the valley bottom, however, the vertical structure may be interpreted as resulting from the extensive pooling of cold air in the valley bottom. There is a marked inflexion in the curve at 40 ft. above ground level on the first ascent which may possibly mark the upper limit of the cold air. This has disappeared in the second ascent, possibly due to a further increase in the depth of the cold air. Strict comparisons of the hill top and valley bottom ascents are not valid on account of their difference in altitude and time. Nevertheless, the mean temperature differences of the order of 4 to 5°F. between the first ascents, 2240 to 2340 hr. in the interval 10 - 40 ft., and of the order of 6.5 - 7.5°F. between the second ascents, 0117 to

0210 hr., will give some measure of the magnitude of the cold air drainage effect. This is larger and of greater vertical extent than was anticipated in this location.

Conclusions

The effects of soil cover, wind velocity and air drainage, together with the meteorological conditions determining the magnitude of the net radiation loss, are inextricably interwoven in determining the temperature profile at any location.

Differences in soil type and cover may produce temperature differences exceeding 10°F. at ground level, but such differences decrease very rapidly with increasing height above ground level. A ground level difference of 8°F. between bare soil and matted grass falls to 2°F. or less at 4 ft., and is, no doubt, further reduced at greater heights.

The observations here recorded apply to an area with a predominant grassland cover which probably imposes a conservative temperature profile on the air traversing it. This profile may persist over the bare soil, modified only in a shallow ground layer. The differences recorded may therefore under-estimate those occurring between large tracts of ploughland and grassland, each developing its characteristic profile. These remarks apply with equal force to the bare soil and grass cover locations in the valley bottom where the pooling of cold air partially marks the temperature difference attributable to soil cover. Nevertheless the maximum difference of

0.9°F. between grassland and bare soil in hill top locations, and of 2.4°F. in valley floor locations at the 4 ft. level, appear small compared with Cornford's (1938) observations of 6°F. between similar locations over grass and bare soil at 3 ft. above soil level. His records were taken later in the season when long meadow grass may not only favour lower relative surface temperatures, but may raise the radiating surface a foot above ground level, thus materially increasing the difference. The importance of the type of grass cover is well illustrated by the much lower temperatures obtaining over coarse matted grass, which, at 4 ft., may fall as much as 3.7°F. below that over bare soil.

Observations on the wind speed and size of temperature inversion at the hill top location were not sufficiently numerous to establish a relationship. The following table indicates the scale of the effect, however. The relationship is modified by the effect of cloud cover and atmospheric humidity on the net radiation loss.

<u>Table 19.</u> Relationship between wind velocity at 4 ft., and temperature inversion on clear nights

Wind velocity at 4 ft., in f.p.s.	<2	2 - 3.5	4 - 6	7 - 11
Temperature inversion 1 to 4 ft. $^{\circ}$F.	2.0/3.0	1.0/1.4	1.0/1.4	0.3/0.6

Best (1935) has determined the mean relationship between wind speed, measured at 13.4 metres, and size of temperature inversion in the layers 2.5 to 30 cms., and

30 cms., and 30 cms. to 1.2 m., on clear nights, in a fully exposed location over short grass. The latter interval roughly corresponds with the interval 1 to 4 ft. but the wind velocities are, of course, not comparable. The following table is derived from his data.

Table 20. Relationship between wind velocity at 13.4 metres and temperature inversion

Mean wind velocity at 13.4 metres in f.p.s.	1.6	6.2	12.7	19.0	26.4
Number of observations	11	13	21	13	2
Mean temperature difference 30 cms. to 1.2 m. °F.	2.24	1.49	0.77	0.62	0.55

His figures for the maximum hourly value of the temperature inversion observed in each month are as follows:-

Table 21. Maximum hourly value of the temperature inversion observed in each month of the year (°F.)

Month	Height interval	
	2.5 - 30 cms.	30 cms. - 1.2 m.
January	4.1	3.2
February	5.2	3.9
March	7.8	4.1
April	6.0	4.0
May	3.1	2.3
June	3.6	3.0
July	2.2	2.7
August	2.9	4.3
September	2.6	3.2
October	7.8	6.3
November	5.7	2.8
December	4.3	3.1

Katabatic winds are relatively non-turbulent at low velocity; one would therefore expect the above relationships between wind velocity and inversion size to be invalid for such winds. It is, therefore, of interest to note that inversions of magnitude 4 - 6°F. between 1 and 4 ft. were recorded in the valley bottom with a katabolic flow down the valley of approximately 2 ft. per sec. at 4 ft.

The development of a katabatic wind on a slope is conditional on the establishment of a temperature inversion of sufficient size. Such winds are, therefore, to be observed much more frequently on slopes with a thick grass cover than over bare soil. The limiting wind velocity above which level katabatic winds do not develop was observed to be 6 - 7 ft. per sec. on the hill top at A, but would be substantially smaller over a comparable slope of bare soil. Variation in exposure and gradient of slope, as well as soil cover and wind direction, all combine to determine the value of the hill top wind which limits the development of a katabatic flow at any given site.

The effect of shelter in reducing wind velocity between hill top and valley bottom, contributes to the temperature difference between them, by favouring the development of larger inversions in the more sheltered location, though it is not easy to determine the scale of the effect.

Temperature differences due to the pooling of cold air, are frequently of considerably greater magnitude at 1 ft and 4 ft. than differences attributable to soil cover. Differences of 7°F. may develop on favourable occasions between the lip and the floor of the Ayr valley at 1 to 4 ft. above soil level, while comparable differences were also recorded between lip and base of the small frost hollow at 'O' with a cover of matted grass. At ground level the effects of both soil cover and air drainage may be large, and may combine to produce quite remarkable temperature variations such as that recorded on March 6th, 1947. The minimum temperature at 'A' over bare soil was 14.1°F., at 'H', over matted grass it was 9.5°F., while over the same cover at 'O' in the bottom of the hollow it fell to -0.5°F. The combined effect of both factors resulted in a total difference of 14.6°F. between the two extreme locations.

The temperature of the cold air draining from the flanks of the valley and collecting over its floor may be lower than that of the ground surface of the valley floor. A characteristic temperature profile then results in which the temperature inversion is reversed in a shallow ground zone. Such a condition develops when the flanks of the valley are grass covered and its floor bare soil.

X

PART III. TEMPERATURE OF THE SOIL SURFACE UNDER NOCTURNAL RADIATION CONDITIONS

Introduction

The fundamental factor controlling the minimum temperature of the air in the zone near the ground under nocturnal radiation conditions is the temperature assumed by the soil surface. In the following section the factors which affect this are considered in detail.

Previous work

The relationship between the net radiation loss from the ground and the fall of temperature at the ground surface under nocturnal radiation conditions, has been analysed by Brunt (1932).

The ground surface behaves as a perfect radiator for nocturnal long-wave radiation. The outgoing radiation from the earth's surface, 'R' is thus:-

$$R = \sigma T^4 \qquad \text{----------------} \quad (1)$$

where 'T' is the absolute temperature of the earth's surface and 'σ' Stefan's constant. Water vapour in the atmosphere, and to a lesser extent CO_2, absorb and radiate back to earth, long-wave radiation within the range 4 to 40 μ. This is the source of the incoming sky radiation, R_s, at night, in the absence of cloud.

Brunt shows that R_s may be approximately expressed empirically as a function of the black body radiation at the temperature of the earth's surface, and of the vapour pressure at ground level 'e'.*

Thus,

$$R_s = \sigma T^4(a+b\sqrt{e}) \quad \text{--------}(2)$$

where a and b are constants, 'a' relates to the contribution of CO_2 and '$b\sqrt{e}$' to that of water vapour in the sky radiation.

The net radiation loss at the earth's surface, R_N, is thus $R-R_s$.

$$R_N = \sigma T^4(1 - a - b\sqrt{e}) \quad \text{----}(3)$$

The fall in 'T' during the night is small compared with 'T' itself, therefore R_N may be assumed to remain constant during the night.

Brunt deduces that the fall of temperature at the soil surface after sunset with R_N assumed constant can be expressed thus:

$$T_1 = T_o - \frac{2}{\sqrt{\pi}} \frac{R_N}{\rho \; c \sqrt{k}} \sqrt{t} \quad \text{-----------}(4)$$

Where T_1 = screen temperature 't' hours after sunset.
T_o = screen temperature at sunset.
ρ = soil density
c = specific heat of the soil.
k = specific conductivity of the soil.

Then substituting for R_N in equation (4)

$$T_1 = T_o - \left[\frac{2}{\pi}\left(\frac{\sigma T^4(1 - a - b\sqrt{e})}{\rho \; c \sqrt{k}}\right)\sqrt{t}\right] \quad \text{----}(5)$$

The term within the square brackets represents the fall in temperature in time 't'.

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* A full treatment of the measurement and estimation of atmospheric radiation when the vertical distribution of water vapour in the atmosphere is known is given by Robinson (1947). Brooks (1941) has shown that the sky radiation attributable to CO_2 is equivalent to 18.5% of black body radiation at screen temperature.

The fall in temperature is proportional to three factors.

i. A soil factor ------- $\frac{1}{\rho c \sqrt{k}}$

ii. The net radiation loss $\sigma T^4(1 - a - b\sqrt{e})$

iii. Time factor $\sqrt{t}$.

The variation of 'ρ', 'c' and 'k' with soil type and soil moisture content is considerable and these factors play no small part in controlling the severity of frosts. Available data on the magnitude of these factors in soils of differing type is reviewed below. It is by no means complete, but nevertheless indicates the range of variation within each factor.

ρ refers to the apparent density, i.e. density of soil particles plus air space. This is dependent upon the degree of compacting of the soil as well as the soil material. Cultivation of the soil reduces its apparent density by the inclusion of air in the top soil. The addition of light humus-forming material has the same effect. The following determinations quoted by Keen (1931), show the range of apparent density in certain soil constituents.

Material	Apparent density
Sand	1.52
Clay	1.04
Humus	0.37
Dry peat, 54% water	0.22
Moist peat, 177% water	0.49

The sharp rise in apparent density which is produced by the addition of water to the soil partially explains the absence of severe frost following heavy rain.

The following table lists the specific heats of a series of soil types, as determined by Patten (1909).

Specific heats of soils (equal weights)

Soil type	Specific heat
Sands of various type	0.180 - 0.190
Podunk sandy loam	0.183
Leonardstown silt loam	0.194
Hagerstown loam	0.191
Galverston clay	0.210
Muck soil (25% organic matter)	0.157

Increase in water content has a large effect in increasing specific heat, as the following determinations, also by Patton (1909), illustrate:-

Specific heat of Podunk fine sandy loan with
varying moisture content

Moisture content % dry weight	Specific heat
0.268	0.185
2.14	0.200
10.08	0.258
26.93	0.356

Determinations of the relative conductivities of various soil materials have been made by Pott, whose values quoted by Baver (1948), are given below.

Material	Relative conductivity		
	Dry		Wet
	Loose	Compact	
Quartz	100	106.7	201.7
Peat	90.7	90.7	94.3
Kaolin	90.7	96.4	155.6
Chalk	85.2	92.6	153.2
Clay with limestone stones	121.1	-	-
Clay with quartz stones	115.6	-	-
Quartz sand of various types	100 - 105.3	-	189.0

The large influence of water content in causing an increase in conductivity is due mainly to the establishment of continuity between soil particles.

Methods

The temperatures assumed by the surface of soils of different type and moisture content under nocturnal radiation conditions can be most conveniently studied in adjacent field plots.

A series of eight such plots were laid down of the following soil types:

(a) Medium loam 'dry' in a loose tilth.
(b) Medium loam 'dry' compacted by treading.
(c) Horticultural peat 'dry'.
(d) Horticultural peat moist.
(e) Medium grade of coarse sand) Differing in
(f) " " " " ") moisture content.
(g) Medium loam moist - loose tilth.
(h) Medium loam moist - compacted by treading.

Each plot was a yard square and six inches in depth. The uniform underlying soil will have a negligible effect on the surface temperatures of the plots since the amplitude of the diurnal temperature fluctuation at that depth is quite small. The plots were all freely exposed to the sky at night, but the plots with low moisture content were covered during rain. Surface minimum temperatures were recorded using standard Meteorological Office pattern minimum thermometers, the bulb being sunk to half its diameter in the soil. Robinson (1947) states that such a method does, in fact, record the true soil surface temperature with a high degree of accuracy. Minimum temperatures were recorded each morning and surface temperatures were also recorded in some instances at sunset and in others at mid-day. Moisture determinations were made on the series at weekly intervals.

Results

Table 22 and Fig. 6 and 7 summarise the minimum temperatures recorded during the months of November, December, January, February and March, 1947-1948 and Table 23 records the soil moisture contents on specified dates.

Fig. 6 illustrates graphically the range of difference between the minimum temperatures developing at the surface of four selected soil types. The soils remain ranged in identical sequence as regards minimum temperature, with minor exceptions, throughout the series. Nights of severe frost result in large differences between the two extreme soil types, moist compacted loam and peat. On seven occasions the difference lay within the range 12 to 16.5°F. These two soils differ markedly in all three factors determining the temperature fall. Peat combines low heat capacity and poor conductivity. Moist compacted loam combines high heat capacity with good conductivity.

Dry soils come to a lower minimum temperature than moist. The effect is most marked in peat where a difference of 7.1°F. is recorded on two occasions. Between moist and dry sand the maximum difference is 2.4°F. while between moist and dry loam (loose friable) it is 5.3°F. It is notable that on this latter occasion fresh plots had been set up employing a freshly dried sample of dry loam of exceptionally low water content. A fairly rapid rise in the water content of such a soil takes place when in contact with the underlying moist ground and subject to dews.

Table 22. Minimum temperatures recorded at the surface of soil plots of differing type and moisture content. 1947-1948 (^{o}F.)

Date	Dry loam		Peat		Sand		Moist loam	
	Loose tilth	Compacted	Dry	Moist	Dry	Moist	Loose tilth	Compacted
Nov.28	20.0	24.7	13.1	19.5	21.2	21.0	20.7	25.7
" 30	20.6	23.9	14.2	17.1	20.4	20.0	20.0	23.8
Dec. 2	19.0	21.7	14.8	17.5	20.1	18.9	19.7	21.8
" 3	21.9	22.9	14.8	17.1	21.9	20.9	21.7	23.1
" 4	30.7	30.4	31.1	31.0	31.2	31.0	31.5	30.6
" 5	29.3	29.2	28.8	29.1	28.9	28.6	30.3	29.6
" 9	28.1	29.2	19.0	25.6	27.2	25.8	28.7	29.5
" 23	21.7	-	14.8	-	23.3	24.2	27.0	29.7
" 24	26.2	-	13.5	-	21.0	21.6	24.6	27.2
" 29	28.9	-	23.0	-	30.4	29.6	30.4	30.3
Feb. 9	35.7	-	29.7	32.6	36.7	36.3	37.1	37.8
" 13	30.5	-	24.0	28.6	31.2	30.8	31.5	32.6
" 18	25.7	-	12.6	19.7	21.2	21.1	26.3	29.1
" 22	28.0	-	20.8	25.6	26.1	25.7	29.2	28.8
" 23	30.6	-	27.3	29.9	31.3	30.5	31.1	31.8
" 24	31.9	-	26.5	28.3	32.1	31.4	32.3	31.9
" 25	29.2	-	23.5	27.1	28.9	28.7	30.6	30.2
" 26	25.8	-	15.0	21.0	22.1	24.5	27.0	28.1
" 27	24.4	-	10.5	17.6	19.1	20.0	24.9	26.3
" 28	29.0	-	21.1	23.9	27.9	28.8	29.6	30.0
" 29	29.0	-	20.5	25.6	26.8	27.5	29.1	30.0
Mar. 3	35.6	-	29.2	32.5	35.0	35.1	35.5	36.2
" 4	30.2	-	22.2	26.7	30.0	30.7	31.0	32.8
" 5	29.2	-	19.0	23.5	27.0	27.6	29.7	30.8
" 6	28.0	-	16.4	21.6	24.2	25.0	28.5	29.1

Table 23. Moisture contents of soil plots expressed as a percentage of dry weight

Soil type		Date						
		27/11	8/12	24/12	13/2	20/2	26/2	3/3
Dry loam	(Loose tilth	32.4	37.3	2.6	17.5	22.5	24.0	29.2
	(Compacted	33.6	36.0	-	-	-	-	-
Moist loam	(Loose tilth	41.1	41.2	32.6	30.1	34.6	36.0	37.2
	(Compacted	38.9	40.3	31.9	33.4	36.2	37.4	38.3
Peat	(Dry	31.4	54.6	33.0	40.2	51.4	56.7	56.2
	(Moist	217.0	177.6	-	172.5	181.3	150.7	153.3
Sand	(Dry	5.4	5.6	4.8	5.4	5.8	6.2	5.1
	(Moist	10.0	15.7	10.5	5.4	10.7	10.1	11.7

Lower temperatures develop over loosely packed soil as compared with compacted soil, due to the low heat capacity and low conductivity of the former. A maximum difference of 5.0°F. was recorded for moist soils. The differences tend to fall in value if the plots remain undisturbed, due to the tendency for a loosely packed soil to 'settle' and establish improved conductivity.

<u>Discussion</u>. On theoretical grounds, if A and B represent the fall of temperature over dry peat on two successive radiation nights and 'a' and 'b' the corresponding falls over moist compacted loam then the ratio $\frac{A}{a}$ & $\frac{B}{b}$ should be equal, according to Brunt (1932). The freezing of the soil moisture, however, is a factor which tends to invalidate this ratio by retarding the fall of temperature during the liberation of latent heat. In a comparison of the fall of temperature over these two soil types between sunset and the time of occurrence of minimum temperature, this ratio is found to vary within fairly wide limits as the following table indicates.

Table 24. Ratio of the fall of temperature from sunset to dawn, at the surface of dry peat to that at the surface of moist compact loam, on selected radiation nights

Ratio	Date														
	28/11	23/1	24/1	18/2	23/2	24/2	25/2	26/2	27/2	28/2	29/2	3/3	4/3	5/3	6/3
Dry peat / Moist compact loam	2.6	3.0	3.6	3.2	2.4	1.6	1.7	2.1	2.2	2.0	2.1	1.5	1.6	1.7	1.8

The larger ratios generally coincide with very low minima, a fact which suggests that the fall of temperature over moist loam may indeed have been considerably reduced by extensive freezing of the soil moisture, thereby increasing the ratio. The data is, however, not consistent in this respect.

The effect is very apparent in the fall of temperature of wet peat, dry peat and wet compacted loam on February 27th.

	Temperature fall (°F.)		Total fall (°F.)
	1430-1630 hr. G.M.T.	1630 hr. - Dawn	
Dry peat	14.7	6.2	20.9
Wet peat	3.5	11.0	13.5
Moist loam compacted	3.8	4.5	8.3

Two further factors seriously modify the assumption that the fall of temperature is a simple function of conductivity.

Keen (1931) notes that distillation of water vapour on the colder soil regions accounts for large transfers of heat from the warmer to the colder soil horizons. On this account the apparent conductivity of the soil varies between wide limits. Swinbank (1948) found it impossible to obtain any constant values of soil conductivity for this reason. He suggests that the condensation of very small amounts of water in the colder horizons of the soil near the surface, liberates sufficient heat to mask completely, the transfer of sensible heat, due to the temperature gradient. The effect will, of course, be exaggerated in soils of low specific heat such as peat.

Dew formation and hoar frost formation at the soil surface are comparable factors having a very considerable effect in reducing the surface fall of temperature by the release of latent heat, and they, likewise, will have a greater effect with soils of low specific heat.

These last two factors will tend to reduce, markedly, the ratio of the fall of temperature over soils of low heat capacity and low conductivity, to that over soils of high heat capacity and conductivity. A comparison of the estimated ratio for peat and moist loam (see Brunt(1932) quoted above) with those obtained experimentally, is of interest. The value of the heat capacity and conductivity of the two soils can be deduced only approximately. The figures for heat capacity and conductivity of peat and loam are those of Von Schwarz (1879) quoted by Baver (1948).

	Heat capacity	Comparative conductivity
Peat, air dry; (30 to 40% moisture)	0.191	51.5
Moist loam	0.762	99.3

Heat capacity $= \rho.c.$

Ratio of the value of $\dfrac{1}{\rho c \sqrt{k}}$, peat: sand. = 5.5

This considerably exceeds the higher values obtained experimentally, and suggests that the factors above mentioned are indeed of major importance in a comparison of such dissimilar soils.

SUMMARY

Section I

Part 1

Records of the absolute minimum temperature in the months of April and May, were abstracted from the Monthly Weather Report for the years 1939 to 1945, for 220 Meteorological Reporting Stations in England, Scotland and Wales. Topographic data relating to 66 coastal stations and 101 inland stations was obtained. The stations were divided into five broad topographical classes and the effect of topography on the mean absolute minimum temperature was assessed, eliminating, as far as possible, the influence of latitude and longitude and of altitude. The effect of the height of valley flank stations above the floor of the valley was investigated and also the influence of proximity to the coast, soil type and urban conditions, upon the mean absolute minimum temperature.

Part 2

The following factors influencing the distribution of minimum temperature under radiation frost conditions, were investigated in a section of the Ayr valley adjacent to Auchincruive.

(a) Soil cover.
(b) Cold air drainage effect.
(c) Wind velocity and exposure to wind and its relationship to the development of temperature inversions in the air zone within a few feet of the ground and to the development of katabatic wind flow.

Differences in surface cover, as for instance, between bare soil and coarse grass, were found to be responsible for differences in minimum temperature exceeding 10°F. at ground level, but such differences decreased rapidly with increasing height above ground level. The differences in minimum temperature between hill top and valley bottom locations differing in height by only 100 ft. occasionally amounted to 7°F.

Four typical occasions when clear radiation conditions prevailed were analysed to indicate the interrelationships between the gradient wind velocity and the development of katabatic air flows down the flanks of the valley, resulting in the pooling of cold air over the floor of the valley: and, also the relationship between wind velocity and vertical temperature profiles on the exposed hill top and in the valley bottom.

Part 3

A series of observations were made on the minimum temperatures assumed by the surfaces of soils differing in type, moisture content and degree of compacting, under nocturnal radiation conditions. It is shown that while large differences are observed between soils of low heat capacity and thermal conductivity, such as peat, and large heat capacity and good conductivity, such as moist loam, these differences would be even larger were it not that the distillation of water vapour in the cold surface zones of the soil, greatly increases the apparent conductivity of soils whose theoretical thermal conductivity is low.

SECTION II

TEMPERATURE RELATIONS OF BUDS AND BLOSSOMS

Introduction

Plant parts cool under nocturnal radiation conditions:

(a) By net loss of heat by radiation.

(b) By cooling due to transpiration.

The temperature differential between air and bud which results from (a) depends upon the rate of net radiation loss and the wind speed. Convective warming of the bud by the air to compensate for radiation loss is rapid when the wind speed is high, and a small temperature differential between bud and air provides the necessary flux of heat from air to bud. Under calm conditions a considerably larger temperature differential must establish itself to maintain the same heat flux.

The rate of transpiration largely controls the degree of cooling due to this cause. This is determined by plant factors, moisture content, distribution and movement of stomata, nature of the cuticle etc., and by the meteorological factors, humidity and wind speed. Depression of bud temperature due to transpiration may be expected to simulate the depression of the wet bulb temperature unless modified by stomatal movement or other internal factors. The effect of wind speed on the wet bulb depression is summarised in the introduction to the Meteorological Office publication 'Hygrometrical Tables' (1940). Wet bulb depression increases with wind speed up to approximately 5 m.p.h., above which level further increase has little effect.

The following example illustrates the effect at temperatures just below freezing.

Dry bulb temperature (°F.)	Depression of the wet bulb temperature (Vapour pressure constant, 2.2 mbs.) (°F.)	Wind speed (m. per sec.)
30	3.9	0 - 0.5
30	5.2	1 - 1.5
30	6.0	2.5

It should be noted that only rarely has the vapour pressure been known to fall to 2 mbs. in this country, and the above figures represent the maximum possible depression of the wet bulb likely to be encountered with dry bulb temperatures below freezing. In plant parts with a low rate of transpiration, the depression of temperature will be considerably less than that of a wet bulb thermometer.

Review of Literature

Grainger and Allen (1936) measured the internal bud temperature of dormant and opening buds of apple, blackcurrant and raspberry, in relation to air temperature, by means of fine thermo-couples inserted into the buds. They found that all buds were cooler than air by night. Blackcurrant buds remained cooler throughout the day also, but insolation by day raised the temperature of apple and raspberry buds above that of the air. Apple buds screened against radiation to the sky or insolation, were cooler than the air at all times. Their depression of temperature appeared to be correlated with humidity, being larger by day than by night. Unscreened buds were cooler than screened buds by night. The temperature depression of screened buds was assumed to be due to cooling by transpiration only; that of unscreened buds, to the combined effect of transpiration and radiation. It was concluded that cooling by transpiration was the major of the two effects, though in the example quoted for apple (Fig. 6) the depression due to radiation would appear to be considerably the greater. Grainger (1939; 1940) suggested that humidification of the air during orchard heating would tend to reduce cooling due to transpiration while dry heating would increase it.

Similar thermocouple methods have been employed by Blackman and Matthaei (1905), Ehlers (1915), and Clum (1925) in the measurement of the internal temperatures of leaves, while Schreve (1919), Miller and Saunders (1923), Eaton and Belden (1929), Watson (1933; 1934), and Curtis (1936) determined leaf surface temperatures by comparable methods.

Miller and Saunders (1923), working on corn, sorghum, cowpeas, water melon, pumpkin and alfalfa, observed that by day, the temperature of turgid leaves in diffuse light was consistently lower than that of the surrounding air. The difference varied from 0.1 to 3°F. In direct sunlight they fluctuated slightly above and below air temperature (alfalfa generally slightly below due to its rapid rate of transpiration). During the night, leaf temperature fell to the same level, or slightly below that of the air. Curtis (1936) records that all leaf temperatures measured in direct sunlight were higher than air temperature. He suggests that

Miller and Saunders' method of measuring air temperature in the shade of a thick canvas screen, yields temperatures 2 to 3°F. too high, thus explaining the discrepancy. Eaton (1930) found that young cotton leaves might be reduced 4.1°C. below the surrounding air temperature. Miller and Saunders (1923) and Ehlers (1915) both observed that leaves assumed lower temperatures in sunlight when exposed to wind, than when in still air.

Miller and Saunders (1923) studied the relationship between transpiration rate and surface temperature in turgid and wilted leaves or corn, sorghum, soyabean, and cowpeas. Turgid leaves were as much as 6.7°F. cooler than the corresponding wilted leaves, corn showing the minimum and cowpeas the maximum difference. The ratio of the transpiration rate of turgid to wilted leaves of corn was 5 to 1, while that of cowpeas was 16 to 1. Clum (1926a) used an alternative method of vaselining the leaf surface to eliminate transpiration. His results substantially confirmed those of Miller and Saunders (1923), but he found no direct correlation between transpiration rate and difference between leaf and air temperature. This may be explained by variation in the intensity of the sunlight incident on the leaf.

Briggs and Shantz (1916) point out that under the condition prevailing in Akron, Colorado, the transpiration loss from the leaves of various crops between sunset and sunrise, amounts to only 3 to 6% of the total for the 24 hr. period. The amount of water evaporated from a free water surface represents a much greater percentage of the total, usually of the order of 30 to 40%. It may be inferred that evaporational cooling of the leaf by night must be correspondingly small.

Methods

Air temperature and internal bud temperatures were measured by means of fine copper-constantan thermocouples, made by soldering junctions of 36 gauge copper and constantan wire. The junction for insertion into buds must be short, of the order of a millimetre, in order that it may be totally enclosed in the bud. It should be noted that the employment of constantan-iron couples, Grainger and Allen (1936) and Grainger (1939), introduces the possibility of error due to the secondary thermoelectric effects at the junctions between the copper leads and the wire of the couple elements, should these junctions differ in temperature. Heavy, insulated copper leads of constant length connected the couples to the recording instrument. This was a Cambridge two-point Thread Recorder (Model A). This instrument gave a deflection on the chart of 1.27 mm. per °F. and had an extreme range of 100°F. The support for such an instrument is of great importance where small temperature differentials are to be recorded. Slight warping of a heavy bench due to the fluction in temperature of a nearby radiator was found to account for a slow zero fluctuation of 0.5 to 1.0°F. This was eliminated on a concrete floor.

The measurement of air temperature requires the maintainance of one junction at constant temperature.

In some cases this 'cold' junction was immersed in a vacuum flask of melting ice. Alternatively it was placed at the bottom of an iron tube, sunk vertically 2 ft. below ground level. The junction together with a thermometer was immersed in a tube of water. The temperature at this level remains relatively constant, the diurnal fluctuation rarely exceeding 1°F.

Junctions for the measurement of air temperature, and buds, when necessary, were screened against radiation to the sky by small conical, double screens of polished copper. Radiation of the junction to the ground surface which, at night, is somewhat below the temperature of the air above it, was not considered likely to introduce any appreciable error.

The following pairs of records were made simultaneously under various meteorological conditions, in the course of the investigation.

(1) Air temperature.
Temperature difference between air and unscreened bud.

(2) Air temperature.
Temperature difference between screened and unscreened buds.

(3) Temperature difference between air and unscreened bud.
Temperature difference between air and screened bud.

(4) Depression of the wet bulb temperature.
Temperature difference between air and screened bud.

Air temperatures were always measured at the same level as, and within, 3 in. of the bud. Buds were pierced with a fine needle and the thermocouple junction inserted with as little injury to the bud as possible. In the case of open flowers the junction was inserted into the receptacle.

Results

The temperature difference established between bud or flower and the air at an equivalent level, was determined under varying conditions of wind, cloud and relative humidity, for the buds of strawberry, pear and raspberry. The effect of screening against radiation on the depression of bud temperature on clear radiation nights was observed, and the relationship between the depression of the wet bulb temperature and the depression of bud temperature was examined.

Strawberry

Buds and flowers of strawberry were found to be invariably cooler than the air at an equivalent height, by night. Opening or fully open flowers showed differences ranging from less than 0.5°F. to 5.0°F. below air temperature. The larger values invariably occurred on calm, clear nights; while under cloudy and windy conditions the difference did not exceed 1°F. This strongly suggests that the temperature depression is chiefly attributable to cooling by radiation loss, and the consequent development of a considerable temperature gradient between the bud and the surrounding air. A comparison of the depression of bud temperature at the time of occurrence of minimum temperature, with the size of the temperature inversion developing between ground level and 4 ft., will provide confirmation of this interpretation. Both minima are assumed to occur at approximately the same time. The following table also includes the estimated depression of the wet bulb temperature at the time of occurrence of minimum temperature. This was calculated from the 9 a.m. dewpoint of the following morning and the minimum night temperature, on the assumption that the dewpoint had remained approximately constant between the time of minimum temperature and 9 a.m. Records taken with open or opening flowers only, are included.

<u>Table 26</u>. Temperature depression of strawberry blossoms and corresponding values of the temperature inversion, and wet bulb depression recorded at the time of minimum night temperature

Date	Depression of flower temperature (°F.)	Temperature inversion between ground and 4 ft. at time of minimum temperature (°F.)	Depression of wet bulb temperature at time of minimum temperature (°F.)
May 7	3.5	12.8	0.3
" 9	4.0	7.6	0.0
" 10	4.5	11.7	2.1
" 12	1.5	7.5	0.0
" 13	1.0	4.6	5.4
" 14	2.5	6.2	5.2
" 31	1.0	5.1	6.5
June 1	2.5	6.3	1.0
" 2	2.0	7.6	0.0
" 3	0.5	3.8	7.5

The correlation coefficient calculated between bud depression and temperature inversion has the value 0.8349, and is highly significant ($p < 0.01$). Inspection shows that no correlation exists between bud depression and the estimated depression of the wet bulb temperature.

