THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

April 1984

Met.O.964 No. 1341 Vol. 113

METEOROLOGICAL OFFICE Met.O.964

THE METEOROLOGICAL MAGAZINE

No. 1341, April 1984, Vol. 113

551.501.9:551.582(41–4)

Climatological network design

By F. Singleton

(Assistant Director (Climatological Services), Meteorological Office, Bracknell)

and E. A. Spackman

(Meteorological Unit, ADAS, Cambridge)

Summary

Generalized requirements are stated for climatological networks on the basis of regulations and recommendations as published by WMO. Proposals are made for the objective assessment of climatological station network densities for the United Kingdom relative to the WMO recommendation for 'geographically fairly uniform' areas.

Introduction

One of the major problems in designing networks of observations for meteorological purposes is to define the station density required. For synoptic use the spacing of stations should be commensurate with the size and lifetime of those meteorological features which it is possible to identify and forecast for periods of a few hours upwards. In the past there have been constraints in the capacities both of communication channels to handle and of forecasters to assimilate the data, but with the advent of high speed communications and computer processing it may become possible to deal with larger quantities of data for real time purposes than hitherto. Currently there are about 200 stations within the United Kingdom producing synoptic reports with schedules varying upwards from one observation per day.

For climatological purposes much higher station densities are both needed and practicable. There may be significant climatological differences between sites only a few kilometres apart but having quite different topographical characteristics. At the time of writing, the climatological network in the United Kingdom comprised 600 stations while the number of stations in the rain-gauge network was ten times greater. The climatological network has developed in a haphazard fashion rather than been planned, and consists of much of the synoptic network supplemented by stations manned by voluntary climatological observers. Traditionally, and regardless of need, the Meteorological Office has archived all readily available climatological data as long as the quality was acceptable. Because archiving and quality control are expensive operations it has become necessary to know where stations are redundant and where, therefore, it is unnecessary to take action to replace any which close. It is also necessary to be aware of requirements for data to help decide upon, and justify the expenditure of, resources in seeking new voluntary observers or in making use of automatic equipment. Such decisions should be capable of being made by different people in a consistent and reasonably objective manner.

The requirement for a climatological network can be stated quite simply as being to provide just enough data to permit the climate of a particular area to be defined within specified limits. Guidance on the density of stations needed to fulfil this requirement can be found in the *Guide to climatological practices* (WMO No. 100) in which it is stated that, 'where the geographical conditions are fairly uniform, then one ordinary climatological station* per 1000 km^2 will normally be sufficient for most climatological purposes'. The *Guide* also says that care must be taken to ensure that all types of terrain are represented satisfactorily and that the demand for information should be taken into account. This means, for example, that there would be a need for a greater density of stations in or near industrial regions and that there is likely to be little requirement for stations above heights where man normally lives or works.

Ideally, the number of stations at which any particular climatological element is observed should be large enough to permit a complete analysis to be made of the geographical distribution of mean values, frequencies, extremes and other characteristics of the element. This means, according to the *Guide,* that the station density depends very much upon the element in question and on the geographical features of the area. A sparse network may be sufficient for the study of surface pressure reduced to mean sea level but, on the other hand, a fairly dense network will normally be required for the study of the wind regime and maximum temperatures, while a very dense network may be required for the study of minimum temperatures or frequencies of frost and fog.

The WMO *Guide* does not quantify what is meant by the words 'sparse', 'fairly dense' and 'very dense'. No indication is given as to what is meant by the term 'geographically fairly uniform' nor any guidance on how many more ordinary climatological stations are required in areas that are geographically complex. It is assumed that an area that is geographically uniform will be climatologically homogeneous. This latter term is taken to describe an area throughout most of which the various meteorological variables behave in similar ways in a given synoptic situation.

In this paper the possibility of trying to determine climatologically homogeneous areas is examined and rejected. A methodology is proposed whereby the climatological complexity, or otherwise, of an area may be determined and, therefore, an estimate made of the optimum number of stations.