Large inversions are characteristic of high net radiation loss, and very low wind velocity. Exactly the same factors determine the temperature gradient between bud and air and consequently the temperature differential between bud and air, if cooling by transpiration is ignored.

Comparison of the temperatures assumed by screened and unscreened buds provides a method of evaluating the size of the temperature depression due to radiation. Under cloudy and windy conditions, the temperatures of screened and unscreened buds and blossoms never differed by more than 0.5°F. On the nights of May 14th and 15th, when relatively calm clear radiation frost conditions prevailed, the temperatures of the unscreened flowers were between 0.5 and 3.0 F. cooler, the differences being generally of the order of 1.5 to 2.5°F. The differences at the time of minimum temperature were 2.0 and 1.0°F. corresponding with temperature inversions of 7.1 and 4.0°F. respectively. These are of the same order as the differences between the unscreened flower and air, with inversions of corresponding size (Table 25).

The temperature depression of young fruitlets appears to be rather smaller than those of opening and fully open flowers. The effect may be due to the greater exposure of the fruitlets to wind following the lengthening of the pedicel of the flower truss.

<u>Raspberry</u>

As in the case of strawberry, the buds and opening blossoms of raspberry were cooler than the air by night, but the temperature difference was slight, generally of the order of 0.5°F. on relatively calm radiation nights, and the largest recorded difference over a period of 15 min. was less than 1°F. The differences were too small to analyse with respect to the size of the temperature inversion.

Pear

Relatively few records were taken with pear buds which coincided with calm radiation conditions. A mean temperature depression of 2 to 2.5°F. was recorded on May 12th, 1947 with open blossoms, and of 1.5 to 1.8°F. with buds in the green cluster stage, on May 1st.

The very high values of the depression of bud temperatures recorded with strawberry blossoms under calm radiation conditions may be largely explained by the position of the flower trusses close to the ground. In this zone, air movement is slight compared with that at three or four feet, and much larger temperature differentials between radiating objects and the air can develop.

Cooling due to transpiration

The magnitude of the cooling effect due to transpiration can only be evaluated in the absence of a net radiation loss or gain, i.e. under conditions in which the bud and the objects to which it radiates and from which it receives radiation are of approximately the same temperature. These conditions are approximately satisfied in a room in which the walls and the air are at approximately the same temperature. Conditions within a Stevenson screen are rather similar, in the absence of rapid changes of air temperature. In order to obtain a wide range of relative humidities, observations were made in a variety of locations, in the laboratory, in a damp, underground lysimeter chamber, and within a Stevenson screen. A small fan was employed to maintain a steady air current past the bud and wet and dry bulb thermometers in the laboratory and lysimeter chamber. Table 26 records the mean depression of bud temperature observed under varying conditions of humidity and wind speed and air temperature.

It is quite evident that the cooling of buds and blossoms by transpiration represents only a relatively small percentage of the corresponding depression of the wet bulb; this varies from approximately 5% in the case of dormant buds in still air, to a maximum of 25% in the case of open pear blossoms in an air current of 7 f.p.s. The absolute minimum vapour pressure encountered with temperatures of 32°F. or below, is of the order of 2 mbs. which coincides with a wet bulb depression of 6°F. Therefore the maximum possible depression of bud temperature due to transpiration is of the order of 1.5°F. when air temperature is at or below freezing point, and under normal radiation frost conditions it will rarely exceed 1°F. The observations on May 12th on the open flowers of pear, Table 26, are characteristic of the records of screened buds under conditions of falling temperature and increasing relative humidity. The progressive decrease in bud depression is obviously correlated with the above factors.

Table 26. Depression of bud temperature due to transpiration

Date	Material	Development stage	Dry bulb temperature (°F.)	Depression of the wet bulb (°F.)	Depression of bud temp. (°F.)	Wind speed (f.p.s.)
Mar.19	Pear	Dormant bud	54.0	7.4	0.4	<2
	Apple		55.0	7.6	0.4	<2
Mar.29	Pear	Bud burst	56.5	5.7	0.7	<2
			56.0	6.4	1.4	6
Mar.31	Pear		53.0	5.9	0.5	<2
			50.5	5.5	1.4	7
Apl. 14	Pear	Green bud cluster	65.0	10.5	1.5	<2
			65.4	10.0	2.0	6
May 9	Pear	Open flower	57.5	3.3	0.3	<2
			58.0	3.8	0.5	<2
May 9	Pear	Pink bud	57.8	3.6	0.3	<2
May 12			57.5	6.7	0.9	5
May 12	Pear	Open flower	58.5	7.8	1.9	5 to 8*
			54.8	5.5	1.4	
			52.0	3.5	0.8	
			48.5	2.4	0.5	
May 21	Pear	Open flower	58.7	5.7	0.5	<2
May 10	Raspberry	Bud	52.2	2.0	0.0	<2
May 12			56.8	6.7	0.8	5 to 10
May 21			58.0	3.5	0.2	<2
May 12	Strawberry	Open flower	59.0	8.0	1.9	5 to 10
May 21			61.0	4.0	0.7	<2

* variable.

Discussion

Grainger (1939; 1940) suggests the possibility that the efficiency of orchard heating by oil burning heaters is considerably reduced, because the raising of air temperature results in a fall in relative humidity, which in turn is reflected in greater depression of bud temperature below that of the air. He maintains that the expenditure of the same amount of heat in warming, and at the same time humidifying the air, results in higher internal bud temperatures than does heating without humidification. A theoretical consideration of the problem shows, however, that humidification is certainly no more efficient in maintaining bud temperatures than is dry heating if the buds behave as wet bulbs, and considerably less so if evaporational cooling is less than that of a wet bulb.

A cubic metre of air at N.T.P. with a relative humidity of 70% has a moisture deficit of 1.4 g., i.e. that amount of water vapour is required to raise the relative humidity to 100%. The conversion of 1.4 g. of water to water vapour requires the expenditure of 755 calories (latent heat of vaporization of water, 539 cal. per g.).

The wet bulb depression at 32°F. with R.H. 70% is 2.8°F. The gain in wet bulb temperature in raising the humidity to 100% is therefore 2.8°F.

The application of the same quantity of heat to a cubic metre of air at 70% R.H. would result in the following rise in temperature.

$$\frac{755 \times 9}{1293 \times 0.237 \times 5} = 4.4^{\circ}F.$$

Density of air at N.T.P. = 1.293 g.per l.
Specific heat at constant pressure = 0.237 cal. per g.

The above calculation has been made for dry air; the correction for the moisture content at 70% R.H. is small, less than 1%. (Weight of 1 m.^{3} of dry air = 1293 g. moisture content at 70% R.H. = 3.4 g.). The corresponding calculated depression of the wet bulb temperature is 4.2°F. and the gain in temperature of the wet bulb 3.0°F. This is practically identical with the result of humidification. The bud, however, does not behave as a wet bulb; its depression has not been observed to exceed 25% of the wet bulb depression. The comparable gains in bud temperature by the two methods of heat expenditure will be 0.7°F. and 3.3°F. Humidification is obviously a much less efficient method of raising the temperature of plant parts than is dry heating. There remains the possibility that the production of a fog of steam and smoke by humidification, may behave as a natural fog in reducing the radiation loss from plant and soil surface. Against this possibility must be weighed the effect of the condensation of moisture on the plant surface, which undoubtedly increases its susceptibility to frost damage.

SUMMARY

Section II

The depression of the temperature of fruit buds and blossoms below that of the surrounding air, under nocturnal radiation conditions, was investigated employing thermocouples and a Cambridge Recorder to measure the internal temperatures of the buds. Of the two factors which may cause this temperature depression,— net loss of heat by radiation to outer space and cooling due to transpiration,— it was clearly established that, under calm nocturnal radiation conditions, radiation by the bud or blossom accounted for the major portion of the depression of bud temperature below air temperature. The cooling due to transpiration from the bud surface was shown to represent certainly less than 25% of the corresponding depression of the wet bulb thermometer under identical conditions. It was therefore concluded that humidification of the air as an adjunct to orchard heating could confer no appreciable gain in temperature to plant parts by reducing transpiration, whatever its effect might be in blanketing outgoing radiation.

SECTION III

THE CONTROL OF RADIATION FROSTS

(a) BY MEANS OF AIR CIRCULATION

(b) BY MEANS OF ORCHARD HEATING

Introduction

The raising of orchard temperatures during radiation frosts, either by orchard heating, or by air circulation with blowers, is strictly limited by the form and size of temperature inversion in the lowest 50 ft. of the atmosphere. On theoretical grounds it would be expected that air circulation or mixing, would tend to replace a temperature inversion structure by a temperature profile approximating to the dry adiabatic lapse rate, which, in a shallow zone, will not differ appreciably from an isothermal layer. The destruction of an inversion by wind achieves just this result. The temperature of the layer should approximate to the original temperature towards the top of the zone in which mixing has taken place. The single trial of air circulation which was carried out here, partially confirms this expectation. If this is generally applicable, it provides a method of determining the expected gain in temperature at any height within the mixed zone, from the form of the temperature inversion. This temperature gain should reach a maximum near the ground and fall off rapidly with increasing height.

Data relating to mean inversion size up to 50 ft., on occasions of severe radiation frost, is essential in order to evaluate the probable effectiveness of air circulation in raising orchard temperatures. As we have already noted, inversion size is determined by location, as it affects exposure to wind, and air drainage, and also by ground cover. Inversion conditions over flat ground covered with short grass, in an exposed site, have been recorded over long periods by Johnson (1929) and Johnson and Heywood (1938).

The size of the temperature inversion similarly tends to limit the temperature rise which may be obtained using standard oil burning orchard heaters. The heat sources must be small and well distributed within the heated area. A single large heat source would produce intense convection and carry the warmed air well above useful limits; many small sources of heat serve to eliminate the temperature inversion in a relatively shallow ground zone and the heated air is retained beneath the inversion.

In both types of attempted temperature control the drift of warmed or mixed air out of the heated zone is a major factor in determining the efficiency of heating, and for this reason the heating of small areas or non-compact areas must necessarily be inefficient. The relative success of heating in Californian citrus orchards is due to the large scale on which it is undertaken, and to the fact that the frosts which have to be combatted are rarely severe in this area.

(a) Air Circulation by Means of a Helicopter

Methods

A trial of the effectiveness of air mixing was made possible by the able co-operation of Wing Commander Capper, who has been associated with the development of the agricultural applications of the helicopter in spraying and dusting crops from the air. The helicopter rotor provides an effective blower, capable of producing substantial air circulation over a considerable area.

The site chosen for the trial was the flat floor of the Ayr valley adjacent to Auchincruive. The ground cover was thick meadow grass about 9 in. high. Both the site and the ground cover favour the development of low surface temperatures and large inversions under radiation frost conditions.

Forecasts of suitable conditions for the trial were obtained from the Meteorological Office at Prestwick Airport and, after a considerable delay, such conditions arose on the night of May 18th. Fig. 23 illustrates the layout of the trial. In the first trial the helicopter was used as a stationary blower; in the second, its effect in destroying the temperature inversion when flying over the trial area at a height of approximately 50 ft. were tested.

Thermometer posts were set in two lines at right angles, converging on the helicopter, A to E and P to T, at intervals of 10 yd. in the rows, the nearest being 13 yd. from the rotor. Thermometers were set at

1 ft and 4 ft. above ground level. An additional pole F, 13 yd. from the helicopter carried thermometers at 10 ft. and 17 ft. All thermometers were screened as previously described.

Wind speed during the periods preceding and following the first trial, and during and following the second trial, was recorded by a sensitive cup anemometer at A. The speed of air outflow from the helicopter down-draft was measured by a series of five anemometers, A to E, set at 4 ft. 6 in. above ground level.

The number of observers available were insufficient to permit observations being taken both in the experimental area and in a corresponding control area. It was therefore decided to use the difference between the air temperature during mixing and the extrapolation of the cooling curve prior to mixing, as a measure of the temperature gain at each location and at each height. The thermograph trace during the trial showed a very regular fall, undisturbed by any major breakdown in the temperature inversion, and it may therefore be assumed that the temperature fluctations recorded, may be correctly attributed to the helicopter circulation and not to local wind fluctuations.

Results

Temperature readings were taken at 3 to 5 min. intervals at all locations throughout the trials. Anemometer readings at one min. intervals were taken at location A with the exception of the period when the helicopter was operating as a blower. During this period anemometer readings at 3 to 5 min. intervals were taken at the five locations A to E. Observations were suspended for a brief period of 10 min. prior to the second trial.

The recordings cover the following periods.

(1)	0112 to 0128 hr.	16 min.	Calm.
(2)	0128 to 0144 hr.	16 min.	Rotor operating as a blower.
(3)	0144 to 0211 hr.	27 min.	Calm.
(4)	0211 to 0227 hr.	16 min.	Helicopter in flight over area.
(5)	0227 to 0246 hr.	19 min.	Calm.

Fig. 25 a,b,c,d and e, show graphically the temperature fluctuations at each height and location during the trials.

First trial - helicopter stationary on the ground, employed as a blower

A summary of the temperature gains at each height and location, at 0140 to 0142 hr. towards the end of the air circulation period is given in the following table.

Table 27. Temperature gains at locations A to E, and P to T, during the operation of the helicopter as a stationary blower (°F.)

Height above ground in feet		Distance from the rotor in yards				
		13	23	33	43	53
17		0.8				
10		1.2				
	Series					
4	A to E	5.0	1.4	0.8	0.5	0.3
4	P to T	6.2	5.2	3.4	0.9	0.4
1	A to E	10.6	4.0	2.0	1.5	0.7
1	P to T	9.4	7.2	6.9	2.6	2.0

Virtual destruction of the temperature inversion takes place 13 yd. from the rotor as the following figures recording the temperature profile before, and during the operation of the rotor, indicate.

Height interval	Increase of temperature with height (°F.)	
	Rotor stationary	Rotor in operation
1 - 4 ft.	6.2	1.8
1 -10 ft.	8.7	0.6
1 -17 ft.	9.6	0.7

The form assumed by the temperature profile during mixing, illustrated in Fig.26 a and b, shows a curious departure from the anticipated isothermal structure in that the temperature at 4 ft. exceeds that at 17 ft. by 0.5 and 1.7°F. at A and P respectively, indicating a superadiabatic lapse rate between these levels. The compression of the air in the outflow zone close to the rotor, may account for this excessive temperature increase. A temperature increase of 1.7°F. results from an increase in pressure of 11 mbs., roughly 1% of atmospheric pressure under adiabatic conditions. An increase of this order is quite probable in the outflow zone near the rotor. The rapid fall off in the temperature gain, both with increasing height above ground level, and with increasing distance from the rotor, is very evident. This fall off is much more rapid along the line A to E, than P to T. This difference can be attributed to the katabatic wind which, blowing roughly in a direction from E towards A, would tend to produce a deformation of the form of the air circulation, which is reflected in the deformation of the isothermal surfaces which would otherwise be symmetrical.

The wind velocity, measured at minute intervals at A during the trials, had the following mean and maximum values:-

Calm periods (hr.)	Mean velocity (f.p.s.)	Maximum velocity over a 1 min. period (f.p.s.)
0112 to 0128	1.7	3.0
0144 to 0211	1.1	2.1
0227 to 0246	1.4	2.7
<u>During flight</u>		
0211 to 0227	2.1	3.0

During the operation of the helicopter as a blower the following mean air velocities were recorded at the anemometers stations A to E.

A	13	yd.	from	rotor	13.3	f.p.s.
B	23	"	"	"	1.8	"
C	33	"	"	"	2.2	"
D	43	"	"	"	2.0	"
E	53	"	"	"	1.5	"

The very rapid reduction in the outflow velocity with increasing distance from the rotor, suggests that a closed circulation of a vortex ring type probably develops. One would expect that the outflowing air would tend to flow along the isothermal surfaces, which slope upwards and outwards from axis of the rotor, in a bowl shaped conformation.

Second trial - helicopter in flight over the experimental area

In the second trial the helicopter flew over the area at an approximate height of 50 ft. for a period of 16 min. Its track was along the line of posts P to T; it made a circuit of about half-a-mile diameter, recrossing the area about every two min. during the period. The maximum temperature gain at each height is summarised in Table 28. The mean gain of each of the two series, A to E and P to T, are separately given.

Table 28. Maximum temperature gain at locations A to E and P to T, with the helicopter in flight over the area

Height above ground level in ft.		Maximum temperature gain (°F.) (Mean of series in the case of 1 ft and 4 ft. levels)
17		1.0
10		1.6
	Series	
4	A to E	2.0
4	P to T	3.0
1	A to E	4.0
1	P to T	7.7

The mean temperature profile at the commencement and termination of the flight is tabulated below.

Height interval in ft.	Increase of temperature with height (°F.)	
	Commencement of flight	Termination of flight
1 to 4	8.1	4.3
1 to 10	10.3	6.3
1 to 17	10.8	6.5

After termination of the flight, the initial temperature gain fell to half its value in 7 min. at 4 ft., and in 11 min. at 1 ft. The marked difference between the gains recorded in the two series A to E and P to T, can be attributed in part to the residual effect of the first trial; temperatures in the series P to T still remained higher than those in the series A to E, but the main cause of the greater gain in the P to T series must be attributed to the effect of the helicopter on take-off, which subjected the area occupied by the line of posts P to T, to a vigorous down-draught. The area A to E was not so affected. The results are clearly to be seen in Fig. 25 c and d. A considerable temperature rise took place in the series P to T immediately after take-off (0211 hr.) whereas series A to E show no appreciable rise until after 0220 hr. It should be mentioned that on the first two or three circuits the pilot was flying considerably above 50 ft. and only after familiarizing himself with the configuration of the valley did he descend to a height of 50 ft. The continued rise in temperature in the series P to T between 0217 and 0220 hr. which is not in evidence in the series A to E is more difficult to interpret. It can only be suggested that the penetration of the down-draught from the aircraft would be facilitated by the partial breakdown of the inversion already in evidence in the area P to T, whereas the pronounced inversion conditions still prevailing over the area A to E would resist penetration and turbulent mixing.

In view of these circumstances the gains recorded over the area A to E must be regarded as a more reliable measure of the true effect of flight over the area, than the series P to T.

(b) Orchard Heating Trials

Methods

Two trials of orchard heaters were carried out on the nights of April 25th and May 1st, 1948, in the same location as that chosen for the helicopter trials. A sheltered valley bottom location, such as this, might be expected to provide favourable conditions for heating. An unavoidable difficulty arises in the carrying out of all such experimental trials - that of scale. Commercial orchard heating should be untertaken on compact areas of not less than 10 acres. A trial on this scale is impossible, unless undertaken in co-operation with a commercial grower, on account of the heavy demands of equipment and labour involved. The present trial on the scale of one acre, must necessarily be very much less efficient, nor can an exact estimate of the loss of efficiency be obtained.

Sixty heaters of the modified Harrington type were employed. These embody a chimney in which the oil vapourizes and burns with little or no smoke production. The fuel used was Pool Gas Oil, a grade of diesel fuel.

The heated and control areas were located on the flat floor of the Ayr valley so that the line joining their centres lay transversely across the axis of the valley. Thus the normal line of flow of the katabatic wind drift which persists down the valley under calm radiation conditions, will not carry warm air from the heated to the control area. Fig.24 shows a plan of the trial, with the disposition of heaters and of thermometer poles, three in the control area and nine in the heated area. In the heated area these were set equidistantly between four heaters, except in the case of pole 'c' which was two yards from a heater. The poles carried screened thermometers at 1 ft and 4 ft. above ground level. Two further poles, one in the centre of each area, carried thermometers at 10 ft. and 17 ft.

Forty-nine heaters were disposed in seven rows of seven, at intervals of 11 yd.; the remaining eleven heaters were set along the windward border of the area to provide border heating of the cold inflow. In the first trial, only the heaters in the body of the area were lit, in the second, the border heaters were also employed.

Oil consumption was determined for six heaters in each trial, and gave an average value of 0.40 gall. per hr per heater.

The ground cover was meadow grass about 3 to 5 in. long.

Records

As in the helicopter trials, temperature and wind speed were recorded at the various locations throughout the trial, with the exception of the period during which the heaters were being lit. Records were commenced about an hour before the heaters were lit, in order that any differences between the temperatures originally prevailing in the heated and control areas might be taken into account.

Meteorological conditions

On the occasion of both trials the sky was cloudless and the wind light. The dewpoints on the evening preceding the trial and on the following morning were as follows:-

			°F.
Evening	April	25th	42.6
Morning	"	26th	42.6
Evening	May	1st	30.0 (hoar-frost point)
Morning	"	2nd	34.0

On both occasions a steady katabatic wind persisted down the valley throughout the trials. The high dewpoint on the occasion of the first trial prevented a large fall of temperature, and by midnight the temperature had become static; the much lower dewpoint on the night of May 1st was correlated with a large fall of temperature, and a screen minimum of 28.2°F. was recorded at the Meteorological Station on the adjacent hill top.

Temperature records

The mean temperature differences, prior to heating, between the experimental and control areas, are recorded in the following table.

Table 29. Mean temperature differences between experimental and control areas prior to heating

Height (ft.)	Mean temperature difference. Experimental area minus control (°F.)	
	April 25th	May 1st
17	- 0.03	0.0
10	- 0.03	- 0.03
4	- 0.02	- 0.2
1	- 1.0	- 0.3

It was assumed that the above differences would have persisted throughout the heating trial, although this may be open to question, and they were therefore applied as corrections to the recorded temperature gains in the heated area. The temperatures within the two blocks show fairly close agreement except at one foot.

Fig. 27 and 28 record graphically, the mean temperature variation at each level within the heated and control areas, and the fluctuation in mean wind velocity throughout the trials.

In the following tables the mean temperature gains within the heated area are recorded. It will be observed that these decrease with increasing height above ground level.

<u>Table 30.</u> Mean temperature gains within the heated area in $^{\circ}$F.

Height (feet)	April 25th, 1948						May 1st, 1948				
	Time (hr.)										
	0133	0150	0205	0221	0237	0248	0209	0221	0246	0300	0315
17	0.4	0.4	0.9	1.0	1.2	0.6	1.4	1.5	1.1	1.6	1.5
10	0.4	0.7	1.0	1.0	1.3	0.4	1.4	1.7	1.3	1.5	1.6
4	0.6	1.2	1.2	1.1	1.0	0.7	2.3	1.9	1.0	2.8	3.0
1	1.4	2.0	2.8	2.2	2.4	2.8	4.3	4.6	2.7	4.9	4.6

The effect of heating on the size and form of the temperature inversion is illustrated in the following record of inversion size in the heated and control areas at the time of maximum temperature gain at 1 ft in each trial.

Table 31. Temperature inversion conditions during heating

Height interval (ft.)	April 25th 0205 hr.		May 1st 0300 hr.	
	Temperature increase with height (°F.)			
	Heated area	Control area	Heated area	Control area
1 - 4	2.1	2.9	3.2	5.2
1 - 10	3.1	3.9	3.5	6.6
1 - 17	5.0	5.9	3.6	6.6

Discussion

Since the effectiveness of orchard heating and air circulation depends upon the size of the temperature inversion prevailing in the lowest 50 or 40 ft. of the atmosphere, data relating to inversion conditions in characteristic locations is of great interest. Unfortunately little data is available in this country other than for flat exposed sites. In America there is a considerable body of data for the citrus growing areas of California and Oregon as a result of the climatological studies of Young (1920; 1921), made in connection with the extensive orchard heating practised in these districts.

The following comparisons of mean and extreme inversion conditions in England and the U.S.A. must be regarded as approximate, due to differences in the mode of measurement of the inversion, in the basis of classification of the data, and in the height intervals adapted. A proportional adjustment of the American values to reduce the base line from which inversions were measured, from 5 ft. to 4 ft. has been made.

Johnson (1929) and Johnson and Heywood (1938) provide data for Porton and Leafield in southern England, based on continuous temperature records over a number of years. Young (1920; 1921) presents extensive data for the Pomona Valley, California and the Rogue River Valley near Medford, Oregon. His determinations of inversion size are based on the difference between the minimum temperature recorded at specified heights. The two English sites are both relatively flat and well exposed and neither are subject to air drainage effects. Both American sites are located in the bottoms of very broad open valleys; the Pomona Valley site was over a mile from the base of the nearest hills flanking the valley, and the Rogue River site appears to be equally unconstricted. The air drainage effect from the relatively low surrounding hills could not be very pronounced.

Data for Porton, Salisbury Plain, Wilts.
Altitude 363 ft., Johnson (1929)
Mean inversion for clear nights in June with light winds,
Period 2200 to 0300 hr.

Height interval	Mean inversion
4 to 23 ft.	2.5°F.
4 to 56 ft.	3.5°F.

Extreme Inversions during Spring

Period		Extreme inversions °F.	
		4 to 23 ft.	4 to 56 ft.
	1923	5.0	6.0
March	1924	6.9	9.8
	1925	4.6	6.6
	1923	5.6	7.0
April	1924	6.1	5.9
	1925	6.0	7.6
	1923	3.4	4.8
May	1924	4.6	5.8
	1925	3.7	5.8
Mean of extreme		5.1	6.7

Data for Leafield, south-east edge of Cotswolds

Altitude 612 ft., Johnson and Heywood (1938)

Mean inversion for clear nights in June with light winds, Period 2200 to 0300 hr.

Height interval	Mean inversion
4 to 41 ft.	2.9°F.
4 to 228 ft.	4.5°F.

Extreme inversions during Spring

Year	Extreme inversion (°F.) (Height interval, 4 to 41 ft.)		
	March	April	May
1926	5.3	6.1	4.0
1927	-	6.5	4.3
1928	4.2	5.5	5.6
1929	10.1	5.9	8.5
1930	4.6	6.2	5.2

Mean of extreme .... 5.7°F.

Data for Pomona Valley, S. California

Young (1921)

Based on minimum temperatures recorded at 5 ft intervals on a 40 ft tower set on the valley floor. (°F.)

Height interval (ft.)	Inversion		Height interval (ft.)	Inversion corrected to a base line of 4ft.	
	Mean	Extreme		Mean	Extreme
5 - 10	1.4	3.2	4 - 10	1.7	3.8
5 - 15	2.8	4.8	4 - 15	3.1	5.4
5 - 20	3.6	8.0	4 - 20	3.9	8.6
5 - 25	5.1	9.4	4 - 25	5.4	10.0
5 - 30	6.3	11.0	4 - 30	6.6	11.6
5 - 35	7.1	12.0	4 - 35	7.4	12.6
5 - 40	8.4	15.0	4 - 40	8.7	15.6

Data for Rogue River Valley, Medford, Oregon
Young (1921)

Based on minimum temperature records at 10 ft. intervals on a 35 ft tower set on the valley floor. (°F.)

Height interval (ft.)	Inversion		Height interval (ft.)	Inversion corrected to a base line of 4 ft.	
	Mean	Extreme		Mean	Extreme
5 - 15	1.9	2.9	4 - 15	2.1	3.2
5 - 25	3.6	5.3	4 - 25	3.8	5.6
5 - 35	4.2	6.8	4 - 35	4.4	7.1

The inversions recorded during the trials of orchard heating and air mixing in the Ayr valley at Auchincruive are as follows.

Height interval 4 ft. to 17 ft.

Date 1948	Mean inversion °F.
April 25th	1.7
May 1st	2.3
May 18th	3.3

It should be noted that extreme inversions are not necessarily characteristic of the most severe frosts. They may follow exceptionally warm days when the surface soil temperature, and therefore the free air temperature, have risen to abnormal levels. The very rapid cooling of this superficial layer of soil results in the development of an abnormally large inversion. The most severe frosts follow days on which the ground surface temperature remains relatively low throughout the day.

For the purpose of comparison, these four sets of data are presented graphically (Fig.29). It will be noticed that inversion size at the two sites in America generally exceeds those recorded in this country. While the valley location of the former probably accounts for a proportion of the difference, a further and probably more important source of difference lies in the exceptionally low relative humidities characteristic of this area of America. Dewpoints frequently fall to 3°F., and relative humidities of 5% have been recorded by day. This favours an exceptionally high rate of net radiation loss, and extremely rapid cooling of the soil surface.

The greater scale of difference between hill top and valley bottom minimum temperatures in California as compared with this country, already referred to in a previous section, can also be attributed, in part, to the same cause.

If we make the arbitrary assumption that a blower destroys the temperature inversion between 4 ft. and 20 ft., then the estimated temperature gains at 4 ft. and 10 ft. in the various sites under review, under mean and extreme inversion conditions, would be of the following order.

Site	Approximate temperature gain (°F.)			
	4 ft.		10 ft.	
	Inversion conditions			
	Mean	Extreme	Mean	Extreme
Leafield	1.6	3.7	1.0	2.1
Porton	2.2	4.7	1.2	2.4
Rogue River Valley, Oregon	3.0	4.5	1.8	2.7
Pomona Valley, California	4.2	8.1	2.5	4.5

These figures assume that mixing is complete and continuously maintained. In practice it is doubtful whether such conditions can be maintained over a large area, economically, with the types of blower at present under trial. The expected gains in this country, on level, exposed ground, if 50% of theoretical figure is attained, would hardly appear to justify their use. In valley bottom locations, where the value of the temperature inversion between 4 and 20 ft. might be double that on level ground, gains of the order of 3 to 5°F. at 4 ft., and 2 to 2.5°F. at 10 ft., might be anticipated under very favourable conditions assuming that 50% of the theoretically possible gain is attained. More information is obviously required on inversion conditions in valley locations, under severe radiation frost conditions.

Turning now to orchard heating, reference to Fig.29 suggests that, under mean inversion conditions at Leafield and Porton, the raising of the air temperature at 4 ft. by 3°F. and 4°F. respectively, would eliminate the inversion to a height considerably exceeding 50 ft. and so produce a very high convection ceiling for the warm air. Under extreme inversion conditions the raising of the temperature at 4 ft. by 6°F. and 7°F. respectively, would produce a comparable elimination of the inversion and a correspondingly high inversion ceiling. When these heating levels are approached under the specified inversion conditions, the employment of additional heaters must result in progressively smaller temperature gains. Under mean inversion conditions in the Pomona Valley, a temperature gain of approximately 9°F. at 4 ft. can be produced while the convection ceiling remains less than 50 ft; while under extreme inversion conditions a similar raising of the temperature at 4 ft. would result in a convection ceiling of a little over 20 ft. The efficiency of heating under such conditions will obviously be very considerably greater than that which it is possible to achieve under the feebler inversion conditions which are suspected to prevail in general in this country.

SUMMARY

Section III

Through the co-operation of Wing Commander Capper of Prestwick Airport, a brief trial of the effectiveness of air circulation as a means of destroying the temperature inversion and of raising the temperature of the zone of air near the ground, under radiation frost conditions, was undertaken. The services of a Bell Helicopter were secured to act as both a stationary and a mobile blower.

On the night of May 18th, a trial was carried out on the floor of the Ayr valley, under calm radiation conditions which resulted in a large temperature inversion.

Records are presented of the temperature changes occurring during operation of the helicopter rotor as a stationary blower, over an area extending 55 yd. from

from the rotor and to a height of 17 ft. above ground level.

Temperature gains of 5 to 6°F. were recorded at 4 ft. above ground level in the near vicinity of the rotor, but these gains fell off very rapidly with increasing distance from the rotor and also with increasing height above ground level. Records of wind speed during the trial, of the rate of horizontal outflow from the down draught of the rotor, and of the rate of re-establishment of the temperature inversion after the rotor ceased to operate were also taken.

The effect of the aircraft in flight over the area was recorded in a second trial. The helicopter continuously recrossed the experimental area at intervals of approximately two minutes, flying at a height of about 50 ft. Temperature gains of 2 to 3°F. were obtained at 4 ft. above ground level, falling to 1°F. at 17 ft.

On the same site, two limited trials of orchard heaters of the modified Harrington type were carried out on the nights of April 25th and May 1st, 1948.

The heaters were used at a density of 60 per acre over a square area of 1 acre. In the second trial border heating on the windward edge of the area was adopted.

Records of the temperature gains obtained at heights of 1 ft, 4 ft., 10 ft., and 17 ft., within the heated area, are presented.

On the night of April 25th these gains were of the order of 1°F. at 4 ft., and slightly less than 1°F. at 10 ft. On the night of May 1st, a larger temperature inversion prevailed and heating was more effective. The temperature gains were of the order of 2 to 3°F. at 4 ft. and 1.5°F. at 10 ft.

The relationship between the form and size of the temperature inversion and the effectiveness of both blowers and orchard heaters in raising the temperature of the air in the ground zone, is discussed.

SECTION IV

THE SUSCEPTIBILITY OF STRAWBERRY, RASPBERRY AND APPLE BLOSSOMS TO FROST INJURY

Introduction and Review of Literature

The importance of frost injury in limiting the geographic areas in which crops can be grown has naturally led to an intensive investigation of the factors, genetic, physiological and environmental, which determine or modify susceptibility to frost injury.

It would be out of place here, to attempt to review in detail the large mass of experimental data relating to frost injury, or the numerous theories which have been put forward to account for its vagaries. For such detailed accounts the reader is referred to the following reviews and bibliographies; Maximov (1929), Harvey (1935), Luyet (1940), Imperial Bureau of Plant Breeding and Genetics (1939), and Levitt (1941). Of these, the critical review compiled by Levitt (1941) gives a very complete account of the experimental data concerned with the factors controlling frost injury and reviews current theories of the physiological nature of frost injury in considerable detail.

It is nevertheless essential, for the correct interpretation of the results of this investigation, to include a brief resumé of what is known concerning the physiological nature of frost injury. In the interests of brevity, reference to the original work on which many of the conclusions, referred to below, are based, has frequently been omitted, except in the case of work specifically concerned with hardy fruits.

There is no evidence that low temperature, in the absence of ice formation within the plant tissues, can cause typical frost injury, though other types of physiological breakdown may result from prolonged exposure to temperatures in the neighbourhood of freezing, particularly when accompanied by strong winds and low relative humidity. Cooling of the plant material below the freezing point of the cell sap, without the formation of ice, i.e., supercooling or 'undercooling', is of frequent occurrence and is never directly injurious. In most plants, however, ice formation occurs when the temperature falls a few degrees below the freezing point of the cell sap. Ice generally forms extracellularly, in the intercellular spaces. As freezing proceeds, there is a progressive migration of water from the interior of the cell to these ice foci. Rapid freezing results in the formation of numerous small foci, whereas slow freezing generally produces a limited number of larger ice masses which grow in size. In non-hardy plants, extracellular ice formation results in typical freezing injury. In most plants the increasing concentration of the cell sap resulting from the progressive withdrawal of water, is sufficient to prevent the formation of intracellular ice in the vacuole or within the actual protoplasm of the cell. Intracellular ice formation does occur in certain cases, and usually results in the death of the cell. Certainly in cases where it is induced to form artificially, by rapid freezing or extreme supercooling, followed by almost instantaneous freezing, injury is much more severe than that caused by extracellular ice formation at the same temperature.

In the case of hardy plants, the water extracted by extracellular ice formation is rapidly reabsorbed on thawing, and the cells regain their normal turger. Not so with tender plants. The water resulting from the thawing of the extracelluler ice remains unabsorbed in the intercellular spaces and the tissue assumes the waterlogged, sodden, flacid appearance, characteristic of frost injury.

Much of the experimental work on frost injury has aimed at elucidating the physiological nature of the difference between hardy and non-hardy plant tissue, frequently with a view to discovering a relatively simple criterion for the measurement of frost hardiness in crop plants.

So far a completely verified theory of the nature of frost injury has not been put forward; the most probable theories remain partly speculative because the cell properties which are believed to be involved in resistance or susceptibility, namely, cell permiability to water, and protoplasmic consistency and structure, are extremely difficult to investigate. No single, simple physiological property has been discovered which will serve to assess frost susceptibility.

It is not proposed to deal with those theories relating to the injury resulting from intracellular ice formation, since it seems doubtful if such injury is encountered during Spring frosts. Only the more important theories concerned with injury resulting from extracellular ice formation will be reviewed.

Contrary to the contention of Stuckey and Curtis (1938) that no evidence has been adduced to show that extracellular ice formation is capable of causing the injury and death of plant cells, many investigators agree in reporting injury under just these conditions, and in the absence of intracellular ice. There is fairly general agreement that the injury which follows extracellular ice formation is the result of dehydration of the cell. On the other hand there is no agreement as to the exact mode in which dehydration operates to produce injury.

Maximov (1914) suggested that injury is in the nature of an irreversible coalescence of the particles constituting the plasma colloids under the combined action of dehydration and pressure which he believed resulted from ice formation either outside the cell, or between the cell wall and the protoplast. The theory was put forward to resolve the difficulty that, while many plants showed parallel injury to dehydration by drought and dehydration by freezing, notable exceptions occurred which might be attributed to a difference in sensitivity to pressure. Further evidence has thrown doubt on the part played by ice pressure particularly in leaf tissues in which the large intercellular spaces may easily accommodate large masses of intercellular ice without constriction.

Müller-Thurgau (1880) recognised the importance of dehydration as a probable cause of injury. He made estimates of the quantities of water withdrawn from tissues in the course of freezing. He suggested that the essential structure of the protoplasm was destroyed by the progress of dehydration beyond a critical point. The toleration, without injury, in certain cases, of the removal of a larger proportion of water by drought dehydration or plasmolysis, he attributed to the fact that dehydration during freezing is exceedingly rapid compared with that occurring during plasmolysis or drying. The greater the water content of the tissue the greater the change in the spatial relations of the cell colloids when it is withdrawn, and consequently the greater the injury. The theory assumes that the amount of ice formed in the tissue is, in some degree, proportional to the temperature fall. This, of course, is true, only above the eutectic point. If, however, freezing injury is merely dehydration injury, one would expect the resistance of plant tissues to both drought and frost injury to run closely parallel. While this is to some extent the case, many exceptions have been observed; moreover, the greater resistance of wilted tissue to freezing injury remains unexplained. Here, it would seem that a certain measure of dehydration by drought protects against a further measure of dehydration by freezing. Nevertheless the changes which take place in plants exposed to drought conditions and which increase their resistance to subsequent drought injury, are closely similar to those occurring during the frost hardening of plants; namely:-

(1) Hydrolysis of starch to sugar.
(2) Increase in the permiability of the protoplast to water.
(3) Increase in cell sap concentration.
(4) Increased resistance to deplasmolysis injury.

Scarth and Levitt (1937).

The theory that the injurious effects of dehydration might be of a chemical rather than a physical nature, was first suggested by Sach (1873). Since then numerous workers have brought forward evidence in support of the view that the concentration of salts in the cell sap resulting from freezing dehydration, causes precipitation of the cell proteins. In opposition to this view, Stiles (1930) remarks that an equivalent degree of cell sap concentration within the vacuole, induced by plasmolysis, is frequently non-injurious. Furthermore, in the case of tender plants, freezing at a level which results in only slight ice formation, quite insufficient to induce precipitation of the colloidal proteins, nevertheless kills the tissue. Lastly, the protective action against freezing injury of salt solutions, applied either externally to the frozen tissue or actually absorbed to some degree by the tissue, is inexplicable on this theory.

Numerous workers have attempted to correlate hardiness with the ability of the plant tissue to resist the withdrawal of water from its cells. They maintain that a certain proportion of the water content is 'bound' by the cell colloids with sufficient osmotic or imbibitional force to prevent its extraction by freezing. Newton

(1922; 1924; 1924a) claims to show that in wheat, the proportion of 'bound' water increases markedly at the onset of winter. As a measure of 'bound' water content he determined the amount of water which was retained by the tissue after expressing as much water as possible under pressures of the order of 400 atmospheres. It is difficult to believe that such tissues do in fact possess imbibitional pressure of this order while retaining over 90% of their total water content. The resistance of a tissue to the removal of water under pressure is a measure rather of the resistance of the tissue to mechanical crushing and disruption of the individual cells than of 'bound' water content. Nevertheless, Rosa (1921) working on cabbage, and Newton (1924; 1924a) on varieties of wheat differing in hardiness, have shown that the percentage of water remaining unfrozen is higher in hardened, as compared with unhardened cabbage, and in hardy as compared with tender varieties of wheat. It should be noted, however, that these differences tend to disappear if the percentage of water remaining unfrozen is calculated on the basis of the dry weight of the tissue, instead of the fresh weight. The issue is confused by the wide variety of methods employed, purporting to measure 'bound' water and by the difficulty of distinguishing between colloidally bound water and water held by the osmotic pressure of the cell sap. It is possible that an increase in colloidally bound water may play some part in the winter hardening of the cortical cells of woody plants which normally possess a high protoplasmic content. In contrast with such cells, the parenchymatous tissue of the majority of herbaceous plants, and of the soft growth of woody plants is, for the most part, made up of cells in which the protoplasmic colloids occupy a very small fraction of the total cell volume. It is inconceivable that the small quantity of bound water associated with those colloids is capable of protecting such tissues against dehydration injury.

Scarth, Levitt and Simonovitch (1940) were led to conclude that the frost resistance of hardy plants was largely due to the inherent resistance of the protoplasm to the injurious effects of dehydration, rather than to the reduction or prevention of ice formation. Levitt (1939) points out that hardened cabbage tolerates, without injury, a much higher degree of dehydration than does the unhardened tissue, and also a much greater percentage change in cell volume. Moreover the lethal volume change, whether induced by freezing or plasmolysis, agrees in being higher in hardened, than in unhardened tissue.

The view of the nature of freezing injury put forward by Levitt (1941) stresses the fact that there is undoubtedly more than one single cause of injury. He suggests that dehydration of the protoplast, if carried beyond a certain point, results in irreversible coagulation of the protoplasmic colloids. He considers, however, that injury may occur before this stage is reached, due to the disorganisation of the structure of the ectoplasm and plasma membrane resulting from the shrinking of the cell and the extreme deformation in shape which accompanies it. This produces shearing stresses which disrupt the gel layers. In this connection, it is interesting to note that hardy plants resist mechanical injury during the manipulation of their cells better than do tender plants. A third suggested cause of injury is bound up with the permiability of the protoplast to water. Cell permiability to water is generally lower in tender than in hardy plants. This may predispose the plant to freezing injury in two ways; firstly by obstructing exosmosis of water from the cell vacuole to extracellular ice foci during slow freezing, thereby favouring marked supercooling of the cell content, and perhaps intracellular ice formation, with its attendant injury; secondly, low permiability may lead to injury during thawing in the following manner. If thawing is rapid, the water released in the intercellular spaces rapidly penetrates the cell walls which quickly expand to almost their normal shape. Owing to the low permiability of the protoplasmic membrane the uptake of water by the vacuole and protoplast is considerably slower. It therefore becomes separated from the cell wall, perhaps becoming torn in the process. On the other hand if the protoplast is highly permiable, the expansion of the protoplast keeps pace with that of the cell wall. Injury of this nature is described by Iljin (1935) in the course of the thawing of the epidermal cells of red cabbage. The relatively higher resistance of small celled tissues to freezing, or rather thawing, injury is readily explicable on this basis, since the ratio of the surface area of the cell to its volume is large, and the passage of water through the protoplasmic membrane, thus facilitated. Shearing stresses are likewise reduced with decreased cell size. It is also significant that the consistency of the protoplast in the cells of hardy dormant tissue tends to be less viscous than that of actively growing tissue. This will be reflected in a greater elasticity of the dehydrated protoplast and a reduced tendency to disruption during freezing and thawing. The protoplasm owes its greater mobility to a greater degree of hydration, which in turn determines a greater permiability of the protoplast to water. A serious difficulty here arises; the change to the hardy condition is, in most cases, accompanied by a decrease in the total water content of the tissue. This is difficult to reconcile with an increase in protoplasmic hydration.

Of the factors involved in the above theory of the nature of frost injury, cell permiability and protoplasmic structure and constancy are inherently difficult to investigate and further confirmation awaits an advance in the methods available for their exploration.

Turning now to the investigation of frost injury to hardy fruits; the work is seen to fall into two broad categories:-

(a) Investigations primarily concerned with the winter killing of the plant, or with winter injury.

(b) Those dealing with spring frost damage to the developing blossoms and fruitlets in the post-dormant stages.

This latter class falls again into two groups, the first dealing with observations on the effects of naturally occurring Spring frosts, and the second with the investigation of frost susceptibility by means of artificial refrigeration treatments.

In this country, valuable records of the incidence of Spring frosts and the resultant damage to the fruit crop, are available in the Annual Reports of the East Malling and Long Ashton Research Stations. Mention may be made of the review of Spring frosts and of the incidence of frost damage during the period 1915 to 1935 (Hoblyn, 1935). Spinks (1936) also gives an account of the results of the severe Spring frosts of 1935 in the west of England.

Of particular value are the observations of Taylor (1929), Potter (1942; 1945) and Bush (1945) on the varietal resistance of a wide range of fruits to frost damage in the field. In every case estimates of relative hardiness are based on many years observations of the varieties in question. Bush (1945) draws extensively on the experience of Mr Norman Grubb of East Malling Research Station and Mr S. Roper Dixon of Teynham, Kent, concerning the relative hardiness of cherries, and the late Mr J. Amos of East Malling Research Station concerning pears.

Varietal differences in the onset and duration of the flowering period, (Potter, 1945; Hatton and Grubb, 1925), complicate the picture of varietal susceptibility, since this factor varies considerably from season to season, and may be modified to a limited extent by pruning methods. In an exceptionally late season, the flowering of all varieties may be condensed into a very brief period, and differences in developmental stage may be of little account in the event of a late frost, whereas in a more normal season they may be the dominant factor determining the varietal incidence of damage.

Potter (1945) points out that resistance may be modified in the case of apples by the type of root-stock, Malling stocks I and II apparently conferring slightly greater resistance on the scion than Malling XII. He has observed that, in general, late keeping varieties suffer greater damage than early or mid-season types, and that young trees are more susceptible than old.

Many investigators have attempted to draw up tables indicating the critical temperatures at which damage occurs in various fruits at various stages in their development, based on orchard observations, (Gardner, Bradford and Hooker, 1939; West and Edlefsen, 1921). While of some value as a rough guide to the minimum temperature conditions under which damage may be anticipated, the limitations of such tables must be realised. They ignore the effect of the duration of the low temperature; they tacitly assume that measurement of orchard minimum temperatures has been standardised, whereas in fact, many departures from the standard measurement made at a height of 4 ft. with a screened minimum thermometer, contribute to the records. A single minimum temperature observation is frequently assumed to be representative of conditions over a considerable area of orchard, in which wide variations do, in fact, occur. Again, little account is taken of the sharp vertical temperature gradient which may result in severe frosting of cordon trees while standards escape much more lightly.

Gardner (1935) in a study of the injury suffered by the flower buds of Montmorency cherry in natural frosts, concluded that the considerable differences in hardiness noted between individual blossom buds could not be attributed to differences in their stage of development, which was relatively uniform at any particular date in a single locality. He suggests that the buds are more sensitive to frost injury when they are a quarter to a half the final size which they attain before flowering, than when fully developed. He does not make it clear, however, that the greater injury may be associated with frosts of greater severity encountered at the earlier stages. He also comments on the fact that the varieties exhibiting exceptional winter hardiness of the flower buds did not necessarily show corresponding spring hardiness. The same lack of correlation between winter resistance and spring resistance to frost injury was observed by Brierley and

Landon (1943) in a study of strawberry varieties.

The earliest extensive experimental work on the frost susceptibility of fruit blossoms and the factors modifying it, was carried out by West and Edlefsen (1921). They employed a refrigeration chamber chilled by a freezing mixture of salt and ice, and maintained at a predetermined temperature by a small thermostatically controlled heating lamp. They investigated freezing injury to the blossoms of Ben Davis apple, subjected to temperatures ranging from 20 to 28°F. employing both detached and growing branches. Equivalent treatments produced rather greater damage during the period when the fruit was 'setting', petal fall stage, than at full bloom. They also remark upon the extreme resistance of occasional blossoms to injury. Occasional fruits matured on branches which had been subjected to 20°F. at full blossom stage.

Osterwalder (1943; 1948) carried out extensive refrigeration experiments on the blossoms of cherries, apples and pears, investigating the effect of variation in refrigeration temperature and duration of treatment and other additional factors. He remarks on the increased susceptibility of wet plants to injury. Syringing the frozen blossoms with water was found to be without effect in mitigating injury, while the use of 2% salt solution proved definitely harmful.

In this country the most extensive work on the frost susceptibility of fruit blossoms was undertaken by Field (1939). Refrigeration trials were carried out with the cut blossom trusses of crab apple and the late flowering apple variety, Court Pendu Platt, and in addition, with blackberry blossoms. Constant temperature chambers running at 26 to 32°F. were employed, and the period of refrigeration varied from 1 to 12 hr. Detailed descriptions of the appearance of frost injury at each developmental stage are given. Rapid chilling resulted, in general, in slightly greater injury than slow chilling; slow thawing on the other hand, had little effect in mitigating damage. In the case of crab, identical treatments produced more severe injury to the open flower than to the bud stage, as determined by browning of the ovary, but in the variety Court Pendu Platt the reverse was observed. It should be noted, however, that trusses in both the greenbud stage and in full flower, collected presumably at the same time from adjacent trees, are here compared, and it must not be concluded that a comparison of the relative susceptibility of the green bud stage with the full bloom stage when the tree as a whole is predominantly in one or other stage, will yield a similar result. Resistance was not appreciably increased by preliminary chilling treatments with a view to hardening the blossoms, prior to refrigeration. Some success was obtained in protecting buds and blossoms from injury by the application of solutions of glycerine, urea and sugar.

The investigation was later extended (Field, 1942) to include a study of the comparative susceptibility of three commercial apple varieties, Cox's Orange Pippin, Bramley's Seedling, and Worcester Pearmain. Identical refrigeration treatments of pot grown trees and cut blossom trusses from these trees, showed comparable injury and established the validity of the use of cut trusses as a guide to the behaviour of the growing plant. A comparison of the relative resistance of the blossoms at four stages of development showed that, in each variety, the green-bud stage was most susceptible to injury. The variety Bramley, showed increased resistance throughout the sequence of stages from green-bud to petal-fall; at every stage it was more susceptible than Worcester Pearmain, but differed little from Cox. Other workers, however, are in disagreement with this result. Geslin (1939) finds a steady increase in susceptibility from closed bud to fruitlet stage in both pome and stone fruits. Field observations, with few exceptions, notably Potter (1945), also suggest increased susceptibility at the later, full bloom and petal-fall stages, and the frequency with which late flowering varieties escape frost injury when earlier varieties suffer damage while in full bloom, provides additional evidence. Variation in moisture content from stage to stage, or between trusses in the same stage, could not be correlated with differences in the degree of injury. While surface moisture on the flowers or buds greatly increased their susceptibility, the water supply to the trees grown in pots, had little effect on the resistance of the blossoms and even when moisture deficit caused the flowers to wilt, their resistance was only slightly increased. Continuous freezing at a given temperature was more injurious than intermittant freezing at the same temperature, for the same total period. This confirms the previous findings of Diehl and Wright (1924) working with apple fruits.

Developing pollen showed considerable, though variable resistance to injury. Orange colouration of the grains was an indication of damage and non-viability. Germinating grains on the other hand, were very susceptible, being injured by brief exposure to a temperature of 29°F.

Reliance upon the effects of natural frosts as a means of establishing the relative susceptibility of the varieties of hardy fruits to spring frost damage may demand a period of many years before their individual performance can be assessed with any degree of accuracy. The many factors such as differing orchard locations, soil cover, state of nutrition and state of advancement of blossoms, may seriously diminish the value of many of the comparisons upon which the conclusions are based.

The need for a rapid experimental method of establishing the frost susceptibility of established and newly introduced varieties, and of breeding material is very evident.

Refrigeration trials provide a convenient method of determing susceptibility to injury under controlled conditions. The following factors must, however, be borne in mind in applying the results of such trials to natural frosts:-

(a) Refrigeration trials are necessarily carried out either on potted plants or on freshly cut material, neither of which is entirely satisfactory. The adaptation of a refrigerator for use in the field is a possibility which might be further explored.

(b) Under natural frost conditions plant parts are cooler than the air, and dew or rime tends to be deposited on them. Within a refrigerator, condensation and rime formation takes place exclusively on the cooling tubes and faces and not on the plant material. It is suspected that this factor may have a large influence in determining the degree of super-cooling of the plant tissue, and therefore on the amount of injury sustained.

(c) The rate of cooling and thawing in refrigeration experiments does not stimulate natural frosts.

The refrigeration trials carried out in this investigation were designed to obtain the following information:-

(i) To determine the changes in susceptibility to frost injury which accompany development from bud to fruitlet stage in strawberry, raspberry and apple.

(ii) To compare the frost susceptibility of certain varieties of raspberry and apple, which show marked differences in the field.

(iii) To investigate the cause of variation in response to freezing, of apparently uniform samples of material of the same variety, and the possibility of eliminating such variation as may be attributable to erratic super-cooling.

(iv) To determine the effect of (a) length of chilling period, (b) rate of chilling and thawing, (c) imbibition of water, (d) surface wetting of the material, and (e) mechanical shock, on the incidence and severity of damage.

Methods

The refrigerator used in this investigation was built to the design of Dr J. Grainger, by Messrs A. & D. Hall Ltd. of Dartford, Kent.

The internal dimensions of the refrigeration chamber were 3 ft. 4 in. x 2 ft. 3 in. Walls and doors were 4 in. in thickness including approximately 3½ in. of insulating material. Cooling faces occupied three sides of the chamber, and an inspection window covered by an insulated door, a fourth. Double, hinged doors of similar construction to the walls, gave access to the chamber at the end.

A fan housed in a compartment behind the back cooling face and driven by a motor external to the chamber, circulated the air continuously within it and ensured relatively uniform temperature distribution. Temperature was controlled by means of a 'Sunvic' variable thermostat, type T.S.1. and hot wire vacuum switch. By careful adjustment it was found possible to control temperature within the limits ± 0.9°F. The large heat capacity of the cooling faces, results in the continuation of cooling after the compressor has cut out. This causes the temperature fluctuation to exceed considerably, the temperature differential of the thermostat. It may be possible to overcome such excessive variation by either of the following modifications. An inner chamber on the lines of a water oven, with oil-filled walls within the refrigeration chamber would effectively damp the temperature fluctuation. Alternatively, a thermostat could be used to control the temperature of the cooling faces slightly below that required in the chamber, and the fine control of air temperature then achieved by thermostatically controlled low temperature heating coils, which, being of low heat capacity, would provide a temperature control approaching the true temperature differential of the thermostat.

During adjustment of the thermostat, records of the temperature fluctuation within the chamber were obtained on a Cambridge Recorder. The mean temperature and the amplitude of the regular temperature fluctuations, remained constant within quite small limits, although the period of the fluctuation varied according to the temperature difference between the chamber and the external air.

Temperature within the chamber was normally read by means of a screened minimum thermometer checked against readings of a screened standard thermometer.

Except where stated, the material to be chilled was placed in the refrigerator which was running at the required chilling temperature. The alternative of bringing the temperature of the refrigerator and material down to the required chilling temperature at the natural cooling rate of the refrigerator, while to some extent simulating the conditions of a natural frost, has the most serious disadvantage that at widely differing external air temperatures, the time taken for the refrigerator to fall to the required temperature varies within wide limits. Since the length of time to which the material is subjected to the chilling temperature is a most important factor in determining damage, such variation is inadmissible.

Material

The following fruit varieties were used in the investigation:-

Strawberry

L.R.19 — 2 yr old plants from the open ground.

Pot grown runners rooted the previous August.

Auchincruive climax

1 yr old plants from the open ground.

In the second year a considerable number of the stock of L.R.19 showed virus symptoms, while others were found to be infected with 'red core' disease. Suspect plants were not included in the trials.

Raspberry

The main investigation was confined to two varieties, widely planted in the Clyde valley, - Burnetholme Seedling and Norfolk Giant. Limited varietal trials of relative susceptibility were carried out on 16 varieties later enumerated.

Apple

Trials of varietal susceptibility were carried out on 7 varieties of apple.

Crawley Beaut

Culinary	Dessert
Bramley's Seedling	James Grieve
Newton Wonder	Cox's Orange Pippin
Crawley Beauty	Ellison's Orange
Edward VII	

The material was obtained from young trees on No.II Malling Stocks, with the exception of Crawley Beauty which was on No.IX.

Records

A. Strawberry

A comparison of the frost injury sustained by the flowers of pot plants of strawberry and cut blossom trusses of similar pot plants showed no significant difference in incidence or degree. The use of cut blossom trusses may therefore be expected to provide a comparatively reliable guide to the susceptibility of the growing plant. Field (1939) found the same to be true of the blossom trusses of pot grown trees of apple. In raspberry, however, large and significant differences were noted between the response to identical chilling treatment of trusses of buds, and buds detached from the truss. The possibility of such effects in dealing with detached trusses must be borne in mind.

(1) Symptoms of injury

Injury of increasing severity exhibits itself in the following sequence.

(a) Slight olive discolouration and water-logging at the base of the carpels at the junction of the style.

(b) Discolouration and waterlogging spreading to the entire carpels and styles which subsequently turn black. Typical black frost 'eye'.

(c) Waterlogging extending to the receptacle.

(d) Discolouration affecting the filaments of the stamens.

(e) Browning or yellowing of the petals and anthers and waterlogging of the sepals and petiole of the flower.

In order to obtain a quantitative estimate of the damage to a sample, qualitative differences in the degree of injury were ignored and the presence or absence of injury alone was scored. The alternative of allotting weighting factors to different grades of injury is unsatisfactory since the grades cannot be clearly defined.

(ii) Treatments

Refrigerations in 1947 covered the six-week period 5th May to 15th June. The late Spring resulted in an exceptionally late flowering period, preceded by very rapid development. In the course of each weekly period, refrigerations of one hour duration were made at 4 or 5 temperature levels, graded to give a range of injury from slight to severe. Exact refrigerator temperatures can only be obtained at the expense of a great deal of time in the adjustment of the thermostat.

It was therefore decided to allow some latitude in the thermostat setting, provided an adequate range of temperature was covered. Samples consisted of 20 bud or blossom trusses, and the percentage of buds showing injury was recorded 24 hr. after removal from the refrigerator.

Fig.30 records the temperature levels at which treatments were made in each of the six weekly periods, and the percentage damage recorded at each level, with the variety L.R.19. Weekly results were graphed and the approximate temperature level coinciding with 50% injury derived. This data is also summarised in Fig.30, together with the mean stage in development of the most advanced flower trusses.

A sharp rise in the temperature causing 50% injury, from approximately 22°F. in the almost sessile bud stage, to 27.5°F. at the period of maximum flowering, is evident.

Similar refrigeration trials on a restricted scale, were carried out on pot plants of the same variety, grown in the cold greenhouse. Twelve treatments, of six pots each, were made during the four week period April 21st to May 17th, 1947. Development was more rapid, and flowering commenced 16 days earlier than in outdoor plants. The estimation of the temperature levels causing 50% injury are indicated on Fig.30. These refer to plants coinciding in the stage of development, but not, of course, in the date of refrigeration. On the approach of flowering, and during flowering, the temperature level necessary to produce equivalent damage appears to be about 1°F. lower for greenhouse plants. This unexpected result may possibly be the result of a restricted root system and a partial curtailment of water supply in pot plants, grown under greenhouse conditions. The error in the estimation of the temperature levels producing 50% damage is necessarily greater, being based on fewer treatments and smaller samples. In contrast to the above result, the lower refrigeration temperatures (21-22°F.) produced injury, in the form of waterlogging and subsequent browning, of the interviemal portions of the younger leaves in greenhouse plants; a symptom not observed in pot grown plants, grown out of doors.

(iii) Length of refrigeration period

Increasing the length of the refrigeration period resulted in an increase in both the incidence and severity of the resulting damage. Table 32 gives the results of five treatments with chilling periods of ½, 1 and 2 hr.

Table 32. Percentage of buds and flowers showing injury with refrigération periods of ½, 1 and 2 hr.

Date	Refrigeration temperature (°F.)	Percentage of injured buds		
		½ hr	1 hr	2 hr.
May 24	26.4	0	20	22
" 26	26.5	0	0	17
" 27	25.7	32	100	100
" 30	27.3	4	12	38
June 2	28.5	3	25	36

(iv) Varietal differences

In 1948, the relative susceptibility of the two vabieties L.R.19 and Auchincruive Climax was compared. The results, summarised in Table 33, suggest that L.R.19 is rather more susceptible, but the difference is not large, and probably depends on the late flowering habit of Auchincruive Climax.

Table 33. Percentage of buds and flowers showing injury in two varieties of strawberry, subjected to identical chilling treatments

Date	Treatment (1 hr °F.)	L.R.19		Auchincruive Climax	
		Development stage	% injury	Development stage	% injury
May 6	24.6	Late bud	100	Bud	40
" 10	26.8	Commencing flowering	7	Late bud	5
" 11	24.8		75		22
" 13	25.8	Flowering	57	Commencing flowering	46
" 21	26.3	Flower & fruitlet	9	Flowering	0

(v) Severity of injury

With a refrigeration period of 1 hr, injury during the flowering period appears to increase from nil or very slight, to severe damage of practically all flowers and buds, within a temperature interval of approximately 3 to 3.5°F.

From the time flowering commences, bud and flower trusses can be found to diverse stages of development on the same plant. These all show a close similarity in the level at which injury occurs. Open flowers do show a rather greater incidence of injury than buds, but the difference is slight. The plant appears to behave as a unit as regards increasing susceptibility. One must conclude that increasing susceptibility is correlated less with the stage of development of individual buds, than with the stage of development of the plant as a whole.

B. Raspberry

Bud trusses were obtained from a plantation of vigorous 5-year old canes of the varieties Burnetholme Seedling and Norfolk Giant. The ground had received a moderate dressing of dung before planting and an annual dressing of general fertilizer at the rate of about 4 cwt. to the acre was applied each spring.

(i) Symptoms of injury

In the early bud stages, increasingly severe injury shows itself in the following sequence.

(1) Discolouration of the carpels and styles.

(2) Discolouration of the entire bud contents, spreading to the receptacle.

(3) Discolouration of the bud contents and waterlogging of the sepals and pedicels of the buds. The whole truss assumes an olive, watersoaked appearance. In later bud stages, the sequence is similar, but the anthers remain rather more resistant to injury than the rest of the bud contents.

> Discolouration in the receptacle first appears at the base of the carpels and extends down the vascular bundles.