Climatological areas

Before the introduction of computer techniques into climatological station quality-control procedures the 'hand and eye' subjective methods depended upon the definition of 80 or so areas which were assumed to be climatologically homogeneous. Each observation within an area was compared with observations from the other stations within the same area. Although defined by experienced staff these areas were inevitably results of subjective judgements which were, no doubt, heavily influenced by individual experience or impressions. To some extent the size of each area was also determined by the need to have sufficient stations within it for quality-control purposes. Fig. 1 shows these areas. Another, still subjective, attempt to define climatologically homogeneous areas may be found in the Ministry of

---

* The definition of an ordinary climatological station can be found in the *Manual on the global observing system* (WMO No. 544). The minimum requirement is to report daily extreme temperatures and amount of precipitation.

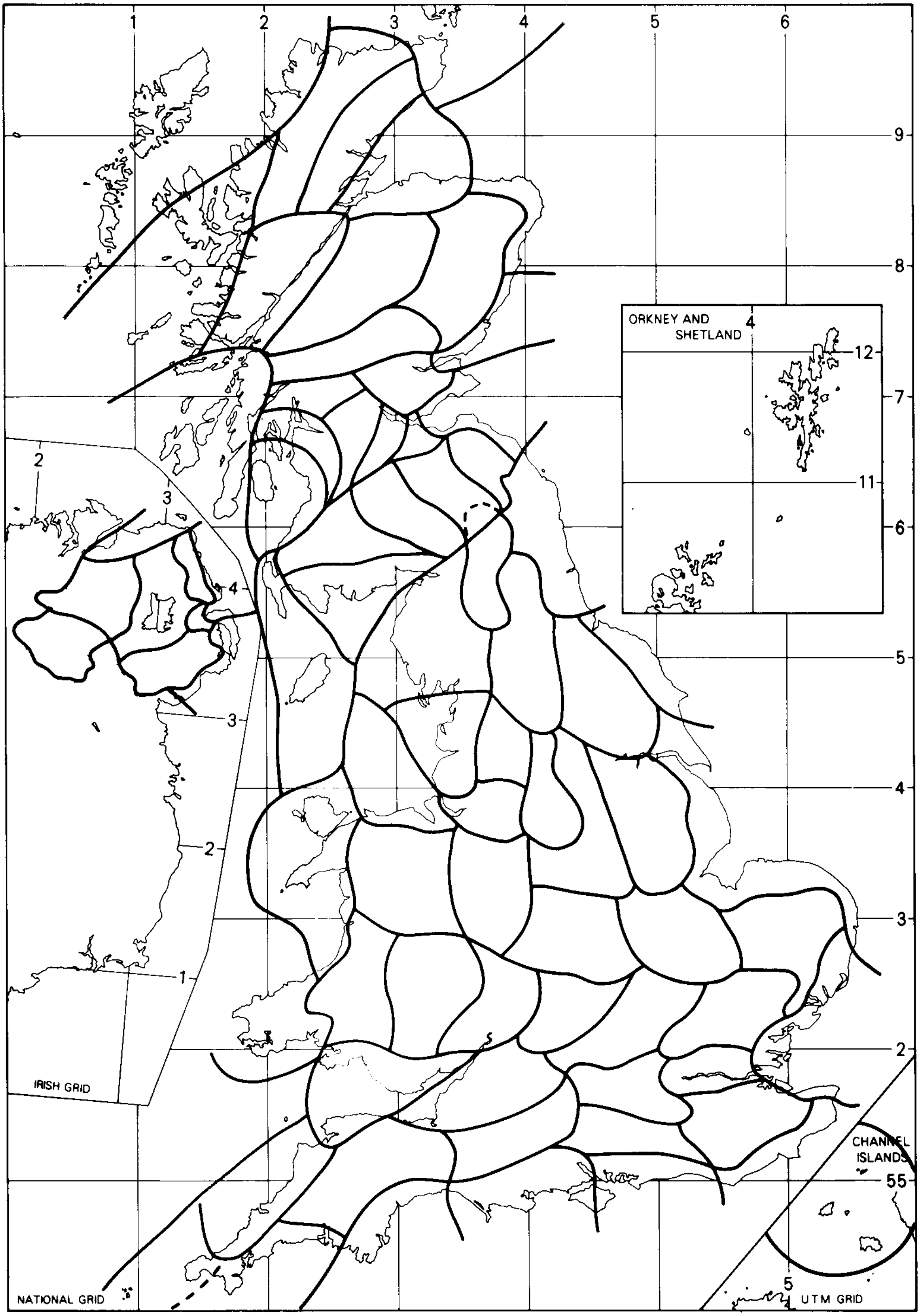

Figure 1. Climatological areas formerly used for subjective quality-control work.

Agriculture, Fisheries and Food Technical Bulletin No. 35, entitled *The agricultural climate of England and Wales.* This publication defines agro-climatic areas primarily on the basis of agricultural land use, although the boundaries of the 52 areas for England and Wales were made to coincide with parish boundaries and, where possible, with those of the Agricultural Development and Advisory Service districts also. Other possibilities include the delineation of areas of the United Kingdom from an essentially topographical point of view. For example, lines could be drawn on a map around the coastal plains, inland mountainous areas, low-lying inland areas, moors, plateaux and major conurbations.

The three possibilities above for defining climatological areas for network design may or may not be equally viable but all leave unresolved the question of the determination of numbers of stations in the more complex areas.

Factor analysis for the determination of climatologically homogeneous areas

Spackman and Singleton (1982) have described the use of factor analysis in areal quality control. The basis of the areal quality-control process is the representation of a climatological element X on day i at station j as being

$$X_{ij} = a_{i1} f_{1j} + a_{i2} f_{2j} + \dots + a_{in} f_{nj} + r_{ij}$$