Here again a quantitative estimate of damage was based on the presence or absence of injury to buds without reference to its severity.

(ii) Treatments

Variation in susceptibility during the development of the buds was followed in these two varieties during a seven week period from May 12th to June 29th, 1947, and in the corresponding developmental period, April 12th to June 6th, in 1948. Development of the buds was retarded and flowering was 20 to 24 days later in 1947 than in 1948 due to the exceptionally cold Spring of the former year.

The refrigeration treatment was identical with that adopted for strawberry. Samples, each of 20 trusses, were subjected to refrigeration periods of ½, 1 and 2 hr. at a range of temperature levels. The one hour treatments were maintained throughout the trials, but the ½ and 2 hr. treatments were omitted when pressure of space demanded.

(iii) Records

Fig. 31 and 32 summarise the treatments at various temperature levels throughout the seven, weekly periods. Treatments were commenced one week later in 1947, and two weeks later in 1948, with the variety Norfolk Giant, due to the immature state of the buds of this later flowering variety, which makes the recording of injury difficult where large numbers of buds have to be examined.

Fig.35 shows the corresponding temperature levels at which 50% of the buds exhibit injury in each weekly period.

In 1947 no marked rise in the temperature level producing injury with the approach of flowering is apparent. A slight rise from 24.5°F. to 27.0°F. in the case of Burnetholme and from 26.0 to 27.5°F. in the case Norfolk Giant, is apparent. Nor do the two varieties appear to differ appreciably in susceptibility. Turning to 1948, the form of the susceptibility graph is strikingly different. On the approach of flowering, the 50% injury temperature level fell in the case of Burnetholme from 25.8 to 23.5°F., and in that of Norfolk Giant, from 25.5 to 23.2°F. This fall was undoubtedly real; it was checked by duplication of treatments with replicate samples at the lower temperature levels required to produce injury. A sharp rise to 24.5°F. followed in the case of Norfolk Giant, in the period 31st May to 6th June.

Weather conditions during the corresponding periods of development in 1947 and 1948, suggest a cause for this disparity in behaviour. In 1947 abundant rainfall and high temperature and humidity prevailed during the later bud development stages. In 1948 these later stages coincided with a period of comparative drought, with high temperature and low mean relative humidity. During the period May 5th to 27th, the total rainfall was 0.1 inch. Drought may be expected to take rapid effect on a shallow rooting plant such as the raspberry, and combined with excessive transpiration, may materially increase its frost resistance by partial dehydration, or alteration of the permeability relations of the cells. In the course of experiments on the effect of imbibition of water by cut trusses of buds on their frost susceptibility, records were taken of the quantity of water imbibed by trusses in a saturated atmosphere, expressed as a percentage of the fresh weight. These were as follows:-

	%
May 18th	2.6
" 21st	5.0
June 4th	0.5 (following heavy rainfall)

It is evident that a considerable water deficit had developed within the bud trusses, at least by day, during the period of the drought.

(iv) Length of refrigeration period

As in the case of strawberry, an increase in the length of the refrigeration period is generally accompanied by a corresponding increase in the incidence and severity of damage. Table 34 shows representative results with the variety Burnetholme in 1948.

Table 34. Percentage of buds showing injury with refrigeration

(Periods of ½ hr, 1 hr and 2 hr.)

Date	Refrigeration temperature (°F.)	Percentage of buds showing injury		
		½ hr	1 hr	2 hr.
Apl. 15	27.3	0	14	2
" 22	27.0	0	15	13
" 23	25.5	10	39	50
" 27	26.0	0	10	20
" 29	24.5	20	66	82
May 5	24.8	35	44	63
" 10	27.2	6	17	19
" 11	24.0	22	60	80

(v) Varietal trials

Trials were carried out in 1948 with a collection of fourteen raspberry varieties, including some unnamed seedlings sent out from East Malling Research Station under number. All the varieties were growing in a south facing border under closely similar conditions of soil, location and exposure.

The results of three refrigerations with samples of 20 bud trusses per variety, at the following temperature levels,

May 12th 1 hr at 25.5°F.
" 14th 1 hr at 24.0
" 18th 1 hr at 24.0

are combined to give a single figure for mean percentage of injured buds.

Variety	Percentage damage	
St Walfrid	90	
Lloyd George	68	(Stock showing severe virus symptoms)
G.32/166	41	
Newburgh	38	
Malling Promise	35	

Variety	Percentage damage
Burnetholme	35
N 32/163	30
Y 33/54	30
Malling Landmark	29
Malling Enterprize	28
Norfolk Giant	28
K 33/115	20
32/41	9
M 32/138	8

(vi) The causes of variation in the response to refrigeration of apparently uniform bud material

The rather wide variation in the response of bud trusses in the same stage of development, to identical refrigeration treatments may be attributable to several causes, amongst which the following may be of importance.

Variation in susceptibility of individual canes.

Variation in susceptibility due to the position of the truss on cane.

Variation in response due to erratic and unpredictable supercooling of the material.

a) Effect of position of the truss on the cane

Comparisons were made between the degree of injury sustained by bud trusses selected from the top, middle and bottom of the canes. The top trusses were of short 'hard' growth, while those located lower down were borne on increasingly longer peduncles of 'softer' growth. Comparisons were also made between selections of these two extreme types. The results are summarised in the following table.

Table 35. Effect of position of bud truss on the cane, and type of truss on the frost susceptibility of Norfolk Giant

Date 1948	Treatment (2 hr. °F.)	Position or type of truss	Percentage of buds showing injury	Water content of a comparable sample of buds. As a % of fresh weight
May 26	23.2	Top	90	74.3
		Bottom	15	74.7
		Short 'hard'	80	-
		Long succulent	50	-
May 27	23.2	Top	38	75.8
		Bottom	12	74.5
		Short 'hard'	77	75.3
		Long Succulent	20	74.8
June 4	23.0	Top	83	74.3
		Middle	53	74.6
		Bottom	22	74.7
June 4	24.0	Top	77	75.5
		Middle	47	75.9
		Bottom	34	74.4

The graduation in susceptibility is definite and marked, and is rather the reverse of what might have been anticipated, in that the upper trusses with short, 'hard' growth are subject to considerably greater injury. This gradation cannot be attributed to differences in moisture content of the buds which shows, if anything, a slight increase from above downwards. An identical graduation of injury has been observed in frosted raspberry bud trusses in the field, but was attributed at the time to greater exposure of the upper trusses to radiation.

Comparisons of the bud trusses of individual canes showed differences not exceeding those occurring between random samples of comparable size, graded as regards position on the cane to correspond with the trusses of an individual cane.

In the course of experiments conducted by Dr J. Grainger on the freezing of potato tubers, it was suggested that the erratic response to chilling - some tubers showing complete disorganization while others of the same sample remained uninjured - was due to the random supercooling of a portion of the sample. Inoculation of each tuber with an ice crystal during refrigeration eliminated this variation, and produced uniform injury at higher refrigeration temperatures.

The response of bud trusses to freezing is also highly characteristic; in the great majority of cases all the buds of a truss coincide in showing the presence or absence of injury; in other words the truss, and not the individual buds, generally behaves as a unit. This may be explained by assuming that ice formation takes place at a focus and spreads throughout the truss. Alternatively, of course, the buds of a single truss may all possess a specific susceptibility, and susceptibility may vary between trusses, or as appears most probable, both assumptions may be partially true.

The question may be decided by splitting a series of trusses into two portions and noting the response of the separate parts to refrigeration.

A series of 60 trusses were so treated, two buds being removed from each truss, and trusses and detached buds subjected to identical refrigerations. The occasions on which trusses and corresponding buds showed similar damage, and on which they differed in response, one showing injury and the other none, are recorded below. Trusses and buds coinciding in showing a complete absence of damage constitute the remainder of the samples.

Date	Treatment (°F.)	Number of trusses coinciding with detached buds in showing injury	Number of trusses differing from detached buds in showing presence or absence of injury
May 5	1 hr 25.8	3	9
" 5	2 hr.24.8	4	7
" 10	2 hr.27.2	0	9

In contrast, refrigeration of entire trusses on May 10th and 18th resulted in damage to every bud in those trusses showing injury, and it is generally the exception to find damage in a proportion only of the buds of a truss, except at the higher refrigeration temperatures where injury is just appearing in the trusses.

The increased susceptibility of wet material to freezing injury which has frequently been recorded (Field, 1942) and which experiments here have also confirmed, may be attributed to the elimination of supercooling by the provision of an ice coating which may be assumed to provide the necessary 'nucleus' from which ice formation may spread to the tissues. Attempts were made to eliminate supercooling in detached buds by subjecting their container, during refrigeration, to intermittent vigorous vibration by means of an electric bell, but without positive results. In potato, the freezing of tissue supercooled 2°F. below its freezing point can be readily induced by mechanical shock, but in very light objects such as buds, a comparable compression effect is more difficult to obtain.

(b) <u>The effect of moisture content on susceptibility</u>

Although difference in moisture content is not responsible for the differences in frost susceptibility found in trusses differing in position on the cane, it can, when produced artificially, cause differences in the degree of injury sustained, as the following experiments indicate.

Freshly cut trusses were compared with trusses whose water content was artificially increased by placing them with their cut ends in water and their tops in a saturated atmosphere for 3 hr., prior to refrigeration. The possibility that surface moisture on the soaked trusses might favour more uniform injury by eliminating supercooling, was circumvented by moistening the bases of the unsoaked trusses, and drying both sets, as far as possible, between a cloth before refrigeration.

The following table records the differences in moisture content, and the corresponding differences in response to refrigeration obtained in three such trials.

Table 36. Effect of increasing moisture content on the susceptibility of raspberry buds to frost injury

Date 1948	Treatment (2 hr. °F.)	Mean moisture content Percentage of fresh weight	Percentage of buds showing injury
May 18	24.5	Fresh trusses 77.9 Soaked " 80.5	35 89
May 21	24.6	Fresh trusses 78.0 Soaked " 83.0	60 100
June 4	24.0	Fresh trusses 73.9 Soaked " 74.4	47 40

It is significant that the water deficit of the buds is considerably greater during the drought period, May 18th to 21st, than following rainfall, June 4th, and that the considerable increase in susceptibility in the soaked trusses is associated with appreciable increase in water content of these trusses, and is not apparent in the final treatment where this increase is small.

C. Apple

A series of refrigerations on seven varieties of apple was made during the Spring of 1948. The amount of material available was somewhat limited and treatments were therefore confined to a standard period of one hour. The size of samples had also to be restricted to 10 trusses of buds.

(i) Symptoms of injury

The sequence of symptoms observed with increasingly severe frost injury have been described in detail by Field (1938), working on two varieties of apple, Court Pendu Platt, and common crab. They agree in all respects with our own observations and may be summarised briefly as follows:-

(1) Loosening of the pericarp skin, commencing at the stylar end, and extending in more severe cases towards the stalk.

(2) Browning or discolouration of the styles, spreading in more severe cases to the placenta.

(3) Extensive browning of the placenta and ovules, and also of the filaments of the stamens.

(4) Browning of the petals and waterlogging of the calyx.

It should be noted that several workers have observed that blossoms and fruitlets may recover from the first category of injury; Field (1942), Dorsey (1940) and Rosen (1936). The pericarp skin reunites with the underlying tissue, more or less completely, though partial failure to do so, or perhaps the partial inhibition of cambial activity in this zone may result in russeting and cracking of the skin of the fruit at a later stage.

In the earlier stages up to pink bud, the stamens turn brown under severe frosting. When in flower or in the hooded petal stage, light frosting, sufficient to cause loosening of the pericarp skin, frequently causes the anthers to turn a light orange colour.

In order to obtain a satisfactory quantitative estimate of injury for the purpose of comparing the susceptibility of varieties, it was decided to allocate buds, flowers and fruitlets to three categories as regards severity of injury, as follows:-

	Buds	Flowers	Fruitlets
1.	Skin loose	Skin loose or skin loose and anthers orange.	Skin loose
2.	As above plus, styles and placenta brown.	As above plus, styles and placenta brown.	As above plus, placenta brown.
3.	As above plus, severe browning of placenta and ovules and perhaps discoloration of petals, sepals, stamens and pericarp.	As above plus, severe browning of placenta and ovules and perhaps discoloration of remaining floral organs.	As above plus, severe browning of placenta and ovules perhaps affecting the whole pericarp.

The three damage categories were allotted the arbitrary factors 1, 2 and 3 in scoring the severity of damage. Thus a sample of 60 buds all showing the third category of damage would show the maximum score of 180, while a similar sample all showing the first category of damage would be scored 60. This system is arbitrary and artificial, as must be any system which attempts to give quantitative expression to qualitative differences, but it does provide a useful, if imperfect, basis for the comparison of varieties, which is certainly better than the mere presence or absence of injury.

(ii) Treatments and Records

The following table summarises the degree of injury, expressed as a percentage of the maximum possible, sustained by the seven varieties in the course of 15 refrigerations. The stages of development of the individual varieties is also indicated. In the final line is given the sum of the percentages of injury in the ten refrigerations, for which complete data for all seven varieties is available. This figure may be regarded as an approximate measure of the comparative susceptibility of these varieties to artificial frost injury over the period under consideration.

Table 37. Percentage injury to the buds and blossoms of seven apple varieties in the course of fifteen refrigerations

Date	Temperature (°F.)	Variety						
		Bramley's seedling	Newton wonder	Crawley Beauty	Edward VII	Cox's Orange Pippin	James Grieve	Ellison's Orange
Apl. 22	27.3	30	-	-	11	22	17	-
" 27	27.0	29	-	-	-	-	-	-
" 29	25.5	13	-	-	33	0	13	22
" 30	25.0	22	-	-	-	-	-	-
May 5	25.8	85	36	30	53	47	47	37
" 6	25.8	81	-	-	-	-	-	-
" 8	26.3	40	33	67	55	42	60	22
" 9	27.5	25	30	56	24	67	7	20
" 10	28.2	8	3	17	0	13	17	0
" 11	25.0	100	83	70	40	93	100	25
" 14	26.0	57	47	33	28	17	40	93
" 17	28.2	3	3	6	6	15	7	0
" 20	26.6	67	72	53	40	73	53	33
" 21	26.5	29	30	20	25	50	44	72
" 25	27.0	17	12	5	13	28	17	5
Total of 10 refrigerations		431	349	357	284	445	392	307
Flowering period) From) To		7/5 14/5	11/5 27/5	17/5 29/5	12/5 25/5	7/5 17/5	5/5 17/5	11/5 20/5

It will be seen that the response to refrigeration is somewhat erratic and that refrigerations on succeeding days at practically the same temperature level, as on May 20th and 21st, yield substantially different results. The greater general susceptibility of Cox's Orange Pippin and Bramley's Seedling, and the relative resistance of Edward VII are notable, however.

The grading indicated by the total of the percentage for ten refrigerations in which all seven varieties were included, given in the final line of the table, are below set against Potter's (1945) grading of these varieties, based on his observations in the National Fruit Trials, following the severe Spring frosts of 1941. He allocates varieties to three categories of susceptibility.

Group 1 **Resistant**	Group 2 **Intermediate**	Group 3 **Susceptible**
(357) Crawley beauty		(431) Bramley's Seedling
(307) Ellison's Orange	(284) Edward VII	(349) Newton Wonder
(392) James Grieve		(445) Cox's Orange Pippin

The chief discrepancies are noted in the varieties Edward VII, outstandingly resistant in our trials, Newton Wonder also more resistant, and James Grieve, relatively susceptible. There is good agreement in respect to the varieties Bramley's Seedling, Cox's Orange Pippin and Ellison's Orange. Both the limited scale of our treatments and also true seasonal differences in susceptibility, together with the fact that our material was obtained from young trees, may severally contribute to these discrepancies. In other respects the results of refrigeration trials appear to differ from the effects of natural frosts; in particular, open blossoms under natural radiation frost conditions always appear to be more severely injured than bud stages. This is not apparent in refrigeration trials.

(iii) Temperatures causing damage

Inspection of the results does not suggest that susceptibility increases markedly between green bud and open blossom stages, and certainly not on the scale of strawberry. The data is inadequate to determine the magnitude of such a change though it would appear unlikely to exceed 1°F. During the flowering period slight injury, loosening of the pericarp skin, appears in the neighbourhood of 28°F. and injury becomes severe and widespread at temperatures of 25°F. and below. Potter (1945) notes that in the field, blossom trusses appear to be most susceptible in the green bud and the open blossom stages, and in comparison the pink bud stages shows some degree of resistance. In the case of the green bud stage, however, injury is chiefly confined to loosening of the pericarp skin and does not affect the ovules.

A comparison of buds of one variety, Crawley Beauty, selected in different stages of development, but on the same date, and subjected to the same refrigeration treatments, showed the following percentage injury to buds in the green and pink bud stage, scored on the system already described.

Green bud	53%
Pink bud	49%

A similar comparison of open flower and pink bud stages show the following injury:-

Pink bud	44%
Open flower	61%

The two comparisons are made separately since open flowers, pink bud and green bud stages are not all present on young trees at the same time. In neither case is the difference large. It should be noted that this differs from a comparison of the relative susceptibility when most of the trusses are in the green bud stage, with that when the tree is, in general, in the pink bud stage, or in full flower.

Under field conditions, the greater susceptibility of open blossom to injury can probably be attributed to the direct exposure of the floral organs, and in particular the styles, to cooling by radiation, and to the large surface presented by the open flower to the sky. Potter notes that blossoms which escape injury in a killing frost are usually situated on the under side of the flower cluster where they are protected from direct radiation loss.

SUMMARY

Section IV

A series of refrigerations was carried out on the cut blossom trusses of strawberry, raspberry and apple. Their susceptibility to frost injury was determined throughout their development from bud to fruitlet stage.

Strawberry

In the variety L.R.19, susceptibility rose sharply during development. In the sessile bud stage, 50% of blossom buds showed injury with 1 hr's treatment at 22°F., while at the period of maximum flowering, corresponding injury was sustained at 27.5°F. Greenhouse grown plants brought into flower about 4 weeks earlier, differed little in their susceptibility at corresponding developmental stages. Incidence of damage increased with longer refrigeration periods.

A comparison of the variety Auchincruive Climax with L.R.19, showed the former to be rather more resistant to injury due, probably, to its later flowering habit.

While the stage of development of the individual bud partly determines its susceptibility, the susceptibility of all stages tends to increase with the advancing season.

Raspberry

Refrigerations carried out in 1947 on the varieties Burnetholme Seedling and Norfolk Giant, showed that increase in susceptibility during the development of the blossom trusses was relatively small; from 24.5°F. in the early bud stage, to 27.0°F. when approaching full flower, in the case of Burnetholme Seedling and a corresponding increase from 26.0°F. to 27.5°F. with Norfolk Giant.

The effect of drought conditions was noted in the course of the refrigerations made in Spring, 1948. The development of drought was accompanied by a sharp fall in the temperature causing 50% injury, from 25.5/25.8°F. to 23.2/23.5°F. Progressively greater injury was induced by increasing the refrigeration period from ½ hr to 2 hr.

Varietal trials with 14 varieties showed wide differences in susceptibility, ranging from 90% injured buds in the variety St Walfrid, to 8% and 9% respectively, in the East Malling varieties 32/41 and M 32/138, under identical refrigeration treatments.

An attempt was made to determine the cause of the wide variation in the response of apparently uniform bud material, to refrigeration treatments. Position of the blossom truss on the cane was found to affect markedly, its susceptibility. Susceptibility increased from below upwards, the incidence of injured buds being two to six times greater in the top, than in the bottom trusses. Variation in the water content of the buds did not account for the difference. Differences in susceptibility between individual canes was small in comparison with the vertical gradation in susceptibility.

All the buds of an individual truss generally react identically in showing presence or absence of injury. This uniformity of response is destroyed when individual buds are separated from the truss. The separated buds then behave in an entirely random manner in showing presence or absence of injury. The suggested cause is erratic supercooling of the material. It is believed that the onset of ice formation in any part of the tissue of the truss results finally, in injury to all the buds of that truss. Attempts to eliminate supercooling by violent intermittent vibration during refrigeration were unsuccessful. An artificial increase in the water content of cut trusses, induced by allowing them to imbibe water through their cut ends in a saturated atmosphere, was found to increase the incidence of injury, although the effect could only be produced under partial drought conditions on plants whose tissues showed considerable moisture deficit.

Apple

Comparative trials of the frost susceptibility of seven commercial varieties of apple were undertaken; namely, Cox's Orange Pippin, Bramley's Seedling, James Grieve, Newton Wonder, Ellison's Orange, Edward VII and Crawley Beauty.

The somewhat erratic response of the material to refrigeration treatments indicated that the accurate assessment of varietal susceptibility at each stage of development would demand a much more extensive investigation with larger samples, than were here available. On the basis of a mean assessment of relative susceptibility throughout development from bud to blossom, the seven varieties can be ranged in the following sequence.

Bramley's Seedling) Susceptible
Cox's Orange Pippin)

James Grieve

Crawley Beauty)
Newton Wonder)

Ellison's Orange

Edward VII Resistant

No great change occurs in susceptibility from green bud to fruitlet stage. A comparison of buds in the green bud and pink bud stages occurring simultaneously on the same tree also showed no significant difference in relative susceptibility. Neither did comparable collections of material in the pink bud and open flower stages.

Slight injury began to manifest itself in the neighbourhood of 28°F. with one hour treatment and injury became severe and widespread at 25°F. and below.

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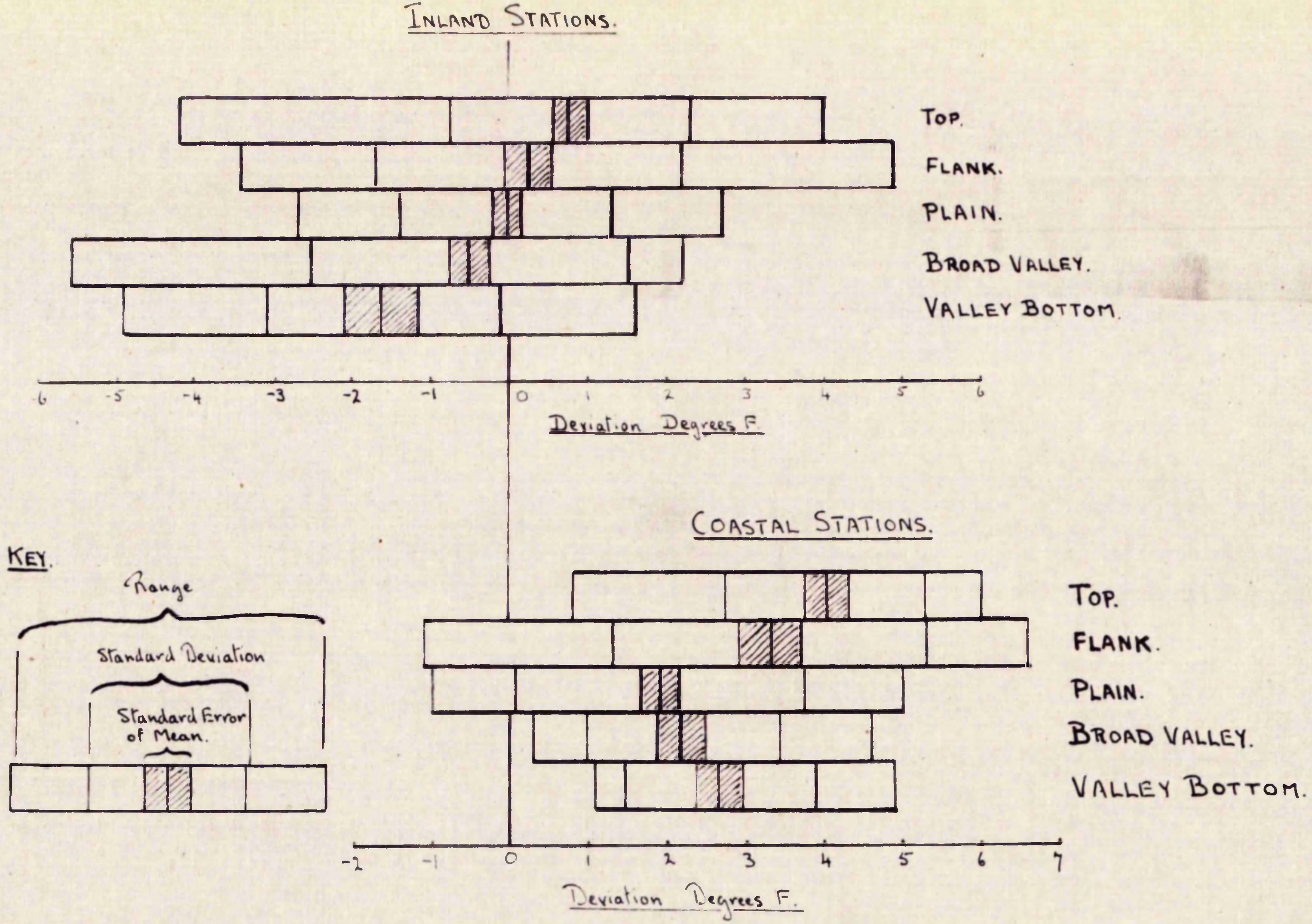


Figure 1. Diagram illustrating the deviation of topographic class means from the area mean, for coastal and inland stations, and the range of deviations within each class. Based on combined data for April and May 1939 to 1945.

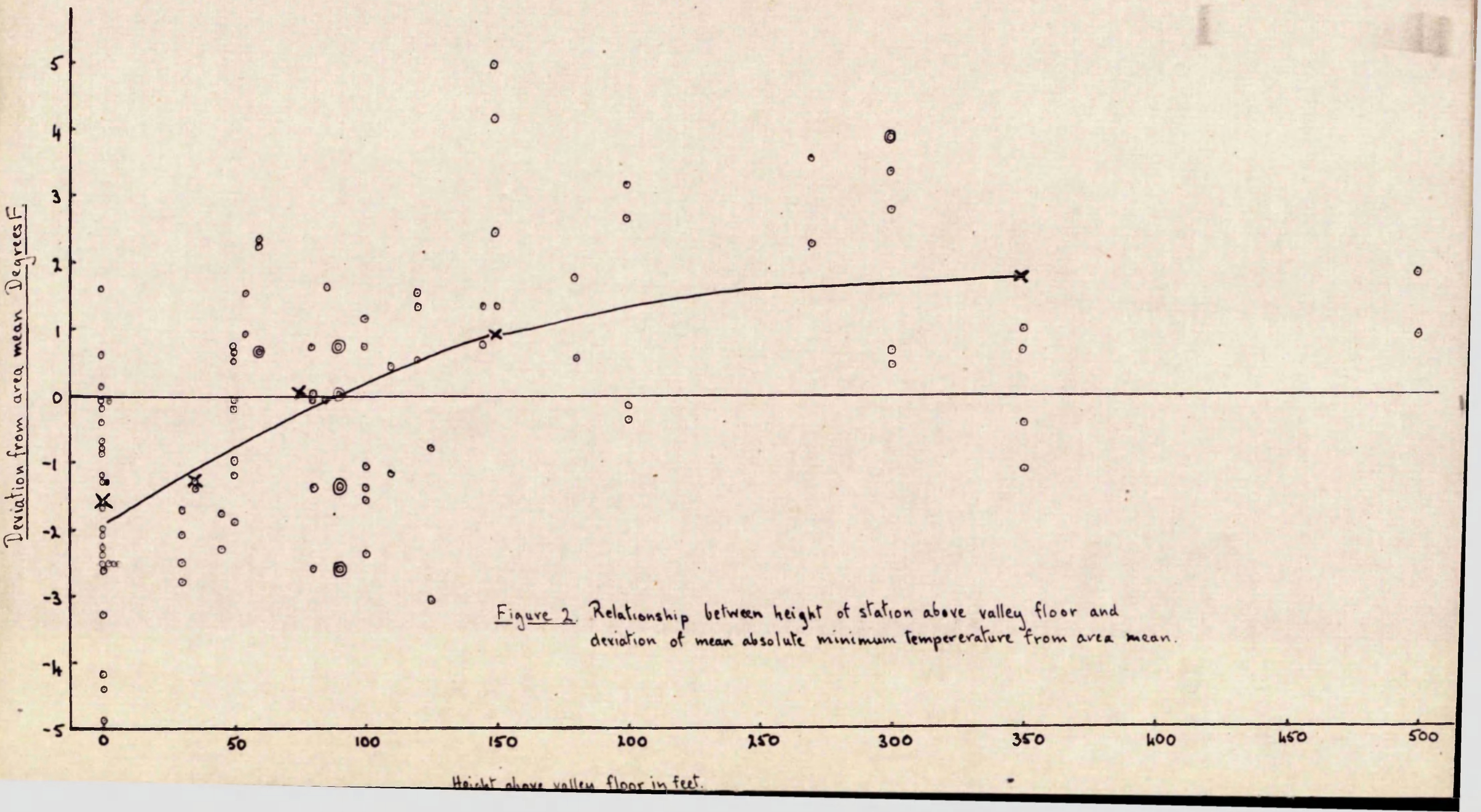


Figure 2. Relationship between height of station above valley floor and deviation of mean absolute minimum temperature from area mean.

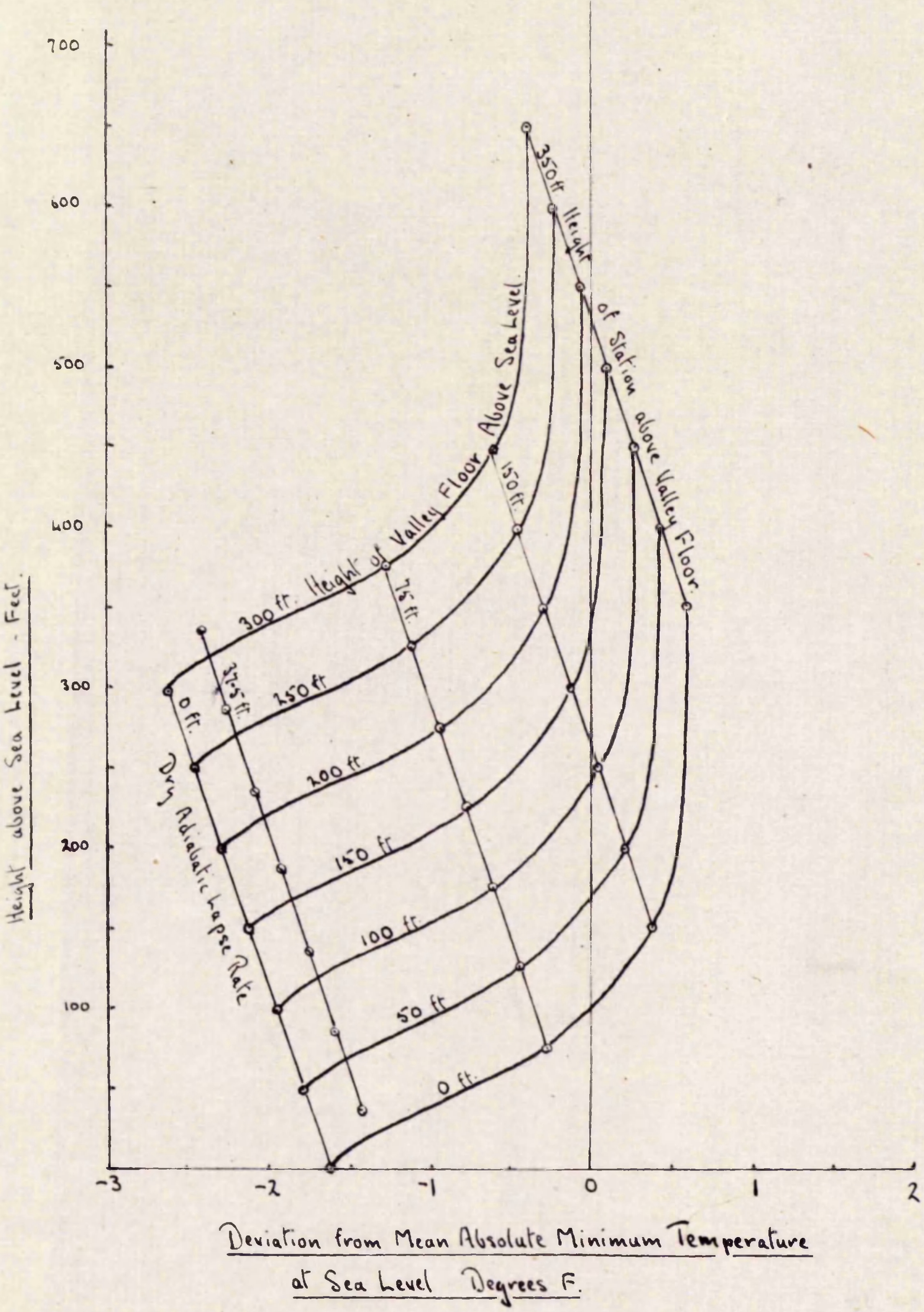
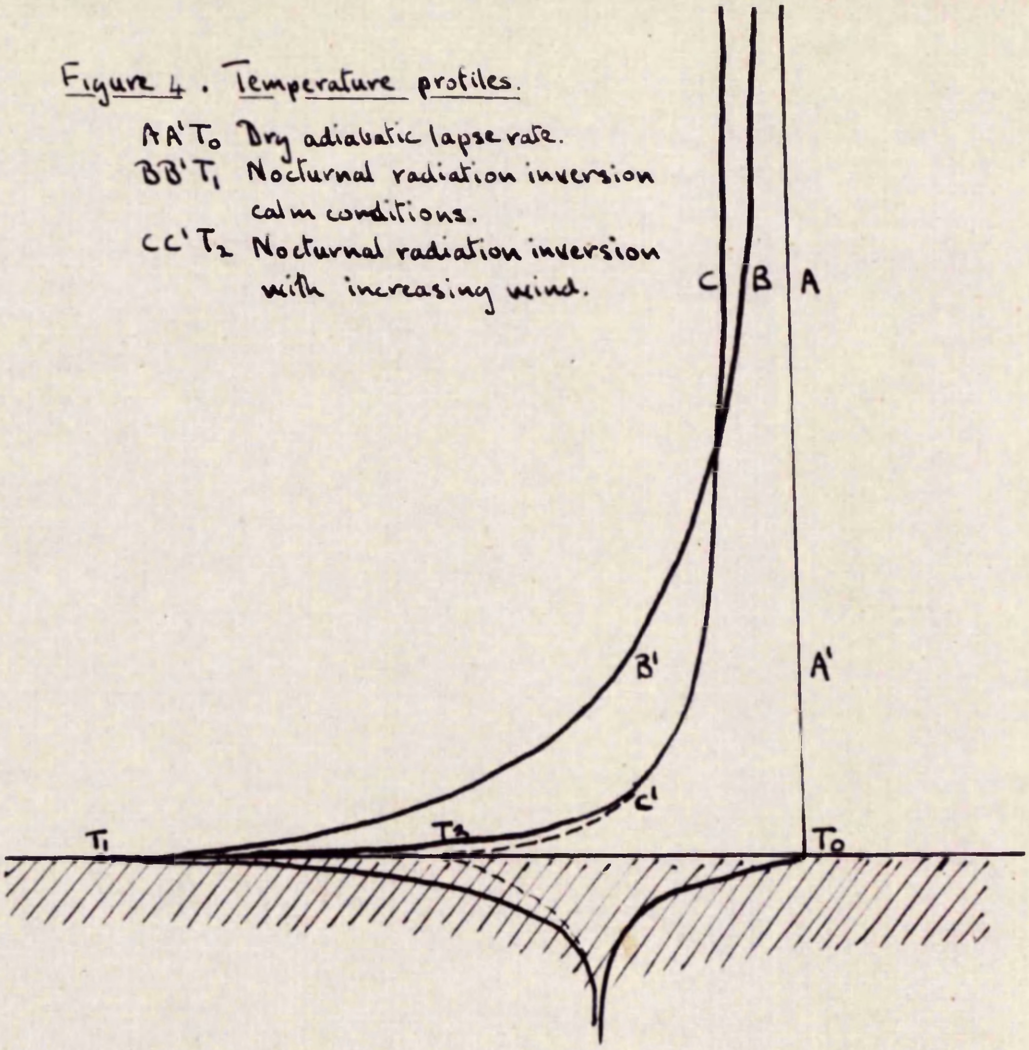


Figure 3. Diagram illustrating the combined influence of the effect of height of location above valley floor and altitude on minimum temperature under radiation frost conditions.

Figure 4. Temperature profiles.

AA'T$_0$ Dry adiabatic lapse rate.
BB'T$_1$ Nocturnal radiation inversion calm conditions.
CC'T$_2$ Nocturnal radiation inversion with increasing wind.



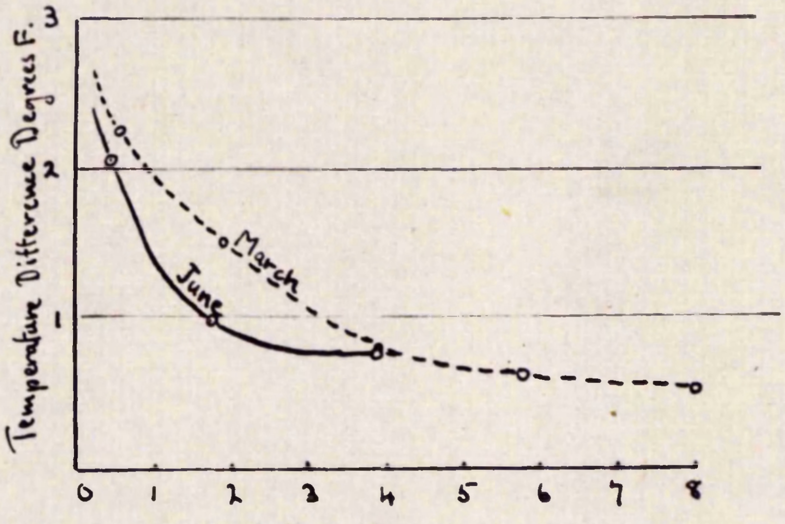


Figure 5. Relationship between temperature inversion from 30 cms to 1·2 metres and wind velocity at 13·4 metres

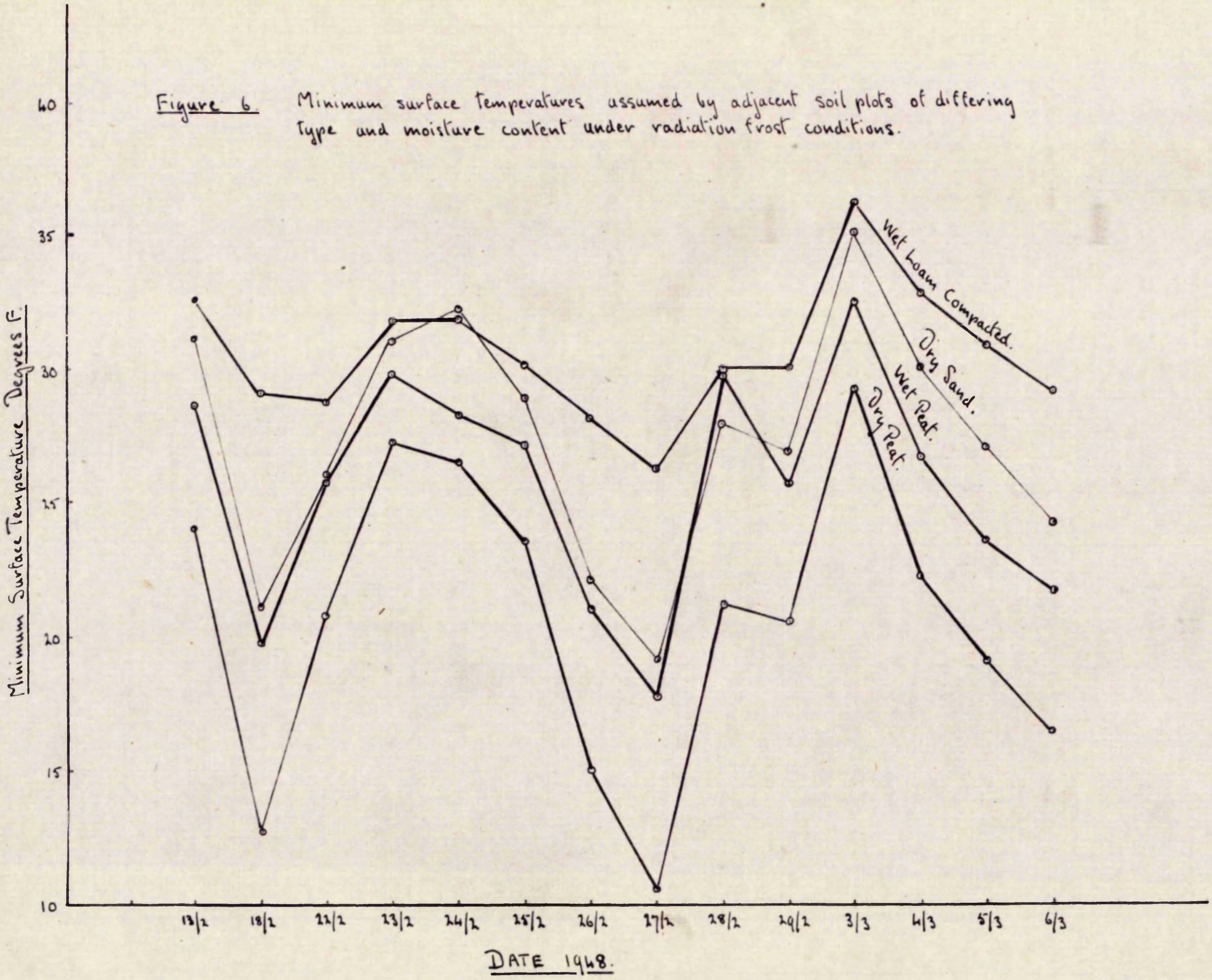


Figure 6. Minimum surface temperatures assumed by adjacent soil plots of differing type and moisture content under radiation frost conditions.

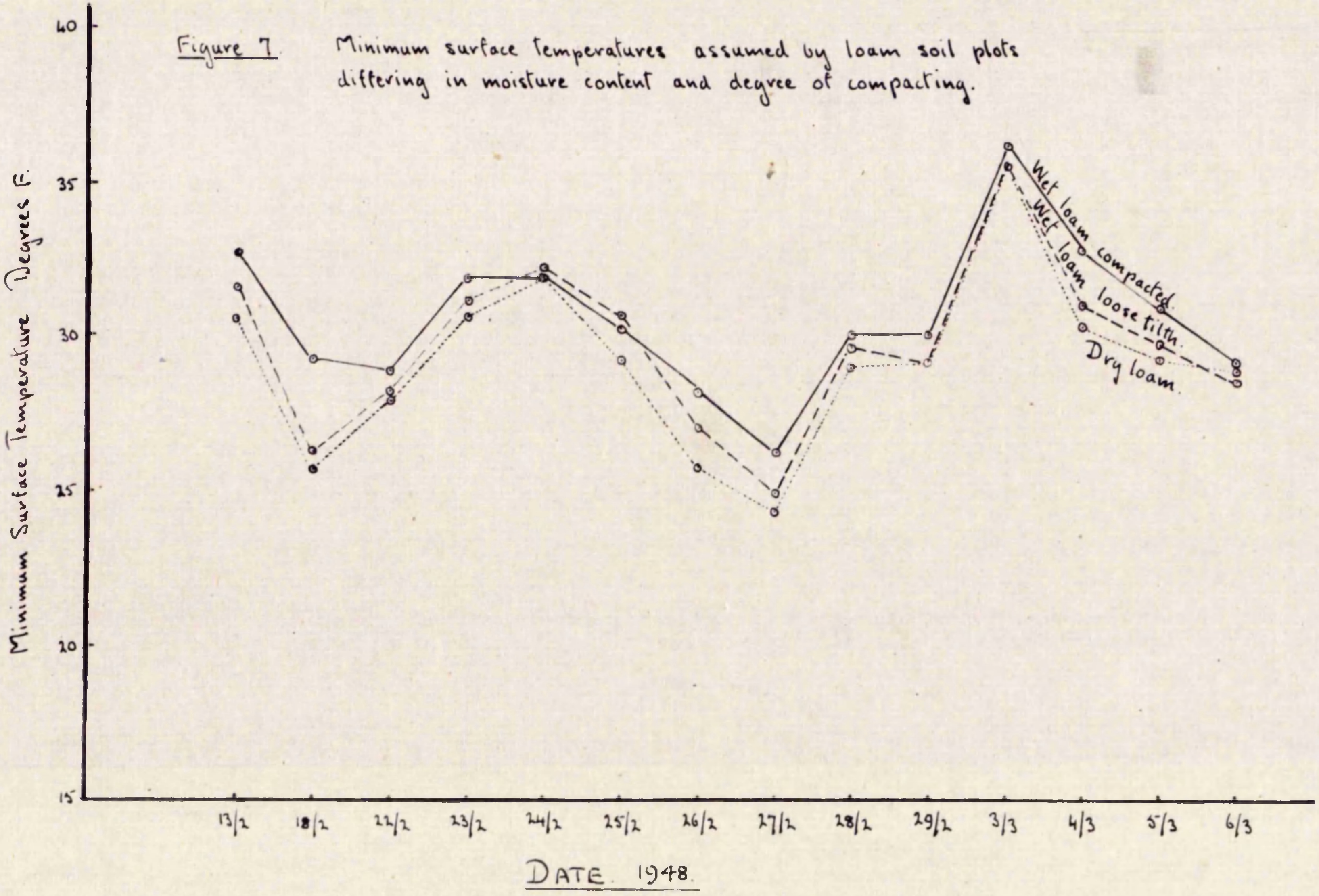
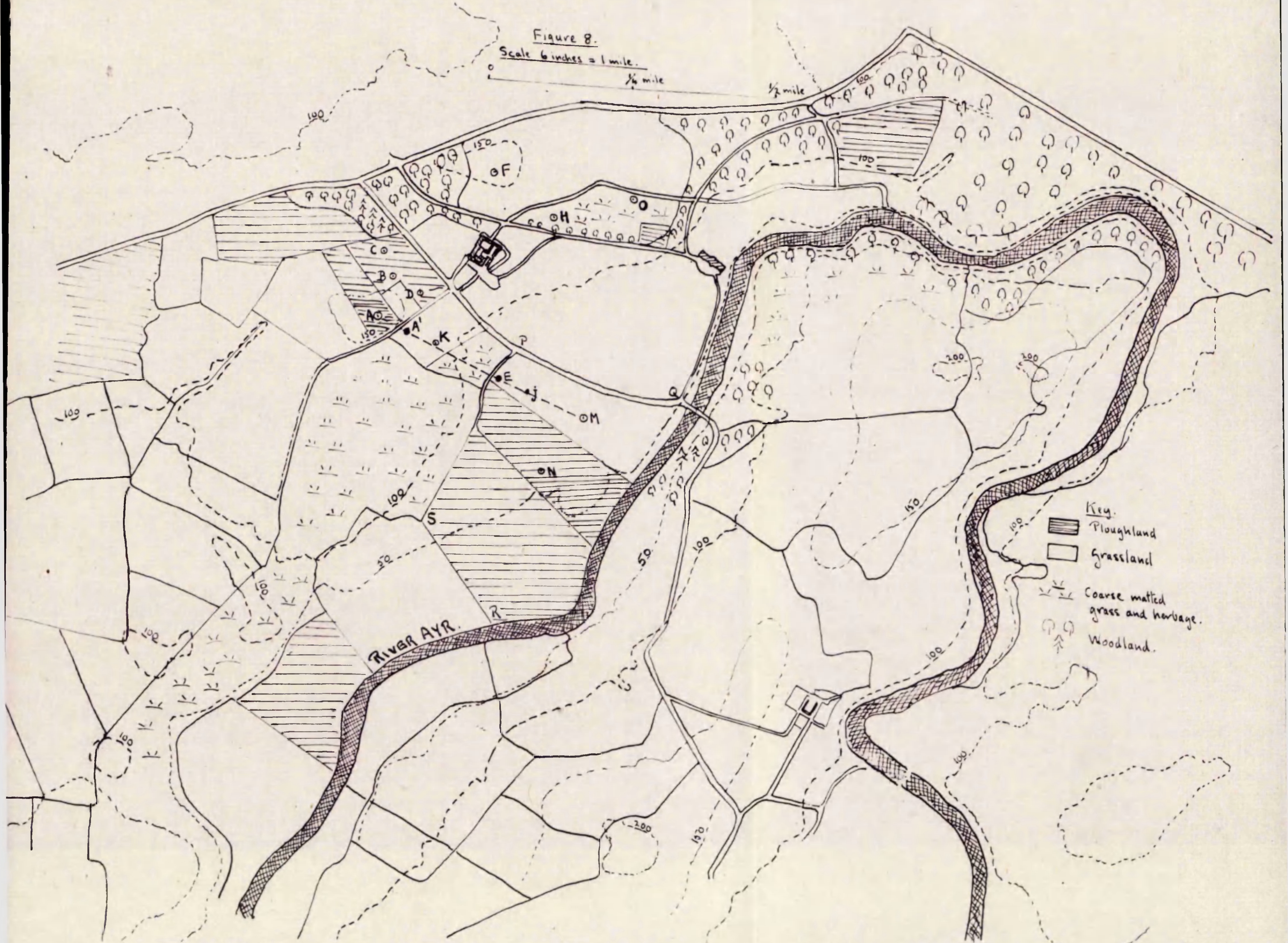


Figure 7. Minimum surface temperatures assumed by loam soil plots differing in moisture content and degree of compacting.

Figure 8.

Scale 6 inches = 1 mile.



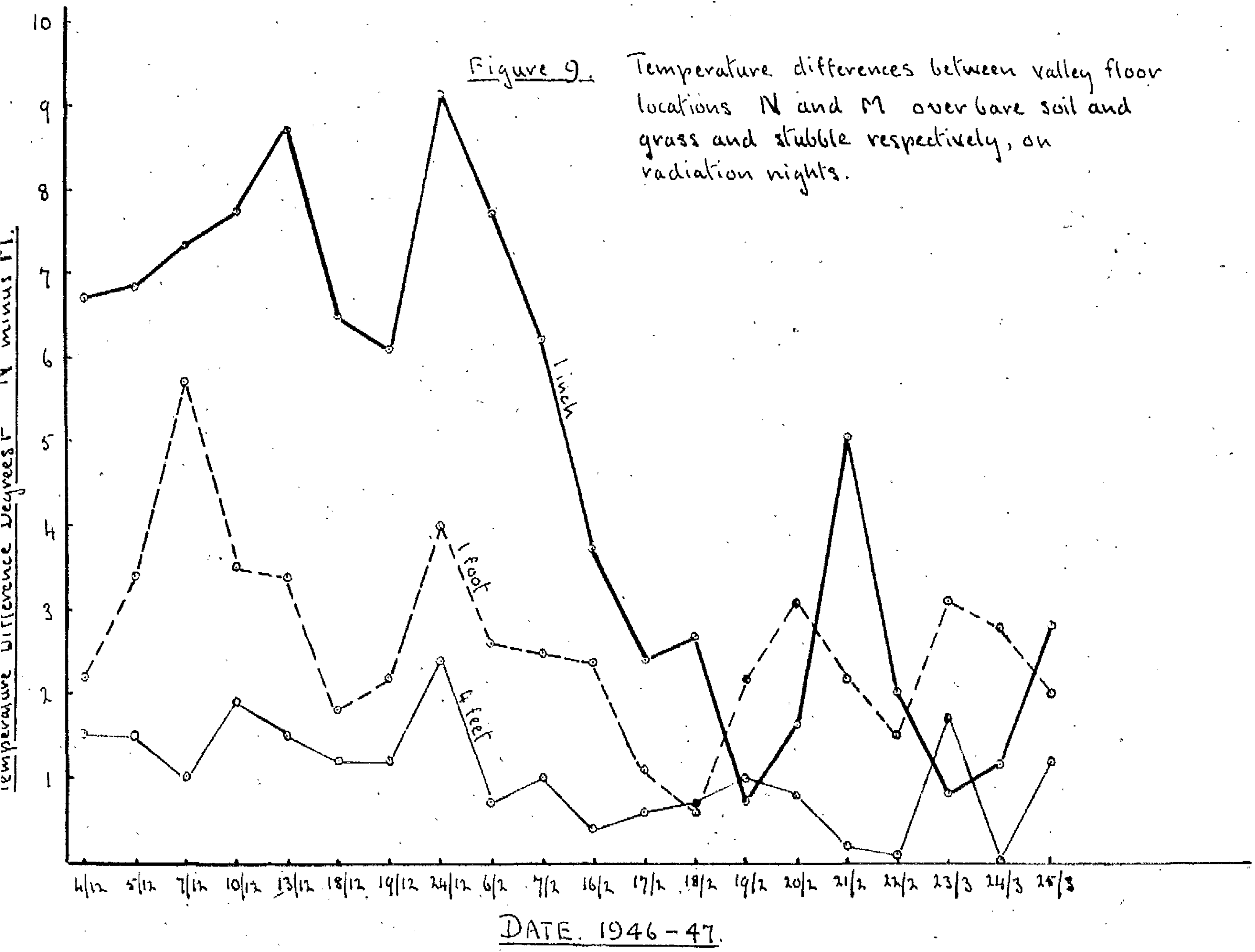


Figure 9. Temperature differences between valley floor locations N and M over bare soil and grass and stubble respectively, on radiation nights.

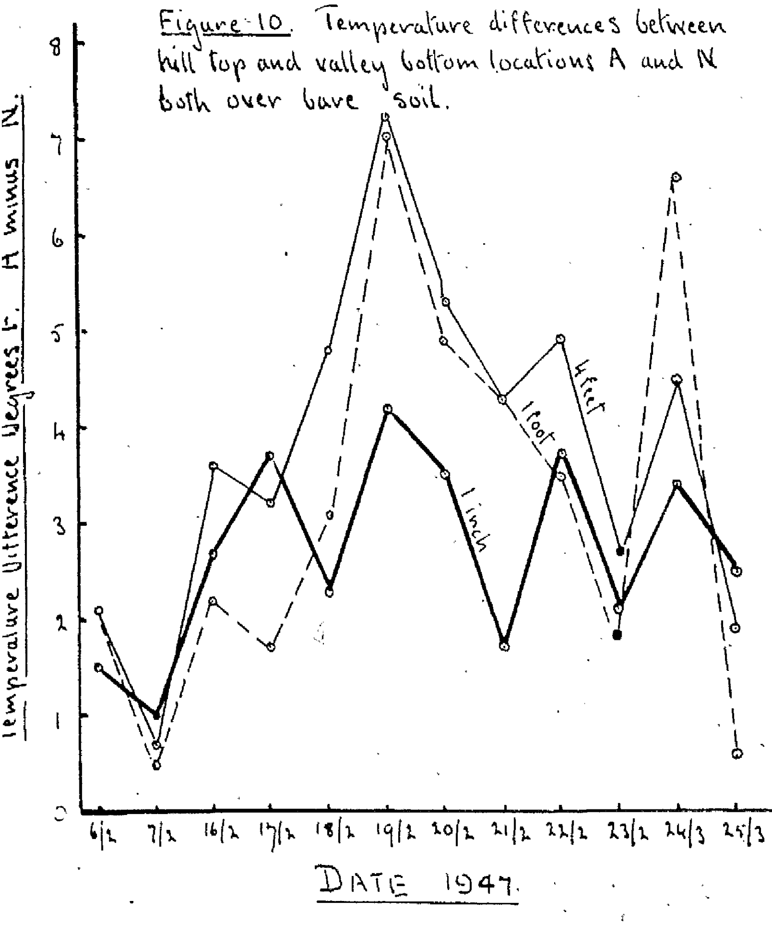


Figure 10. Temperature differences between hill top and valley bottom locations A and N both over bare soil.

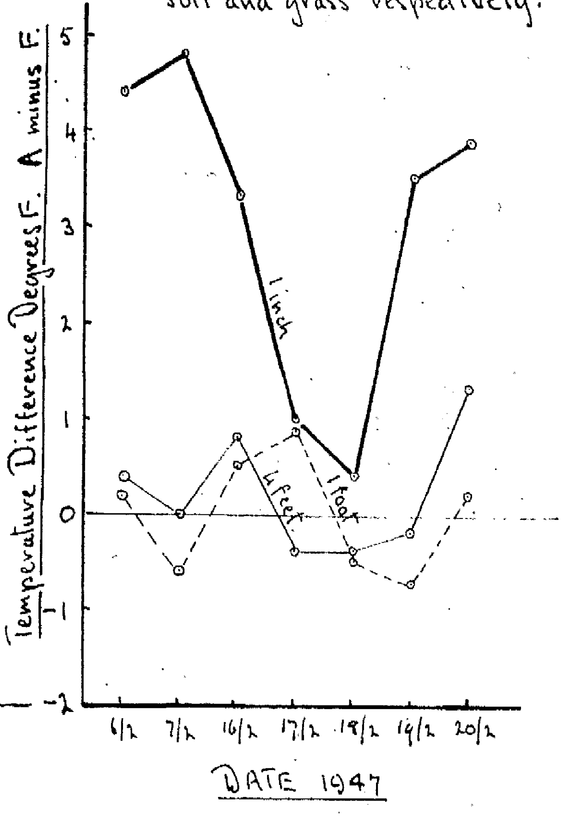


Figure 11. Temperature differences between hill top locations A and F over bare soil and grass respectively.

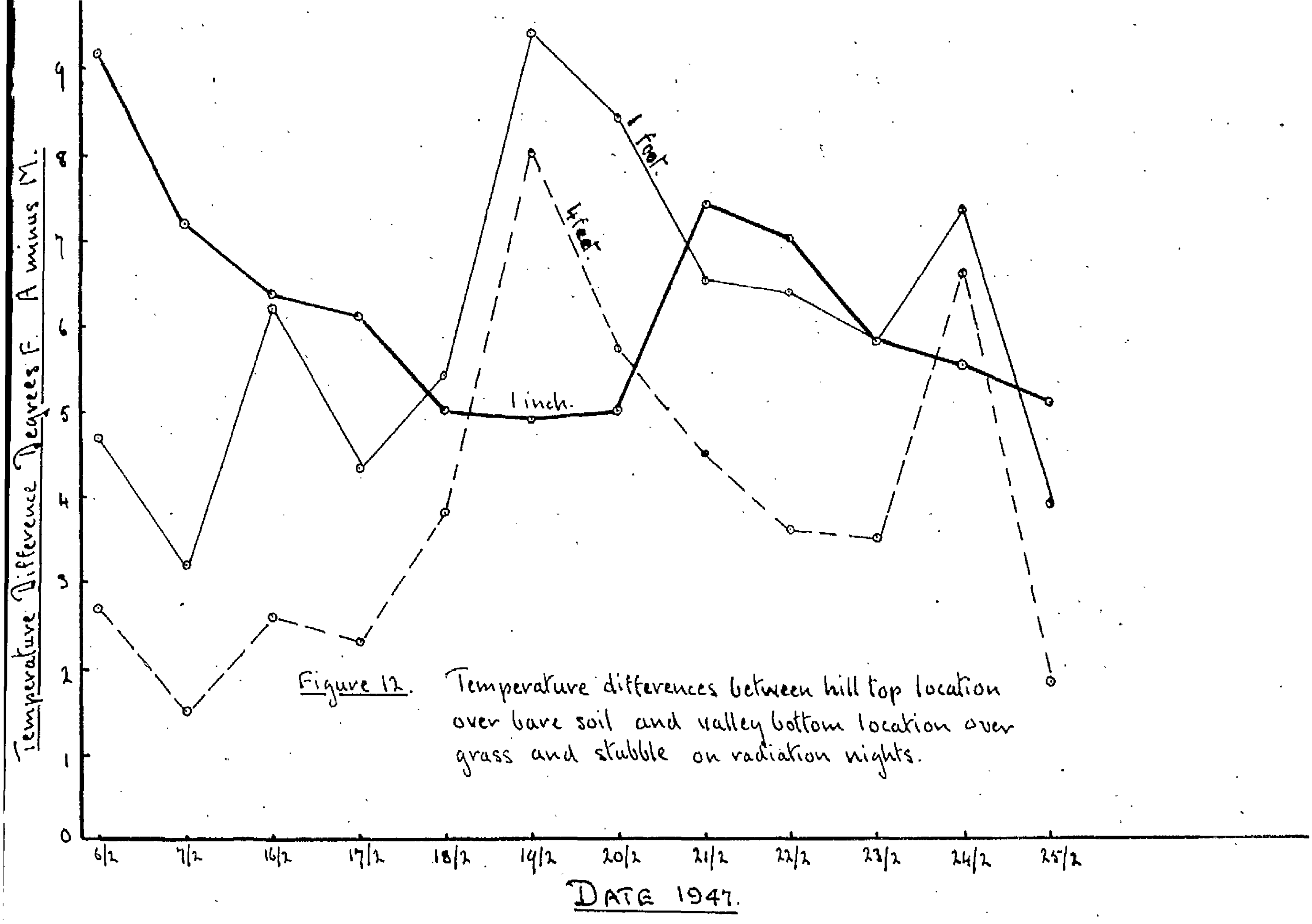
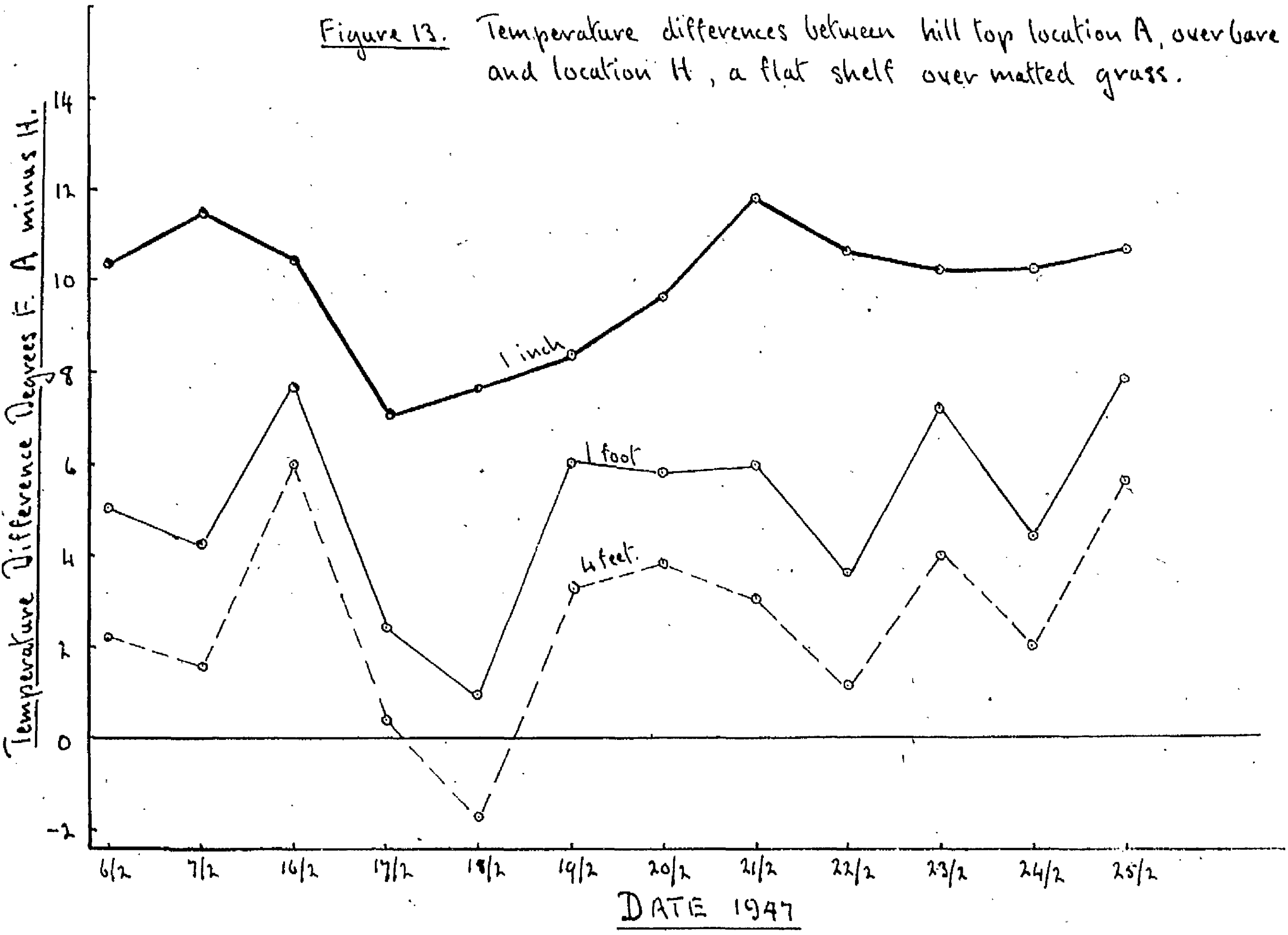


Figure 12. Temperature differences between hill top location over bare soil and valley bottom location over grass and stubble on radiation nights.