where $f_{1j} \dots f_{nj}$ are factors at station j, $a_{i1} \dots a_{in}$ are factor loadings on day i and r_{ij} is the error or the residual on the specific day. It was found that 85% of the total variance of X_{ij} can be described by means of the first 15 factors ($f_{1j} \dots f_{15j}$) and the corresponding factor loadings ($a_{i1} \dots a_{i15}$).

The factors are station-dependent and result from physical features (or combinations of physical features) at each station while the factor loadings depend upon the synoptic situation. Thus in a westerly situation, when considering temperatures, the latitude factors would be important and the corresponding factor loadings would be high. On the other hand, in an anticyclonic situation there would be high loadings of the factors representing night-time radiation when minimum temperatures are considered. Stations that behave in similar ways in similar synoptic situations will have similar factors. It would, therefore, seem logical to try to define regions that are climatologically homogeneous by looking for groups of stations that have similar factor values. This selection or grouping can be achieved in a number of ways and that chosen was by means of a 'clustering' algorithm.

The basis of the clustering process is the definition of distances of stations from each other in 15-dimensional factor space, i.e.

$$d_{ij}^2 = \sum_{k=1}^{15} (f_{ik} - f_{jk})^2$$

where d_{ij} is the 'distance' apart of stations i and j, and f_{ik} and f_{jk} are the kth factors at those same stations. The clustering algorithm produces a predetermined number of groups, the stations in each being nearer to each other in factor space than to stations in any other group.

Lines can then be drawn around stations grouped together using either subjective or objective analysis methods. Fig. 2 shows, for various elements, analyses of the results of clustering into 40 groups. For temperatures and rainfalls over 700 stations were used in the clustering analysis but only around 460 for sunshine. The stations used were the climatological stations and not the rainfall only stations. On three of the maps analysed there are more than 40 areas delineated because stations may be near in factor space and yet be well separated geographically. This happens, for example, with headlands exposed to a common wind direction, and frost hollows. Such locations can be climatologically similar for particular elements even though they are some considerable distance apart and separated by areas that are climatologically different. The varying complexity of the analyses in Figs 2(a), (b), (c) and (d) for the