Figure 13. Temperature differences between hill top location A, over bare soil, and location H, a flat shelf over matted grass.



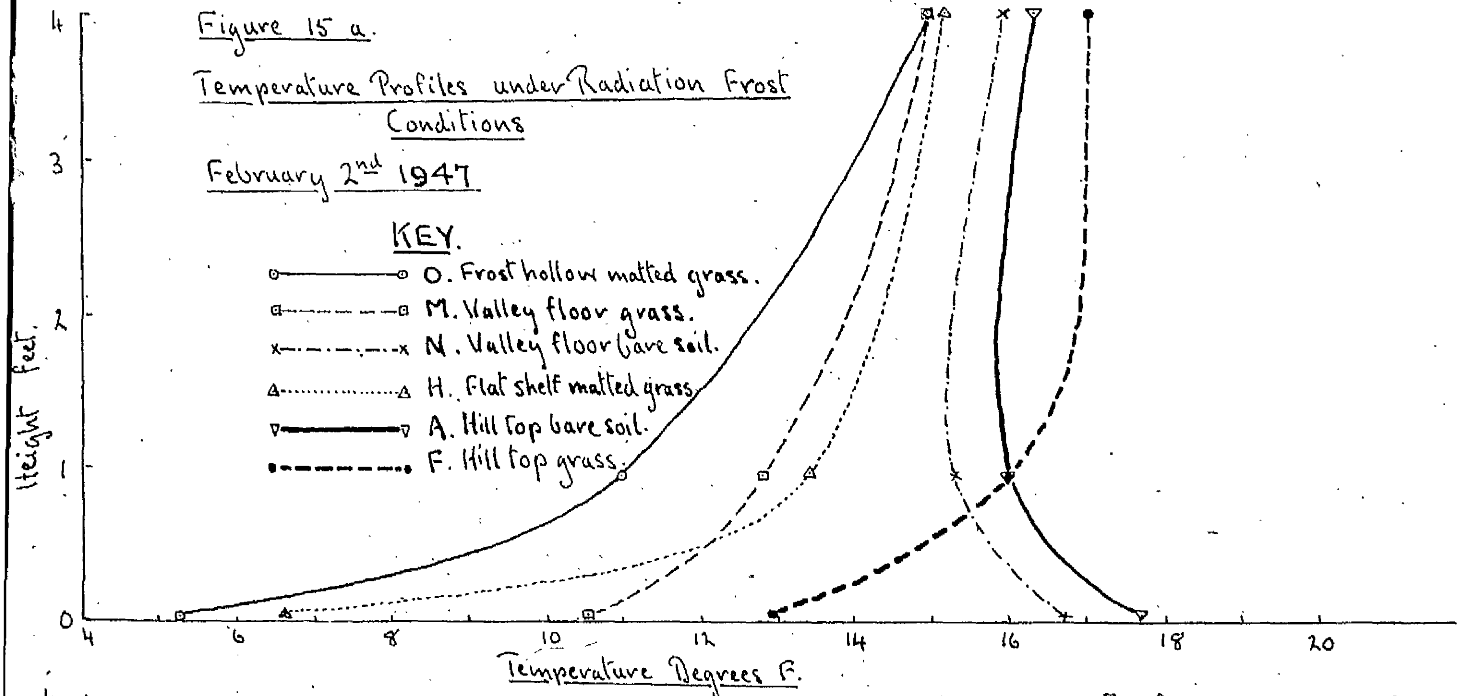


Figure 15 a.

Temperature Profiles under Radiation Frost Conditions

February 2nd 1947

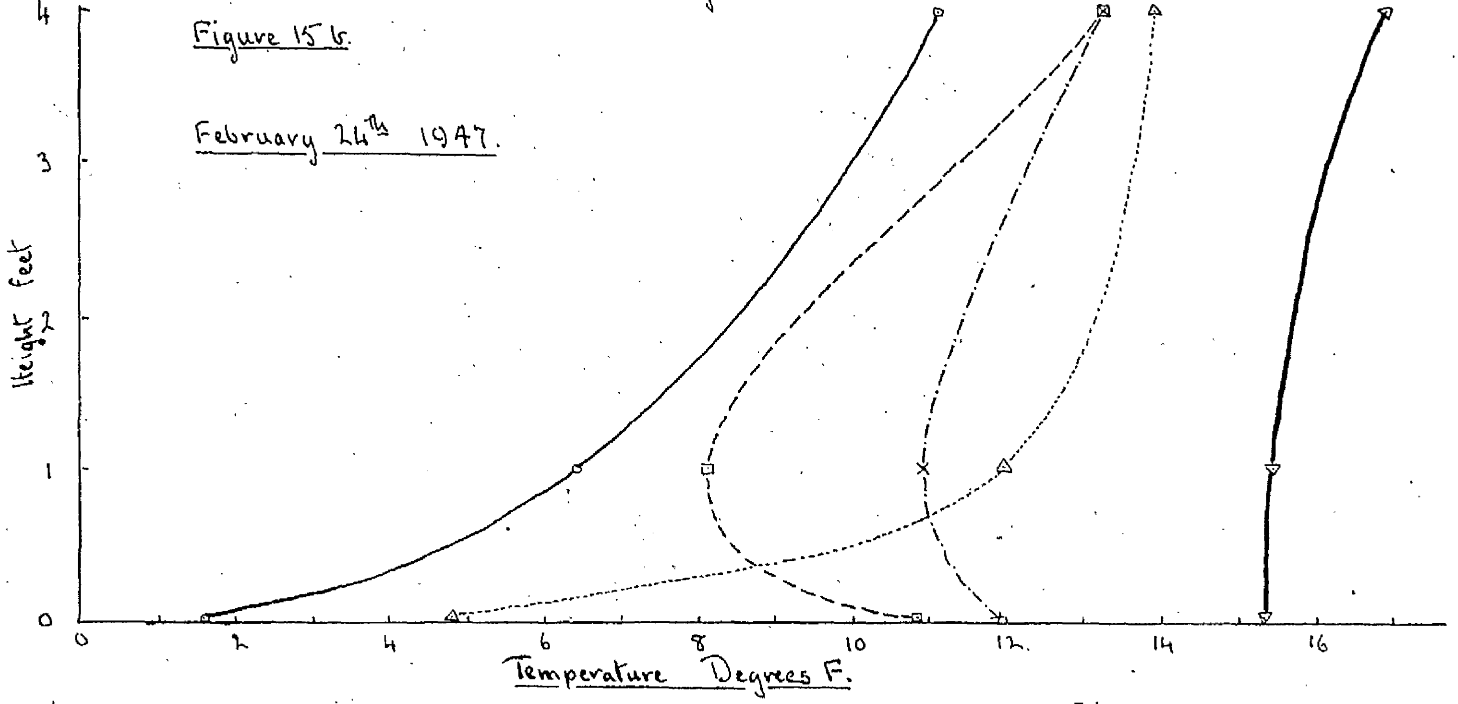


Figure 15 b.

February 24th 1947.

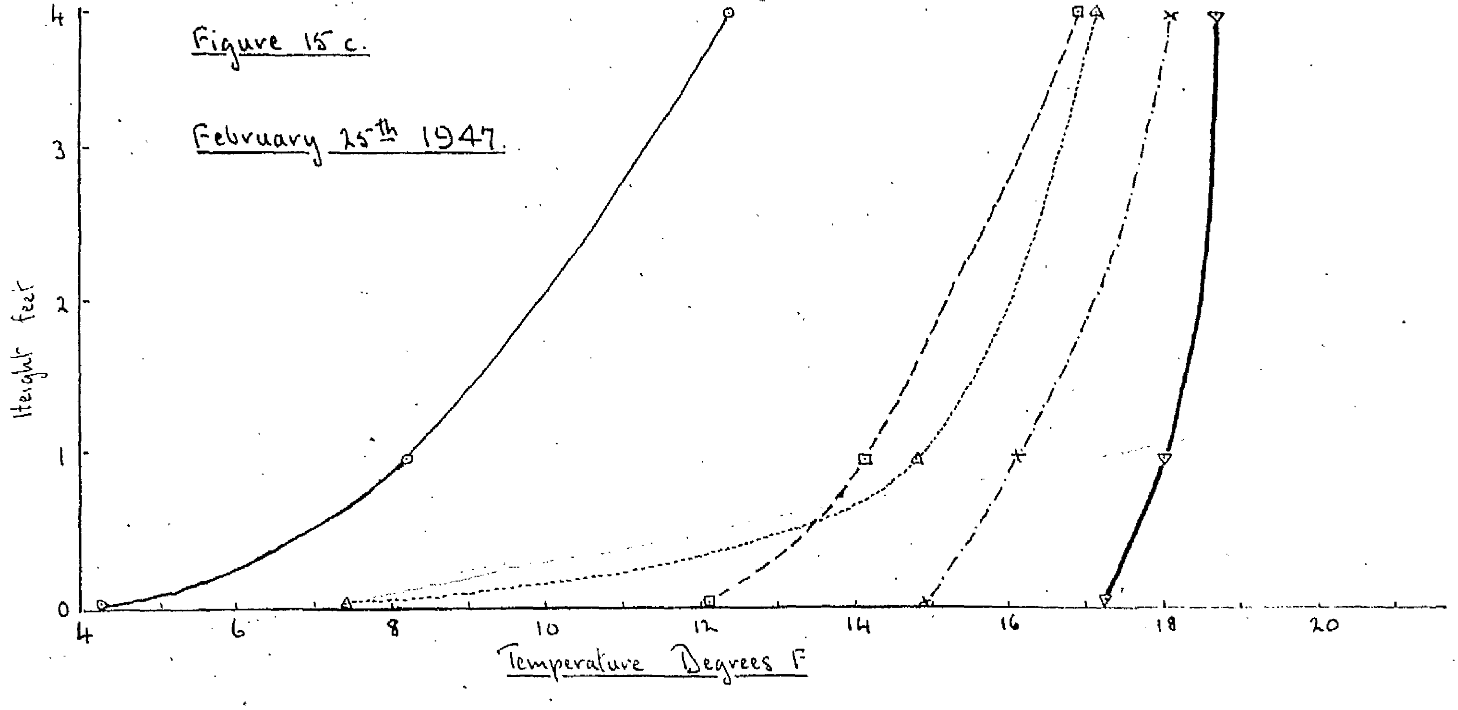


Figure 15 c.

February 25th 1947.

Figure 15 d:

February 19th 1947.

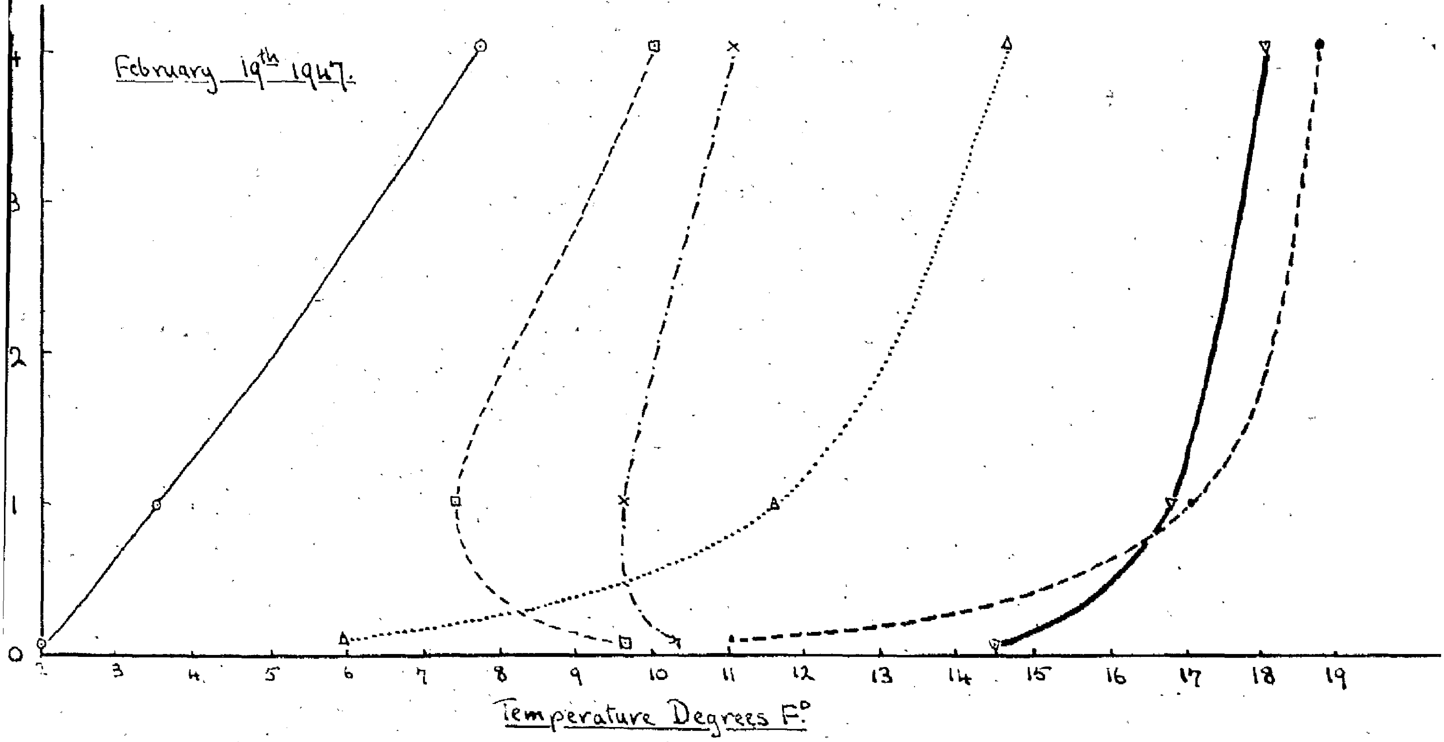
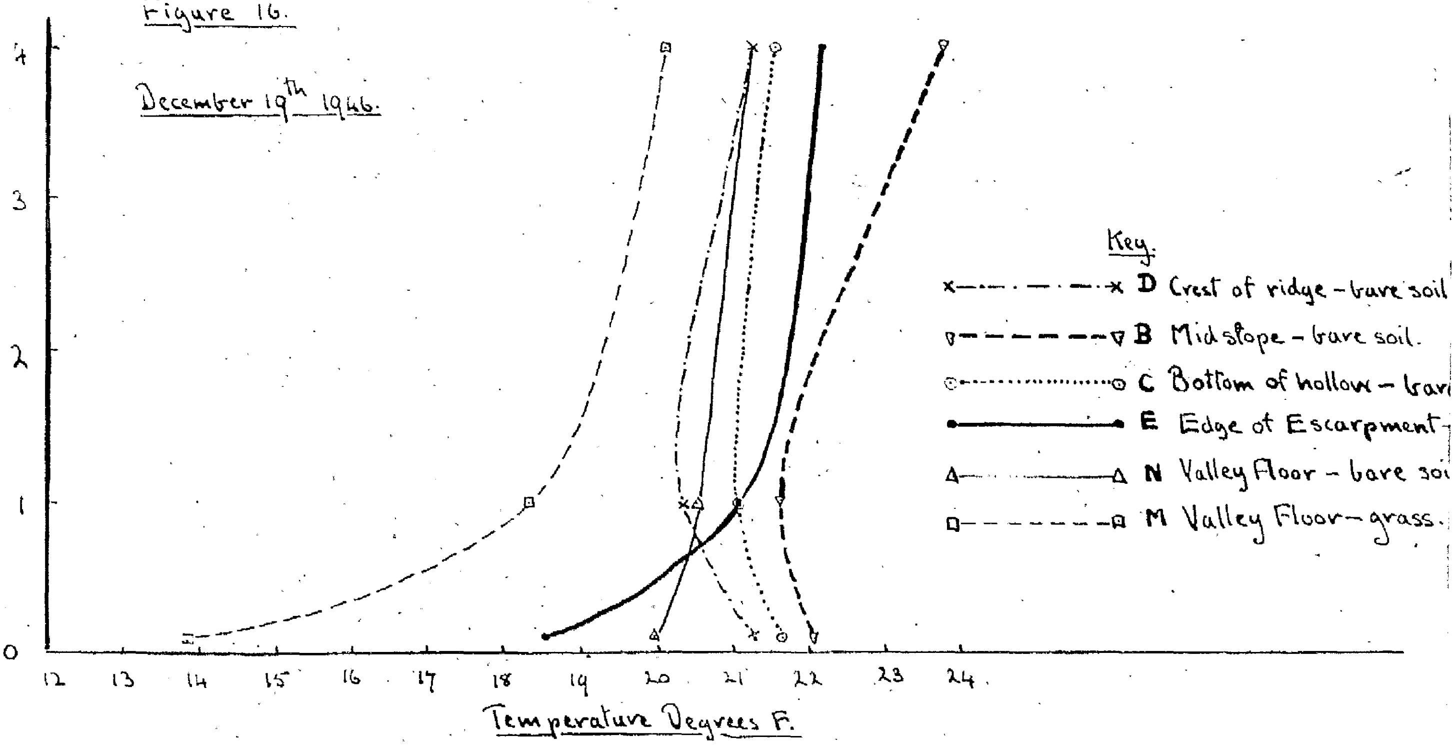


Figure 16.

December 19th 1946.



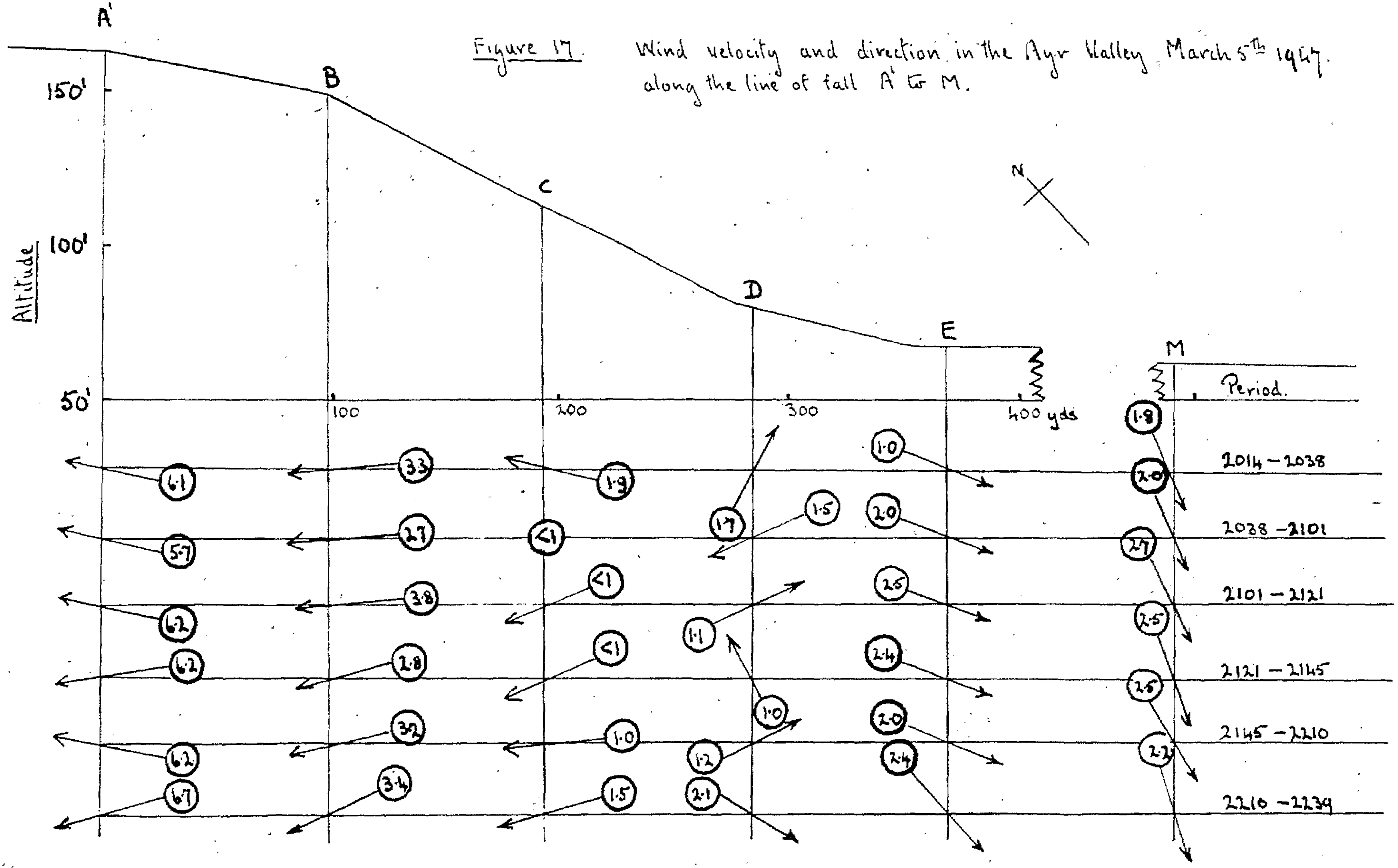
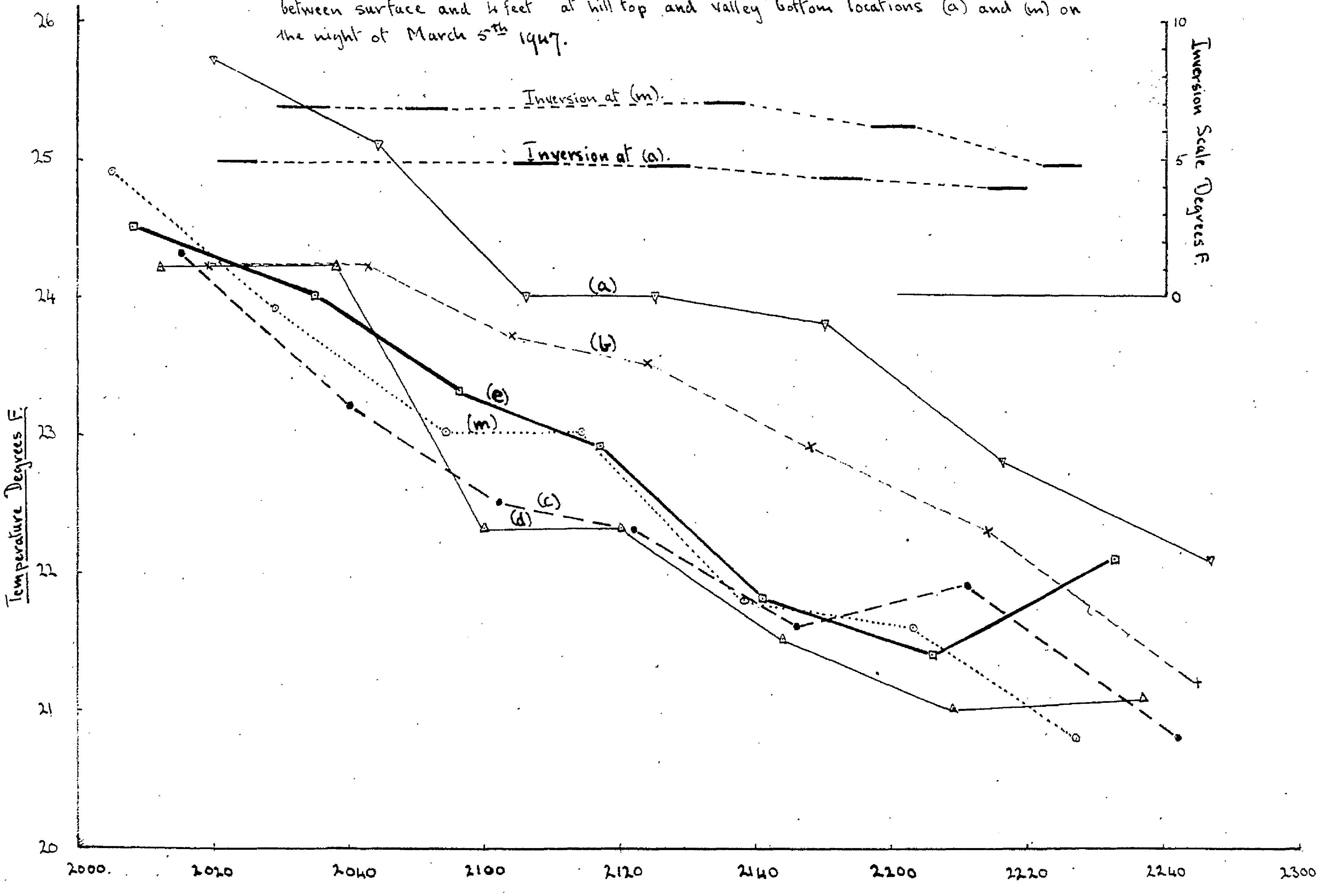


Figure 17. Wind velocity and direction in the Ayr Valley March 5th 1947. along the line of fall A' to M.

Figure 18. Temperature fall at locations (a) to (m) in the Ayr Valley, and inversion conditions between surface and 4 feet at hill top and valley bottom locations (a) and (m) on the night of March 5th 1947.



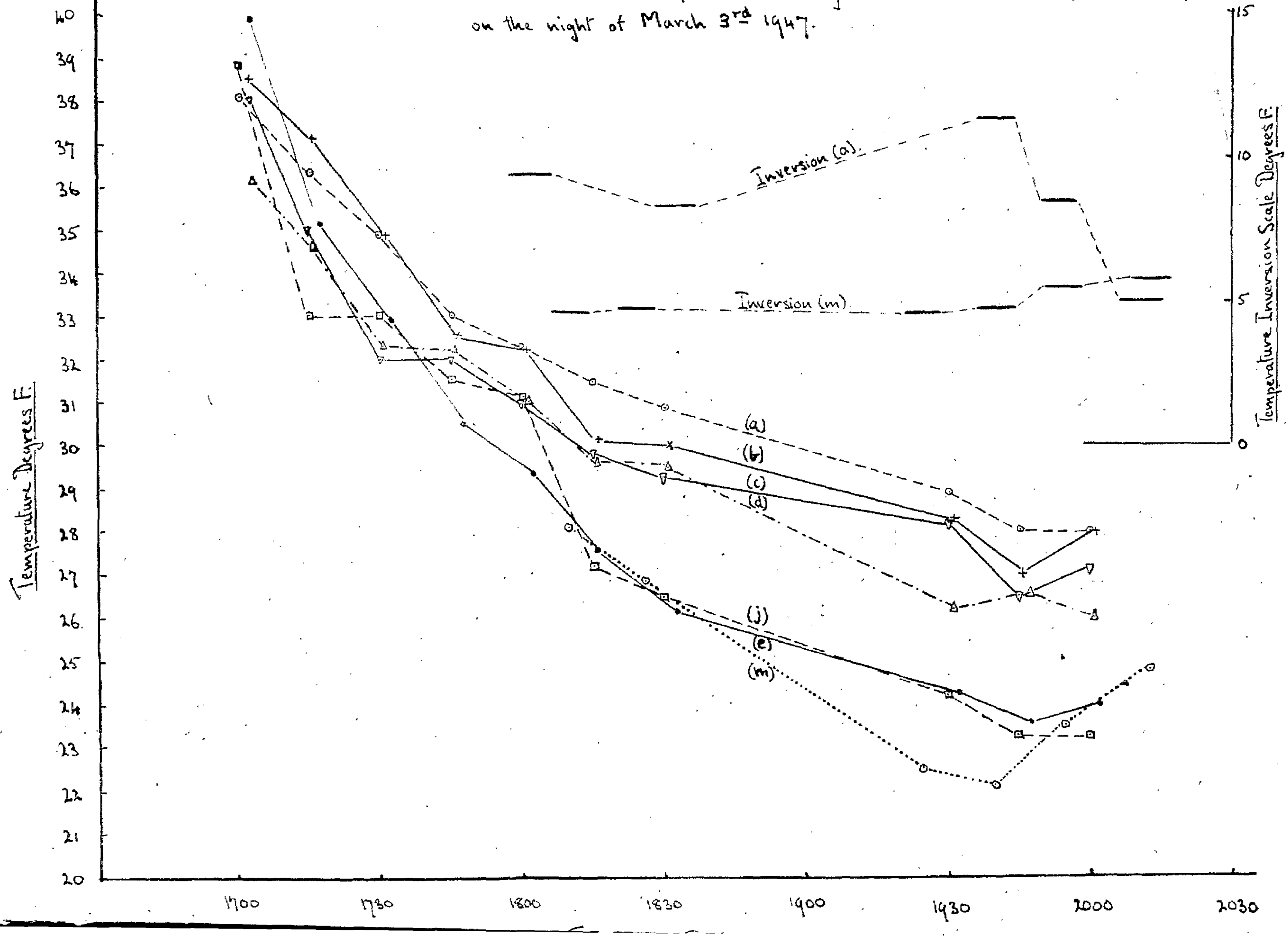


Figure 20. Temperature fall at locations (a) to (m) in the Ayr Valley, and inversion conditions on hill top and on valley floor between surface and 4 feet, on the night of March 3rd 1947.

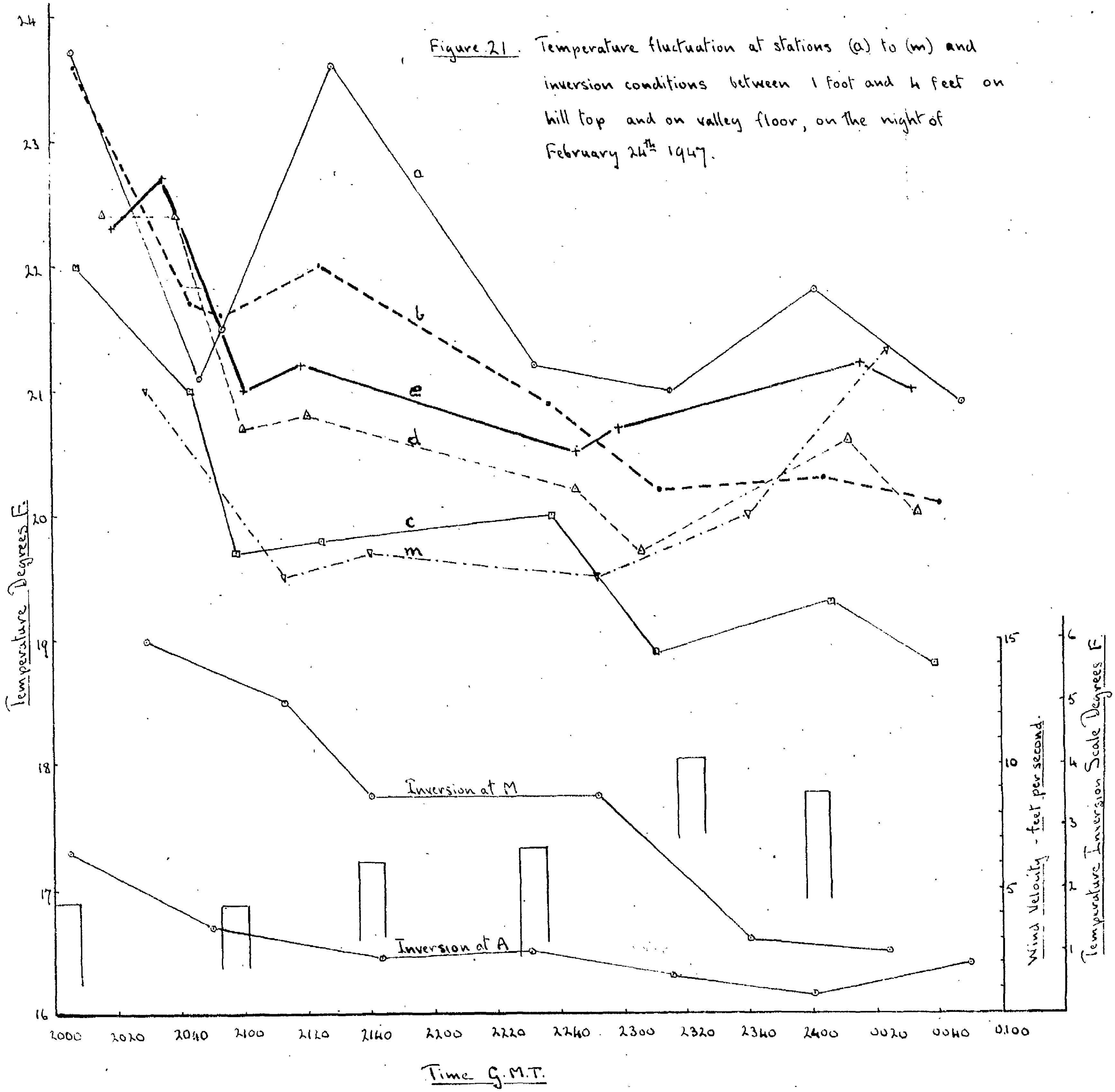


Figure 21. Temperature fluctuation at stations (a) to (m) and inversion conditions between 1 foot and 4 feet on hill top and on valley floor, on the night of February 24th 1947.

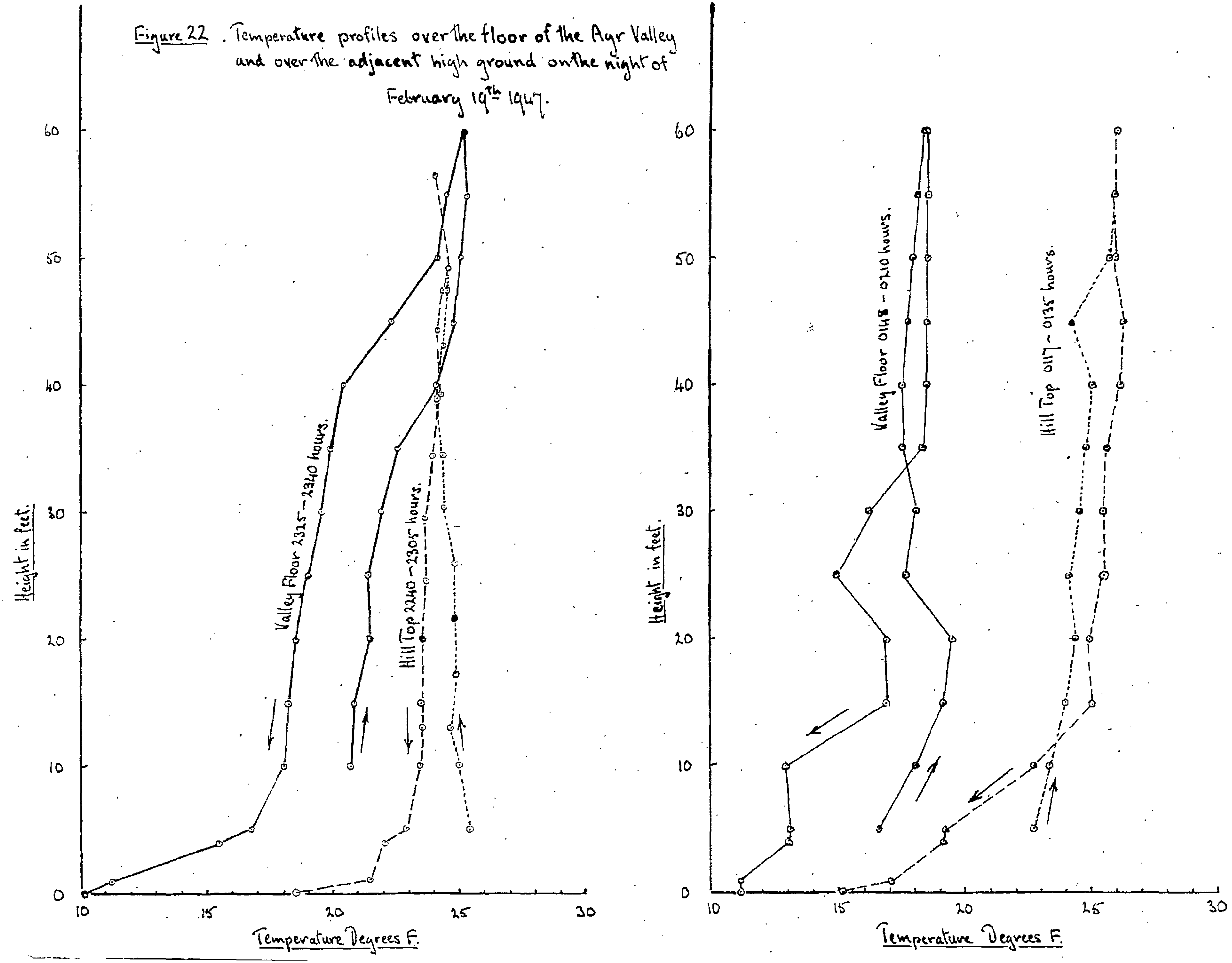


Figure 22. Temperature profiles over the floor of the Ayr Valley and over the adjacent high ground on the night of February 19th 1947.

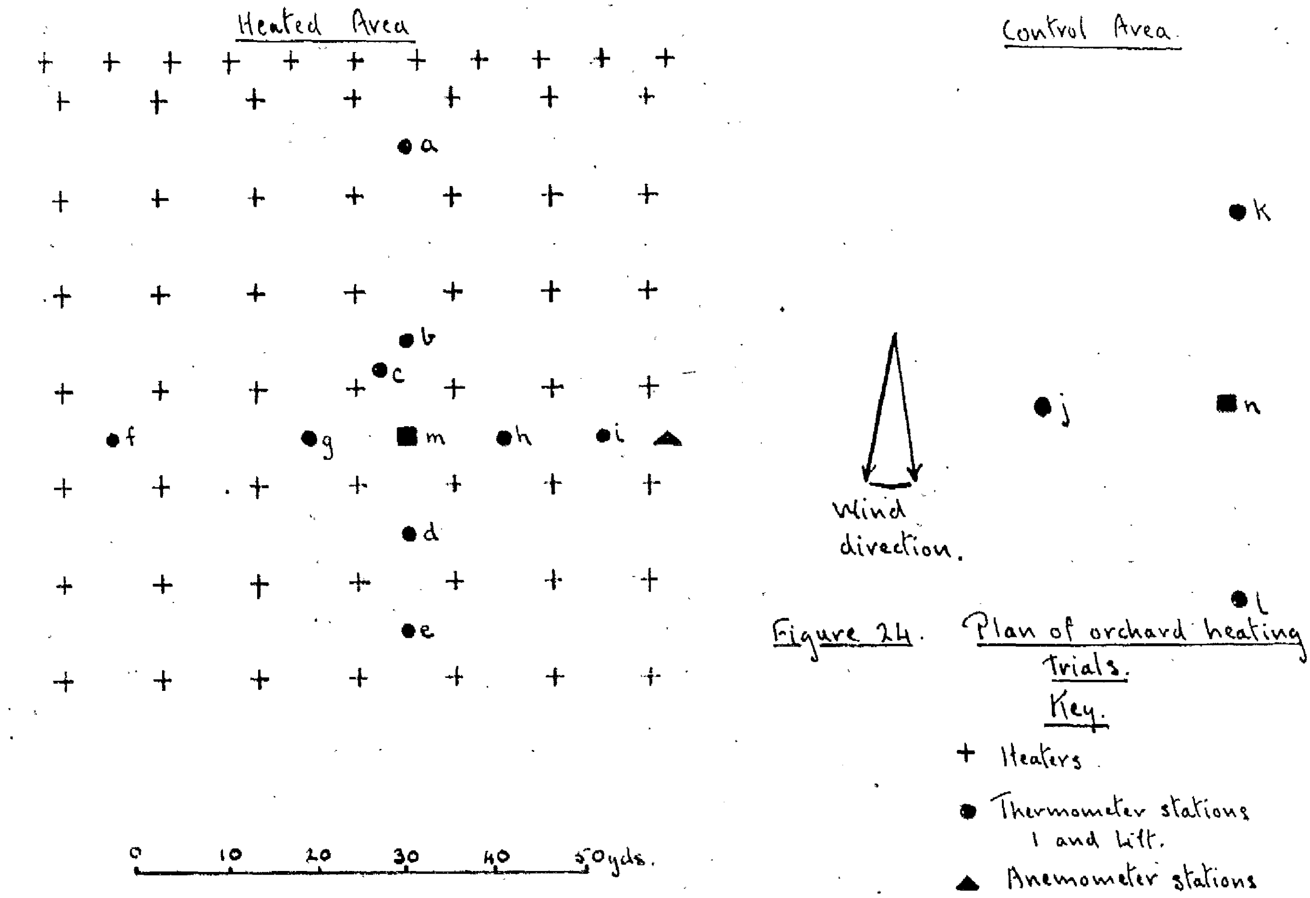


Figure 24. Plan of orchard heating trials.

Key.

+ Heaters

● Thermometer stations 1 and 4ft.

▲ Anemometer stations

■ Thermometer stations 10 and 17 feet.

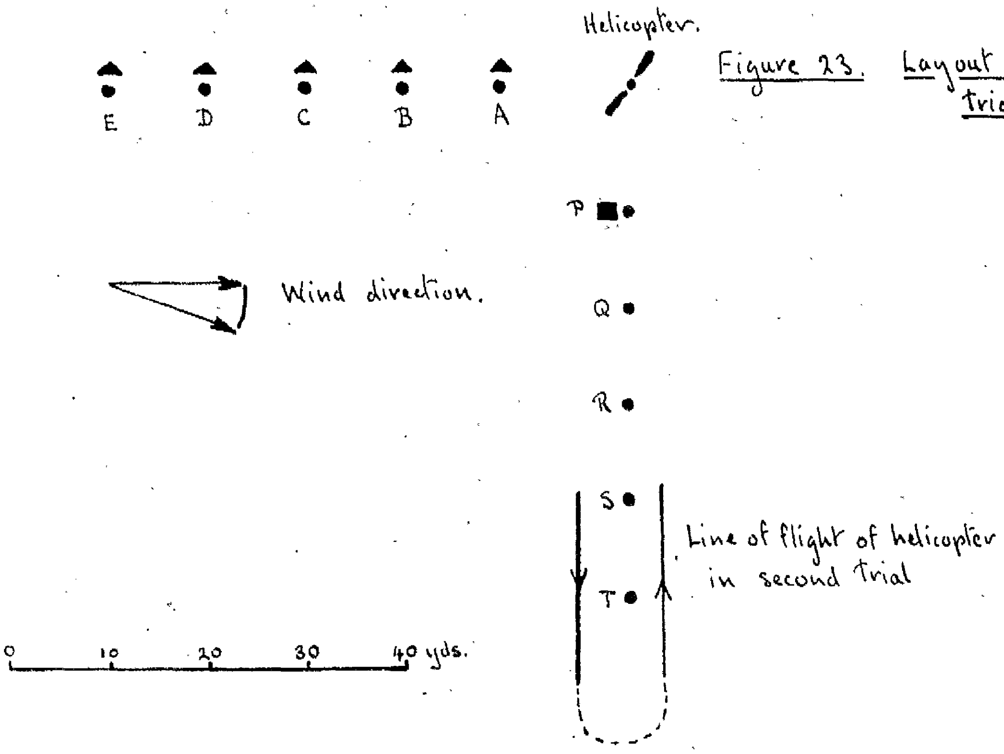


Figure 23. Layout of helicopter trial.

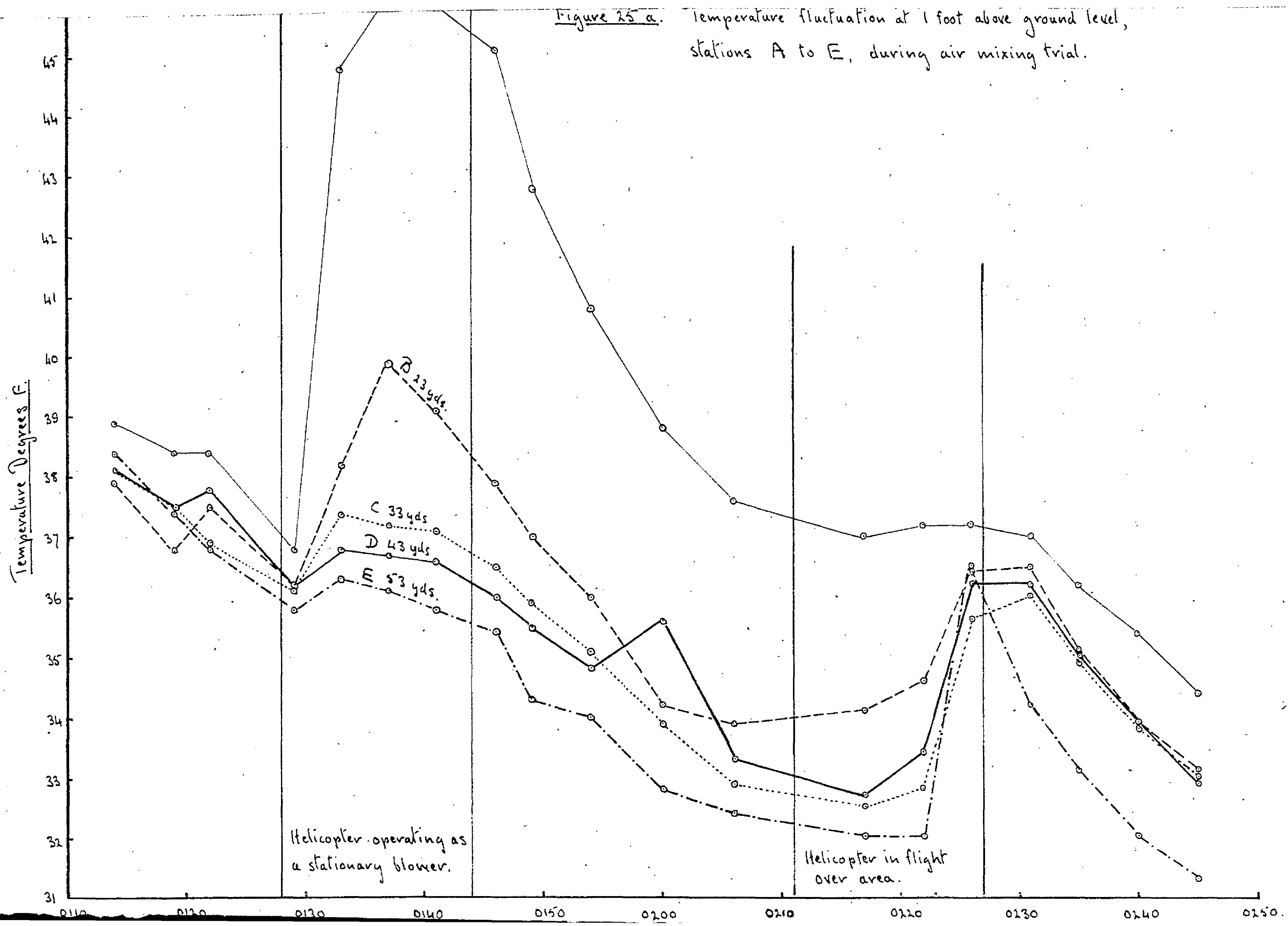
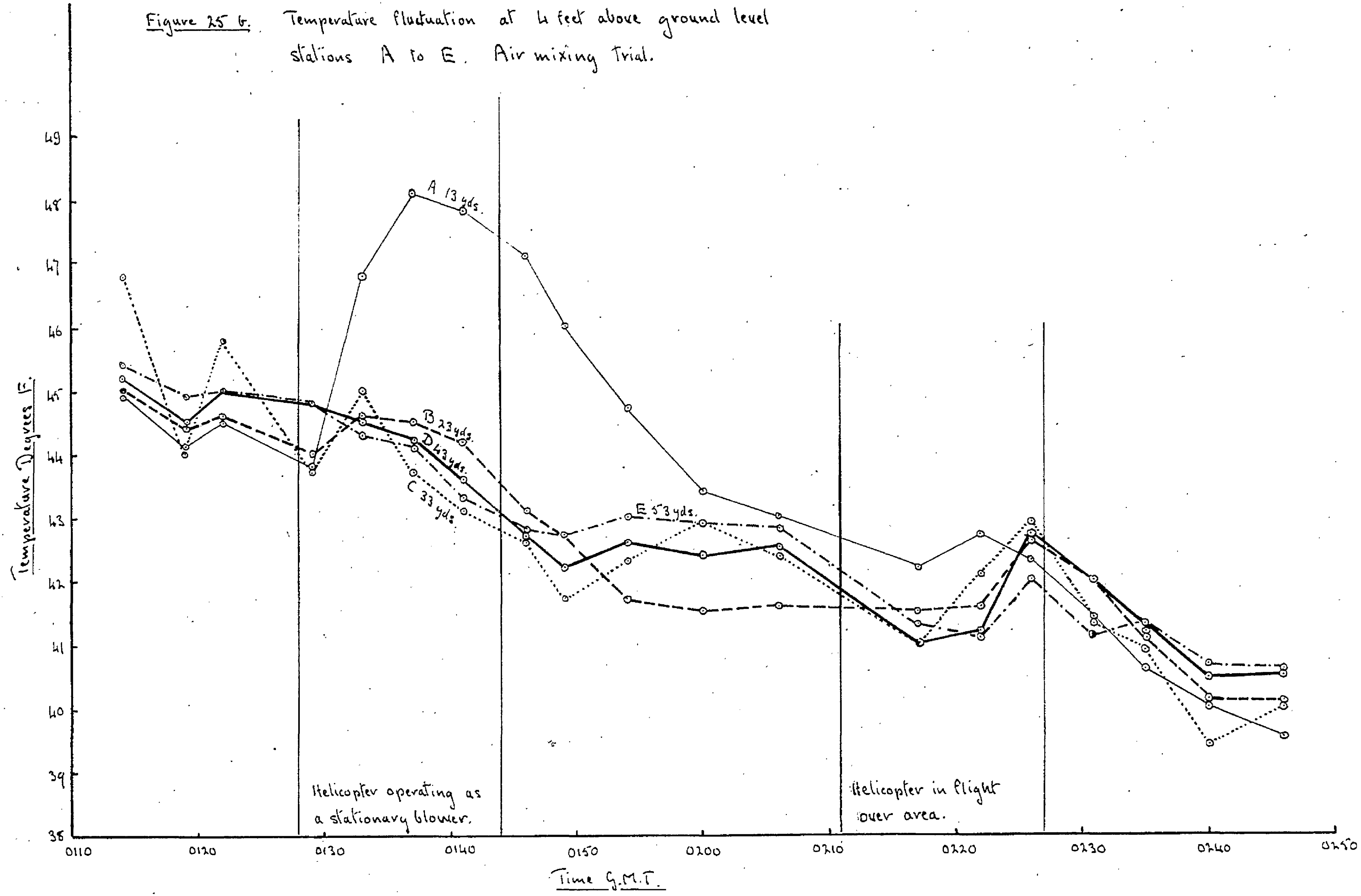


Figure 25 a. Temperature fluctuation at 1 foot above ground level, stations A to E, during air mixing trial.

Figure 25 G. Temperature fluctuation at 4 feet above ground level stations A to E. Air mixing Trial.



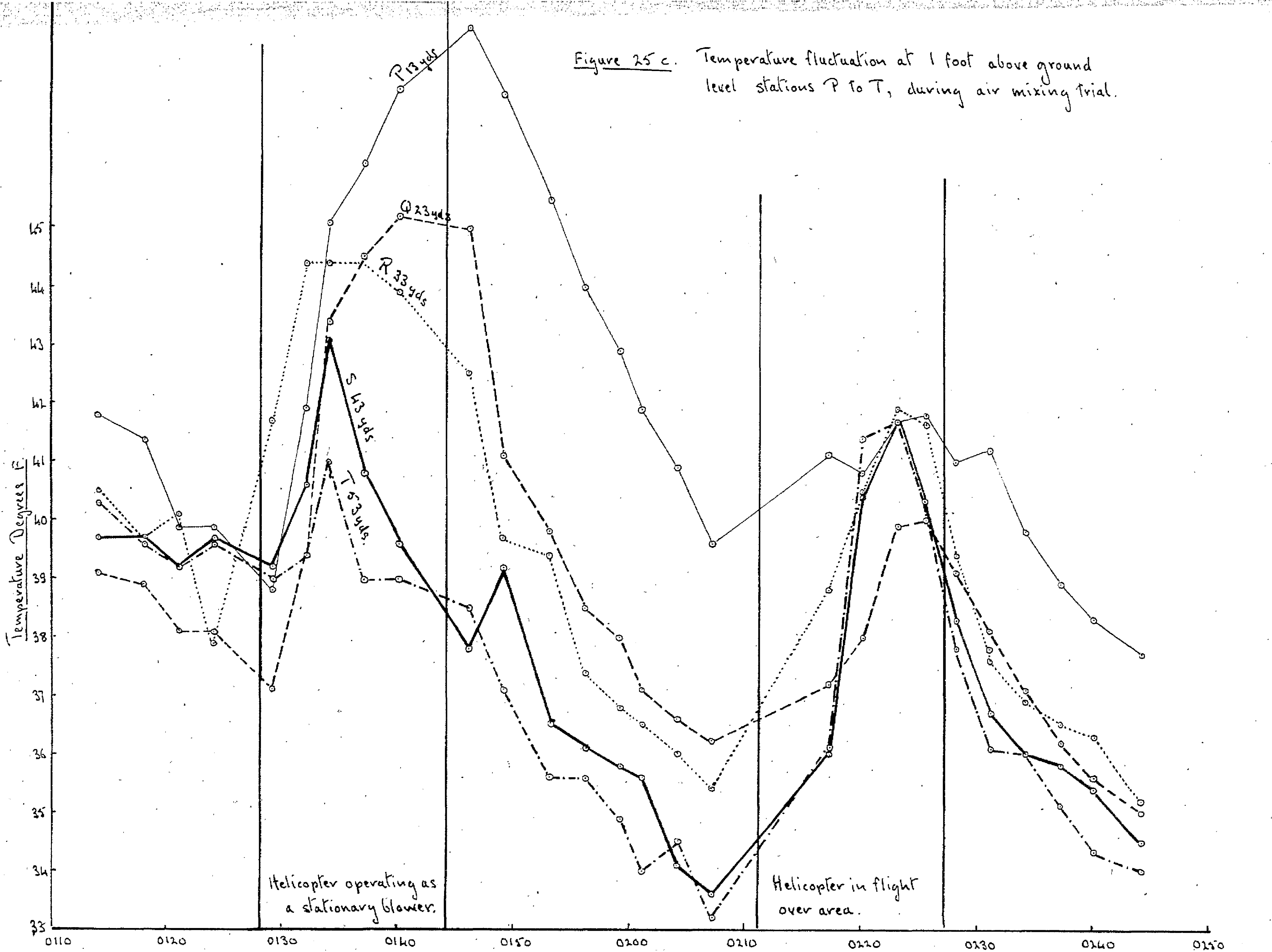


Figure 25 c. Temperature fluctuation at 1 foot above ground level stations P to T, during air mixing trial.

Figure 25 d. Temperature fluctuation at 4 feet above ground level, stations P to T, during air mixing trial.

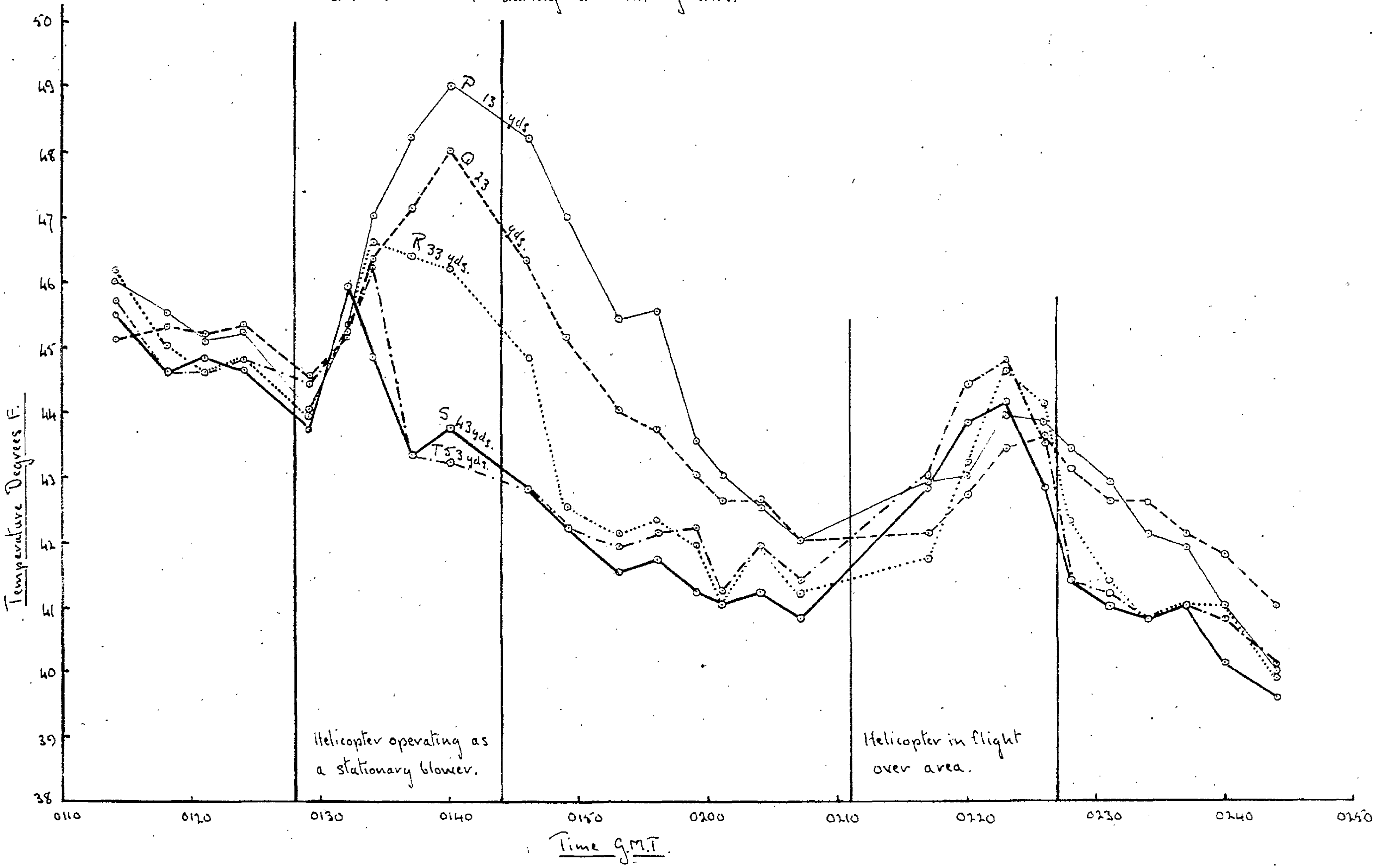
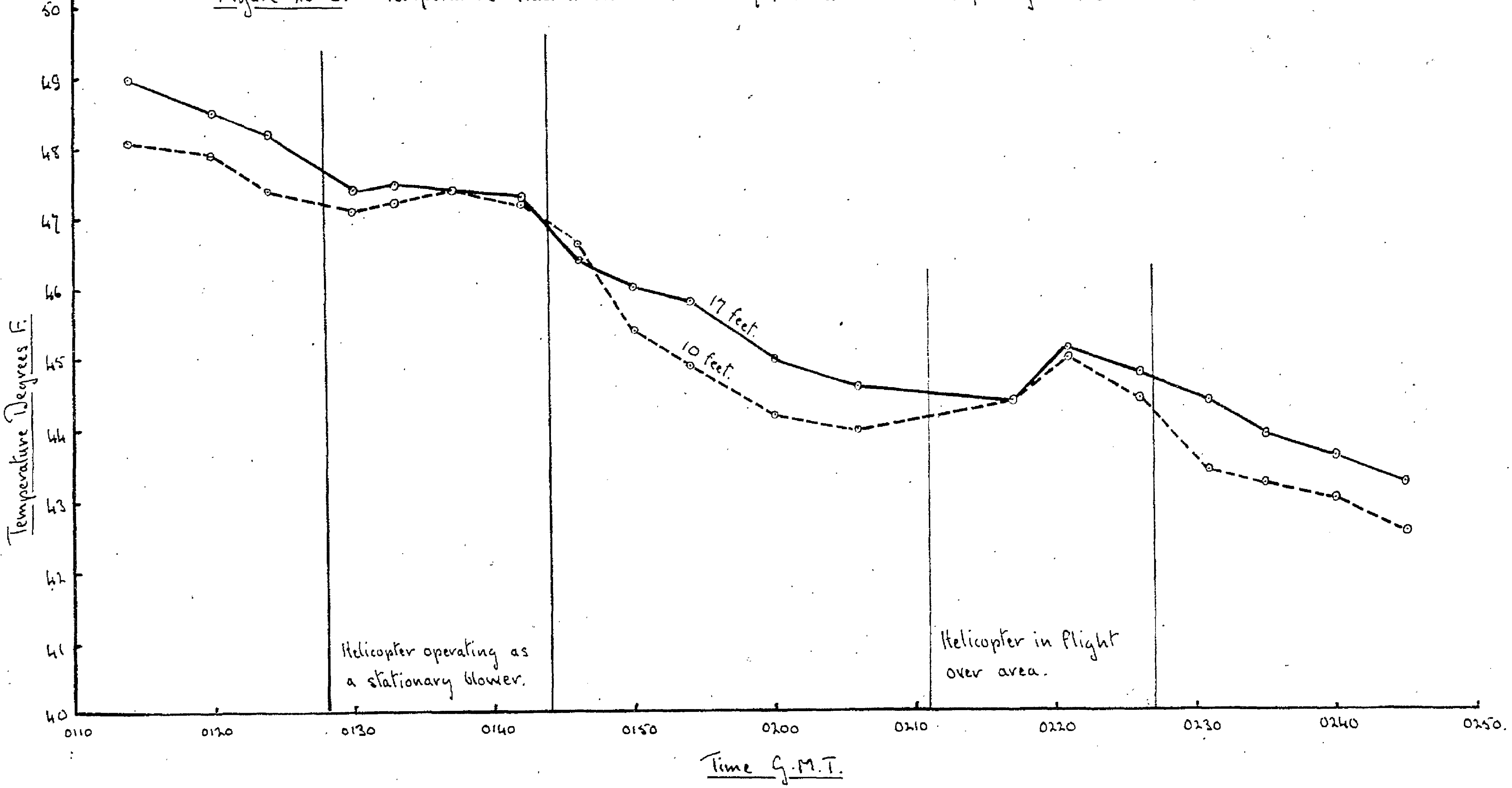


Figure 25 e. Temperature fluctuation at 10 and 17 feet at station P, 13 yds. from rotor.



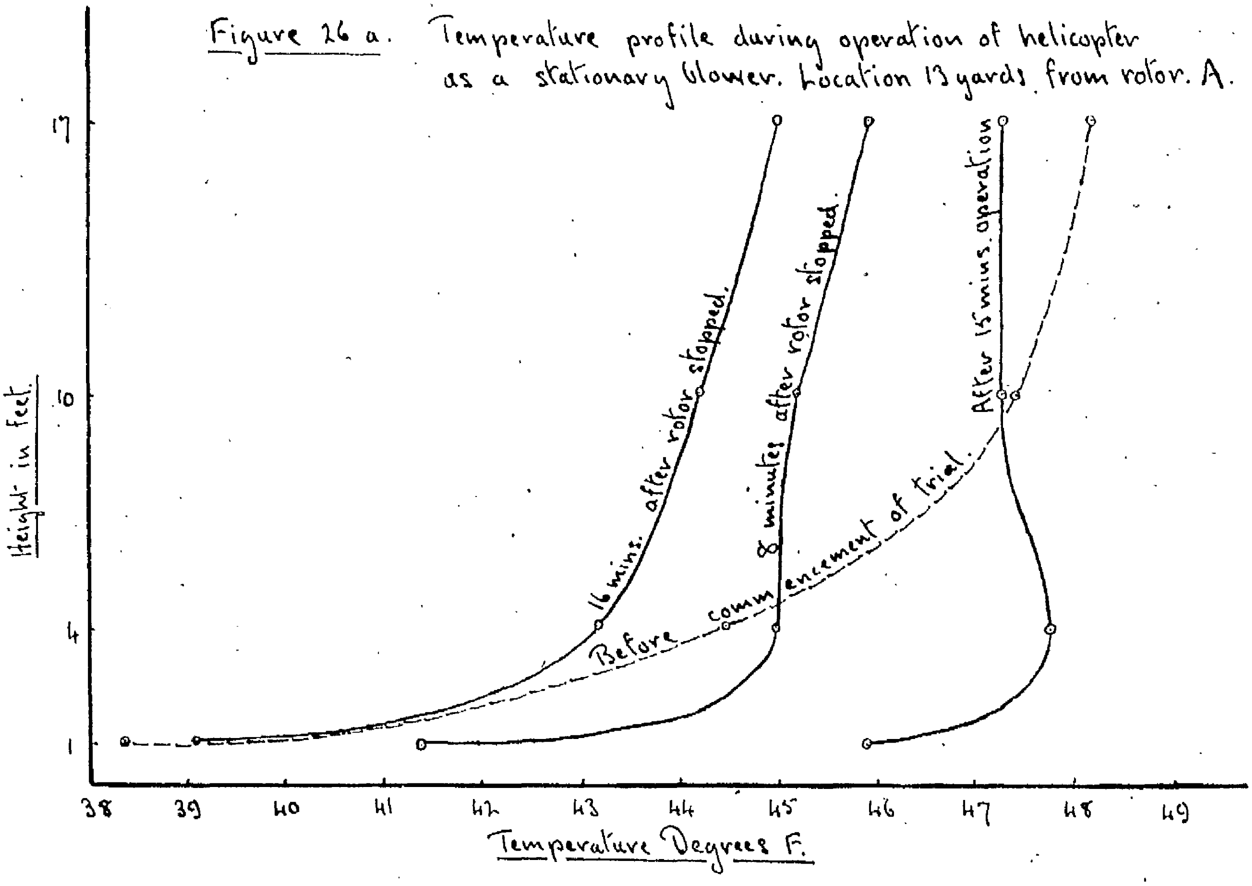


Figure 26 a. Temperature profile during operation of helicopter as a stationary blower. Location 13 yards from rotor. A.

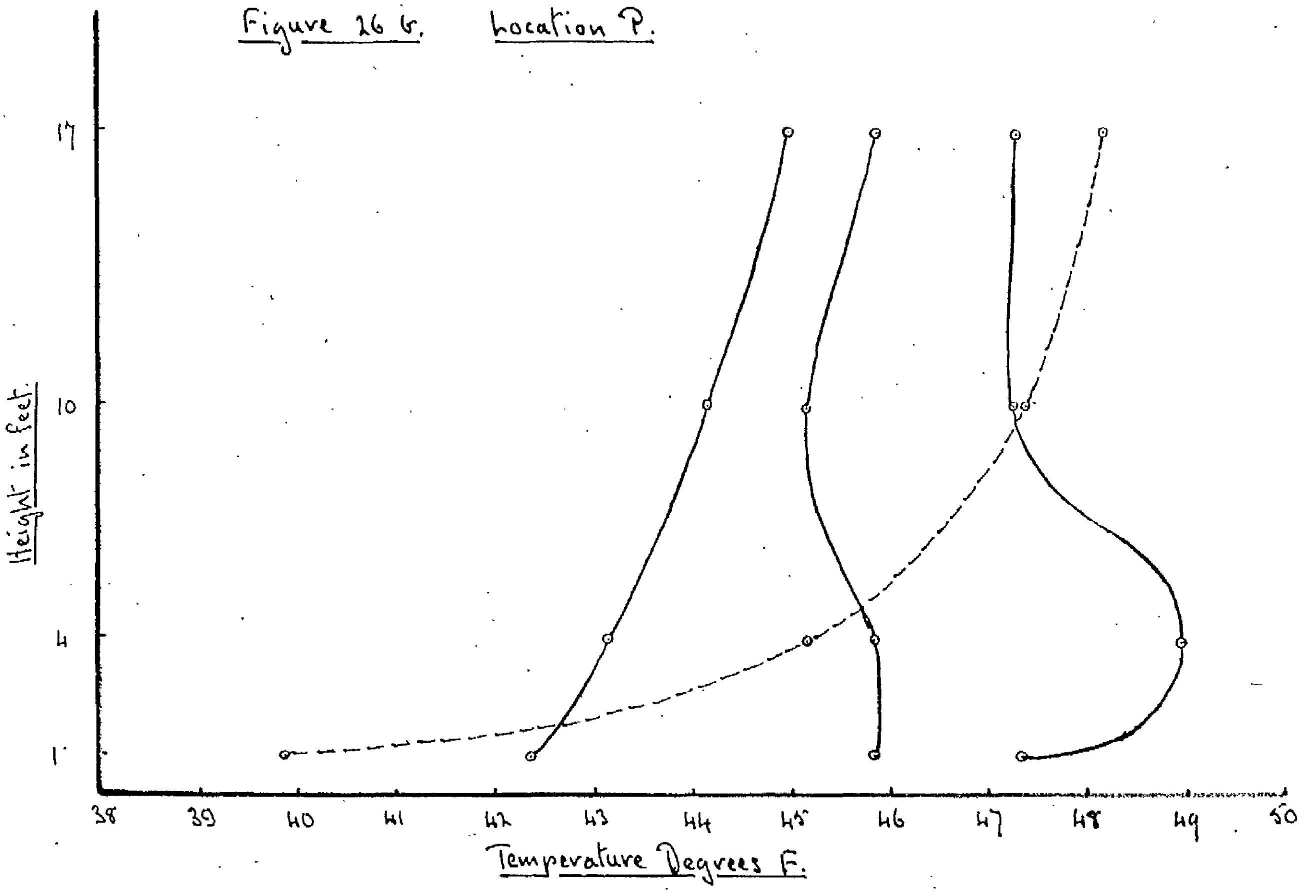
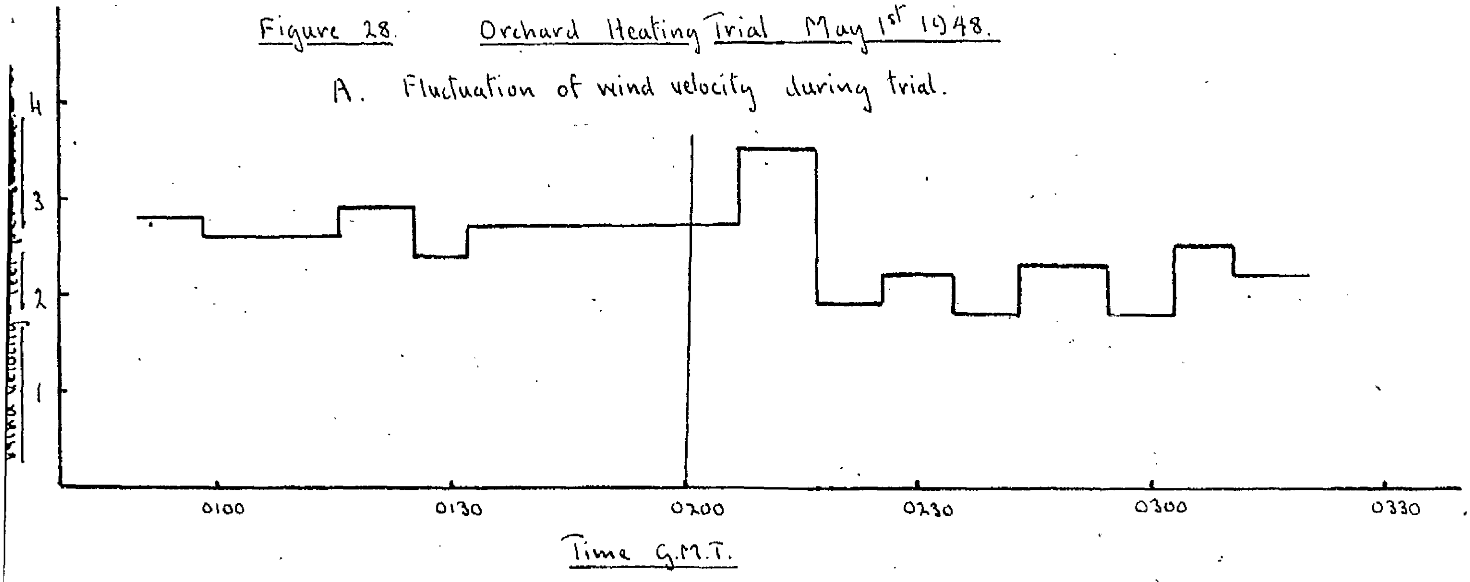


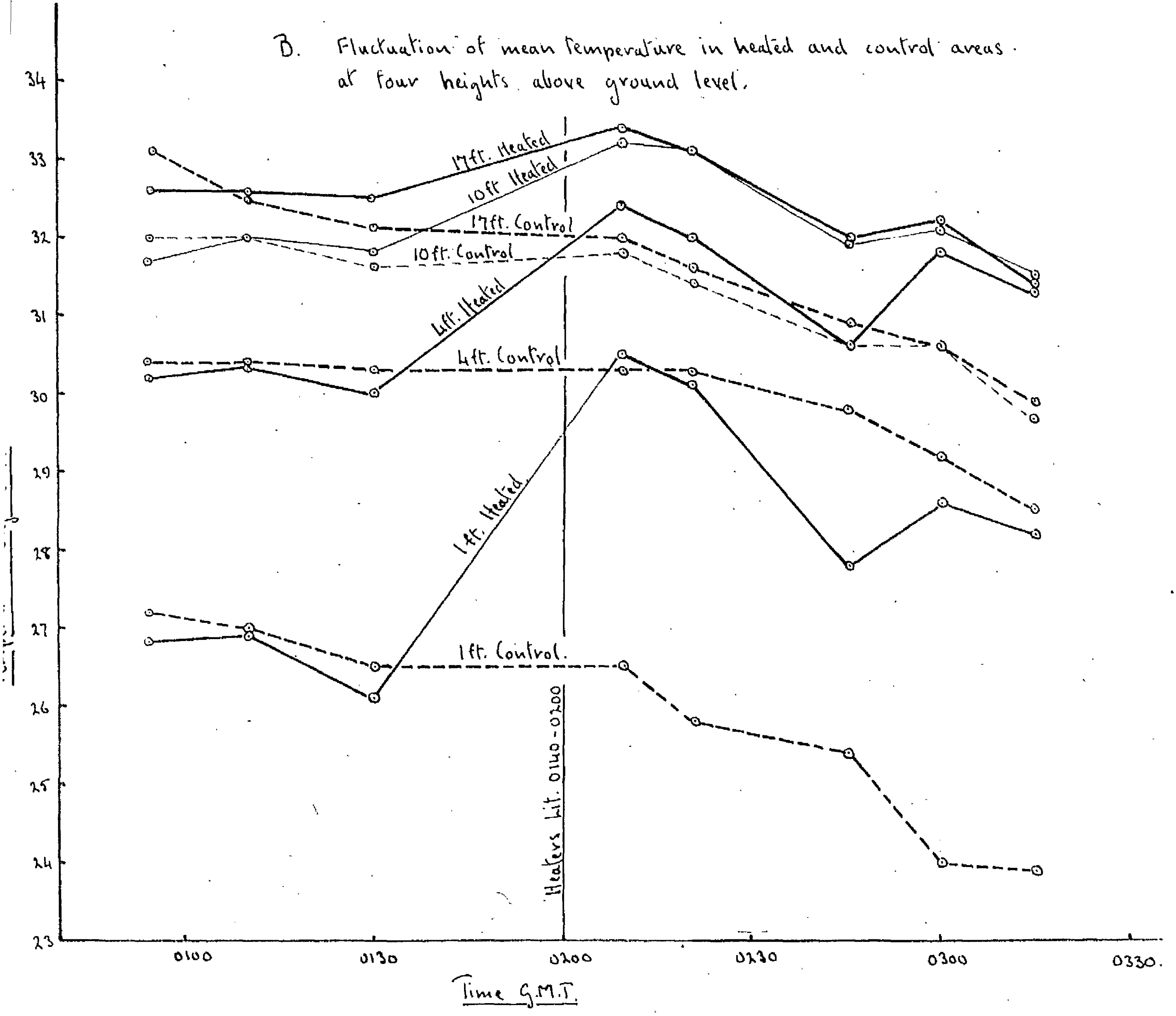
Figure 26 b. Location P.

Figure 28. Orchard Heating Trial May 1st 1948.

A. Fluctuation of wind velocity during trial.



B. Fluctuation of mean temperature in heated and control areas at four heights above ground level.



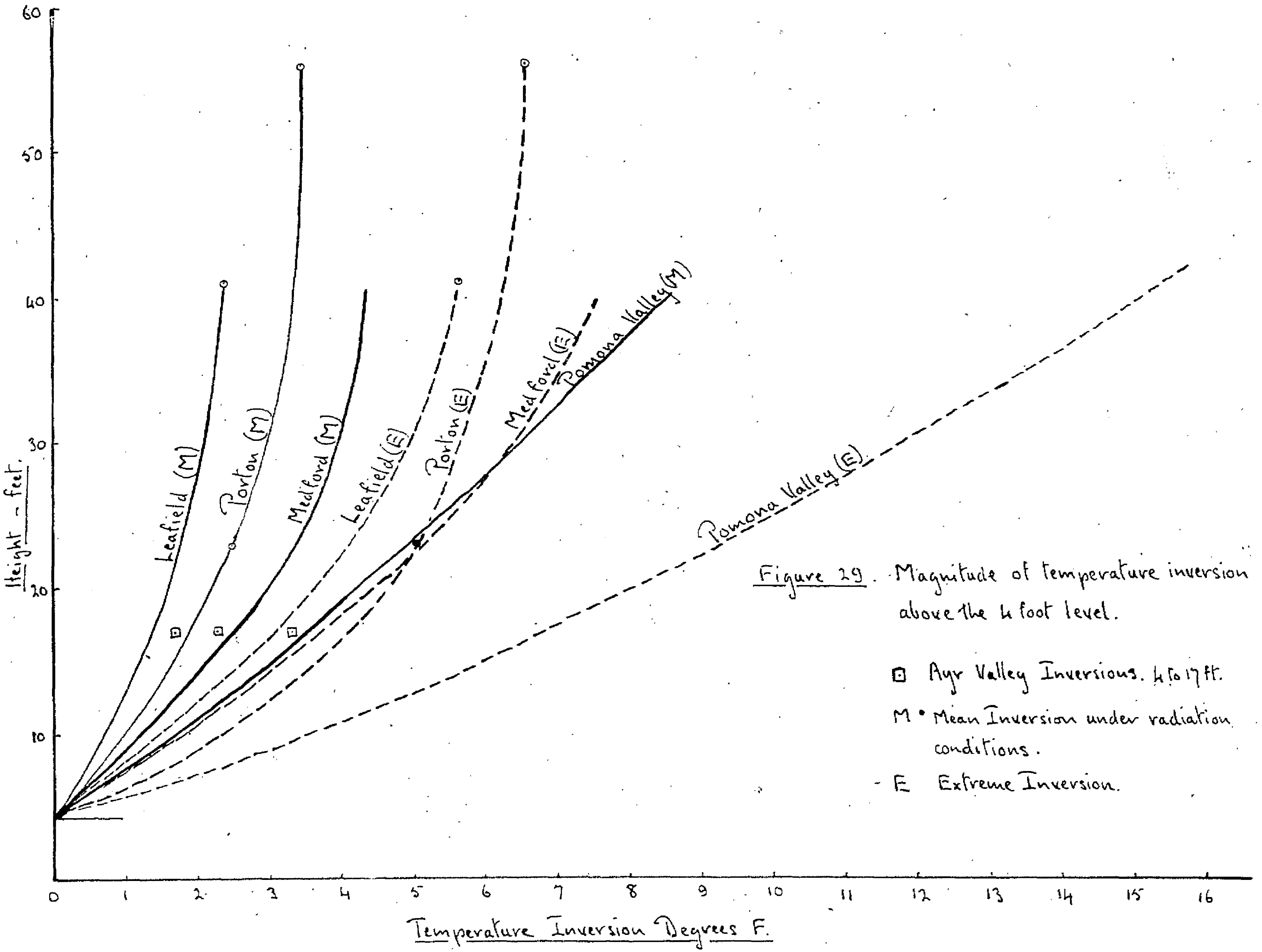
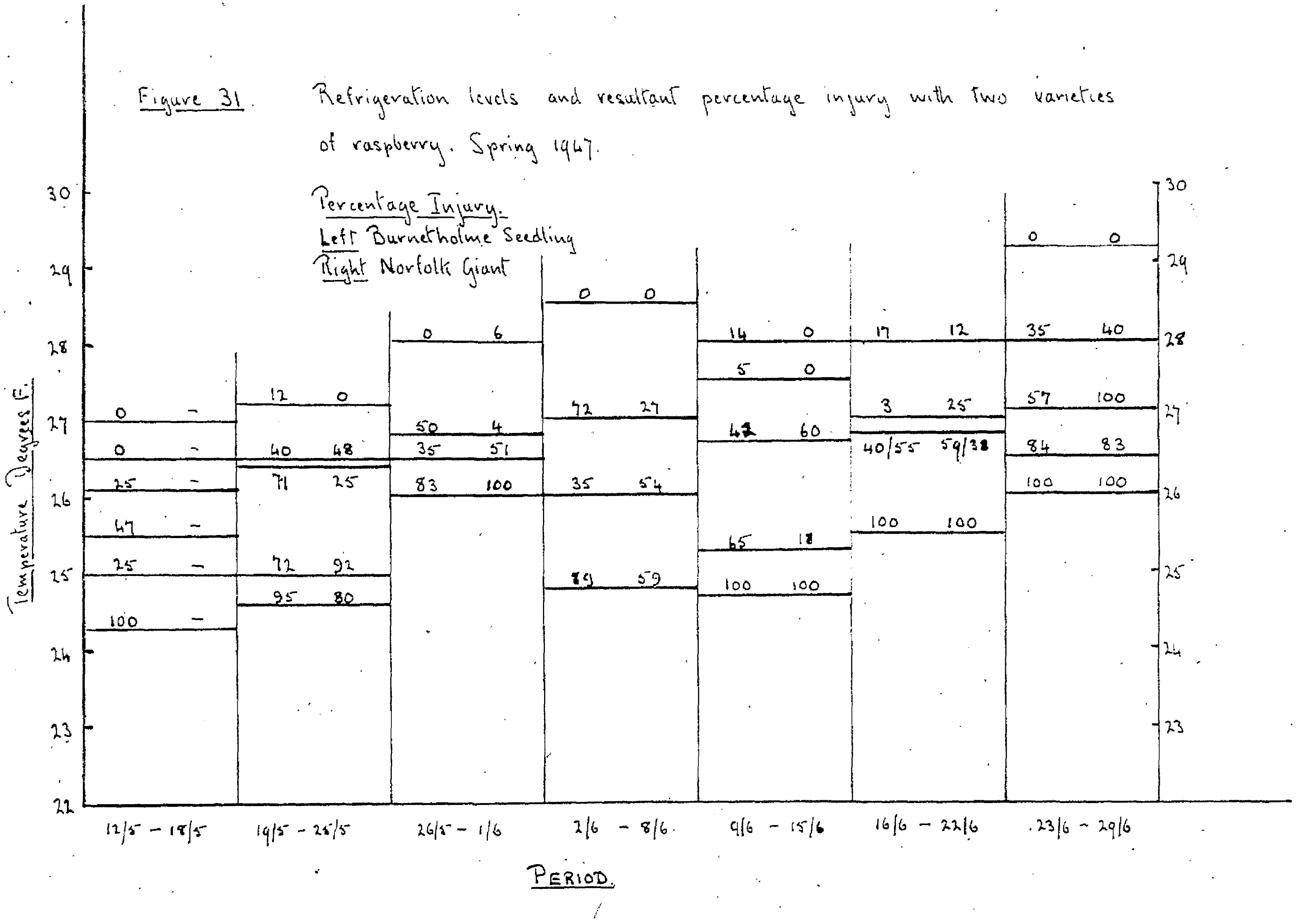
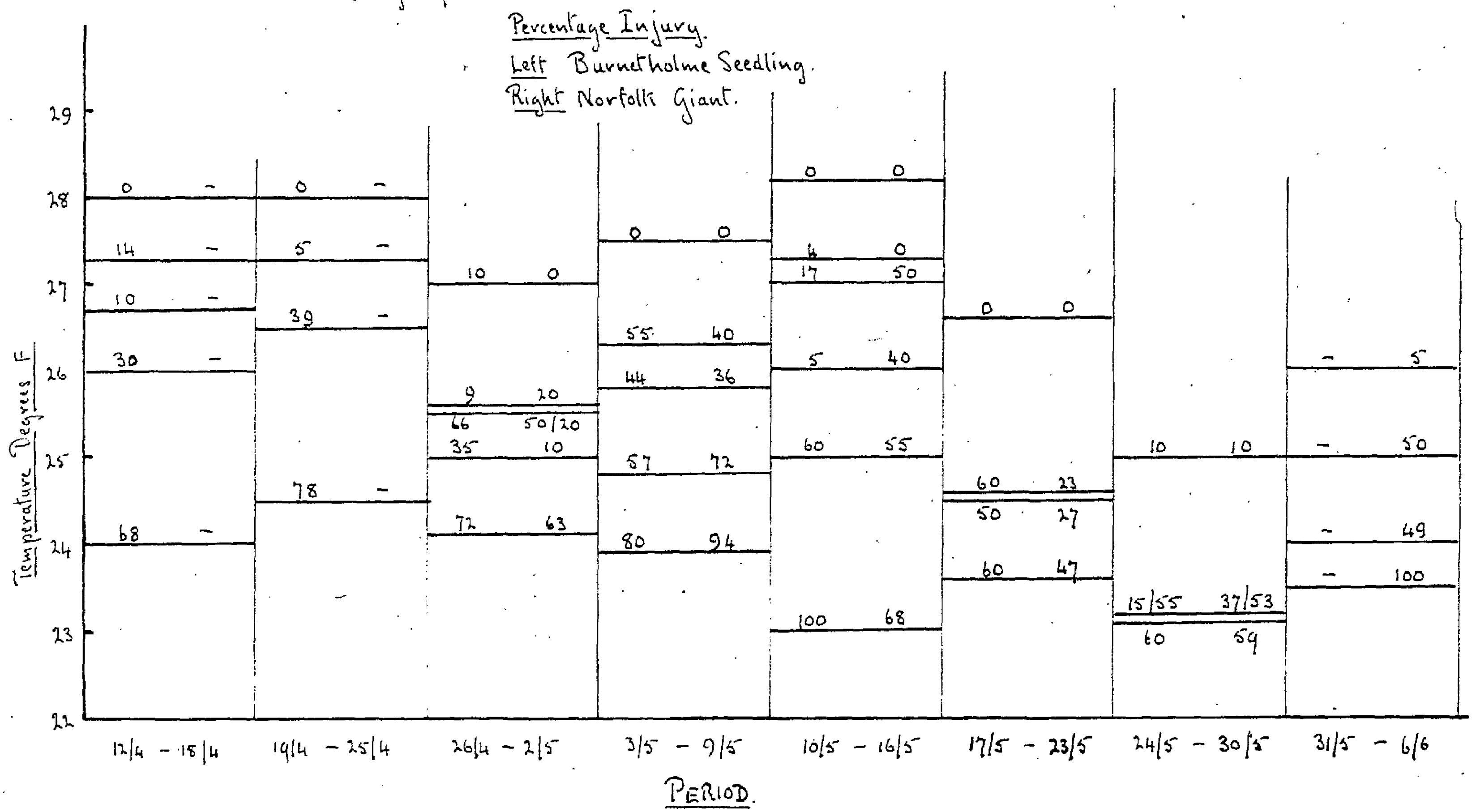


Figure 29. Magnitude of temperature inversion above the 4 foot level.



<u>Figure 31</u>. Refrigeration levels and resultant percentage injury with two varieties of raspberry. Spring 1947.

Figure 32. Refrigeration levels and resultant percentage injury with two varieties of raspberry Spring 1948.



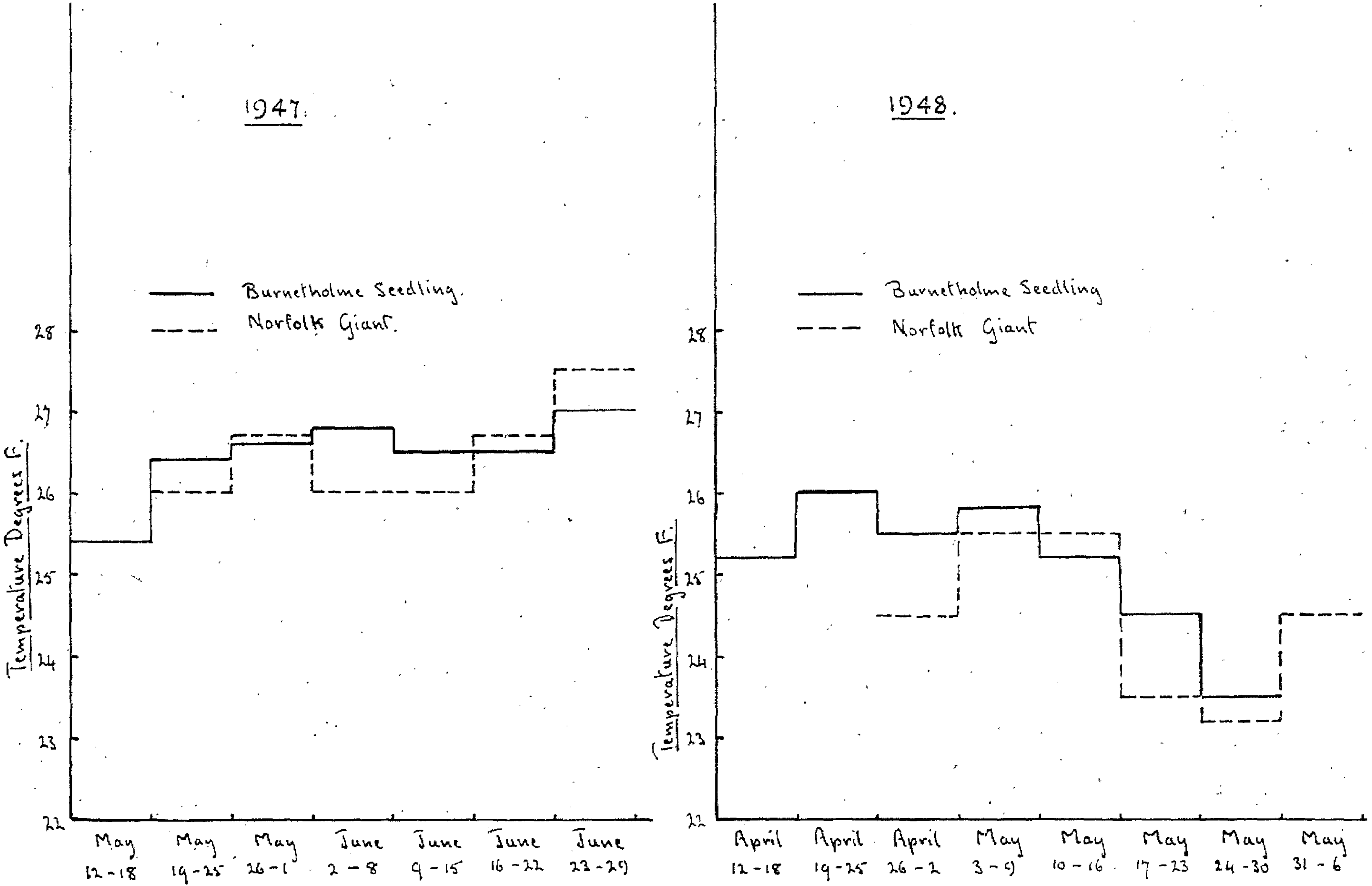


Figure 33. Variation in the refrigeration level producing 50 percent injury to the buds of two varieties of raspberry during development. Refrigeration period 1 hour.