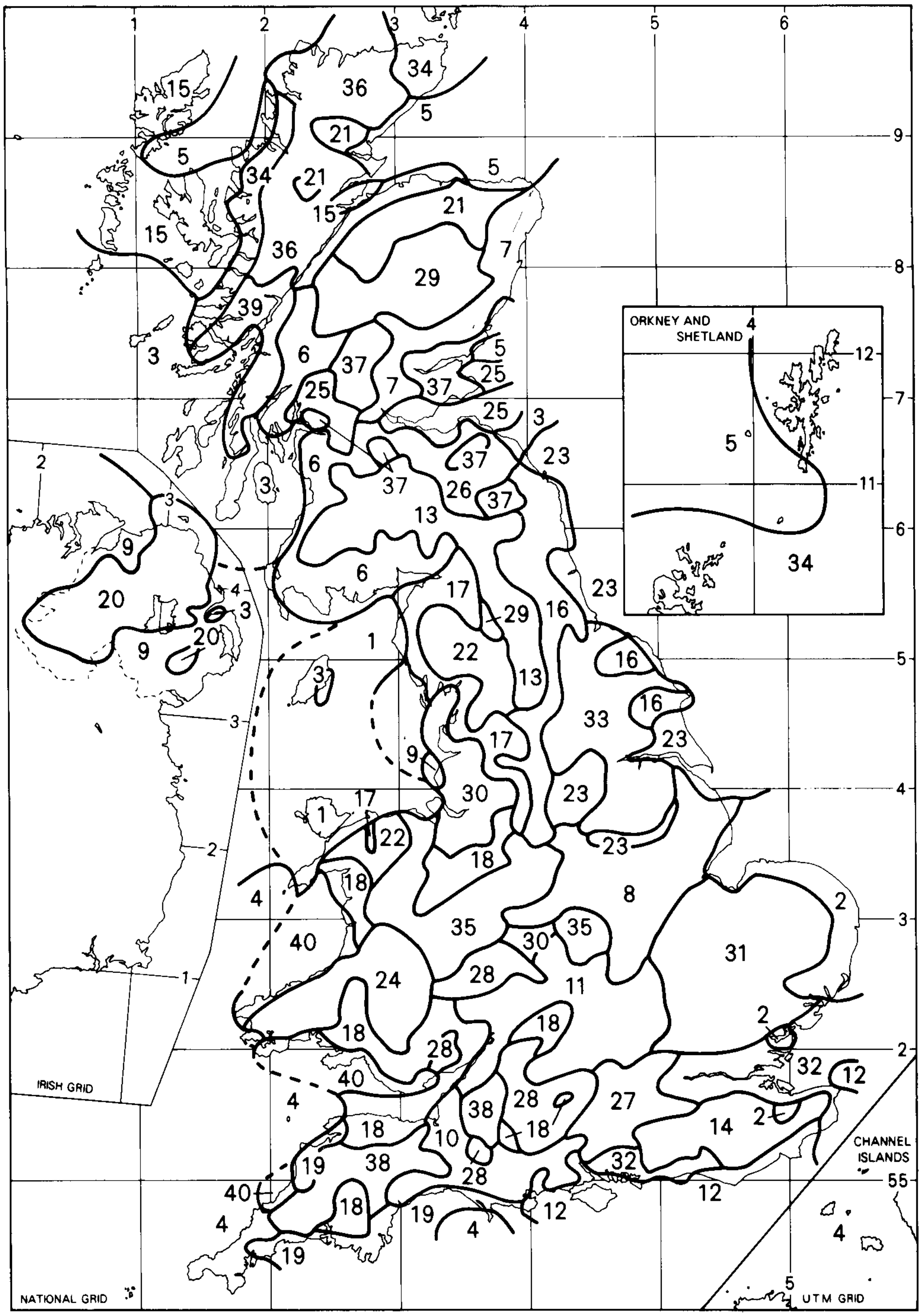

Figure 2(a). Climatologically homogeneous areas for minimum temperatures derived from clustering analysis into 40 groups. Areas with the same number belong to the same group.

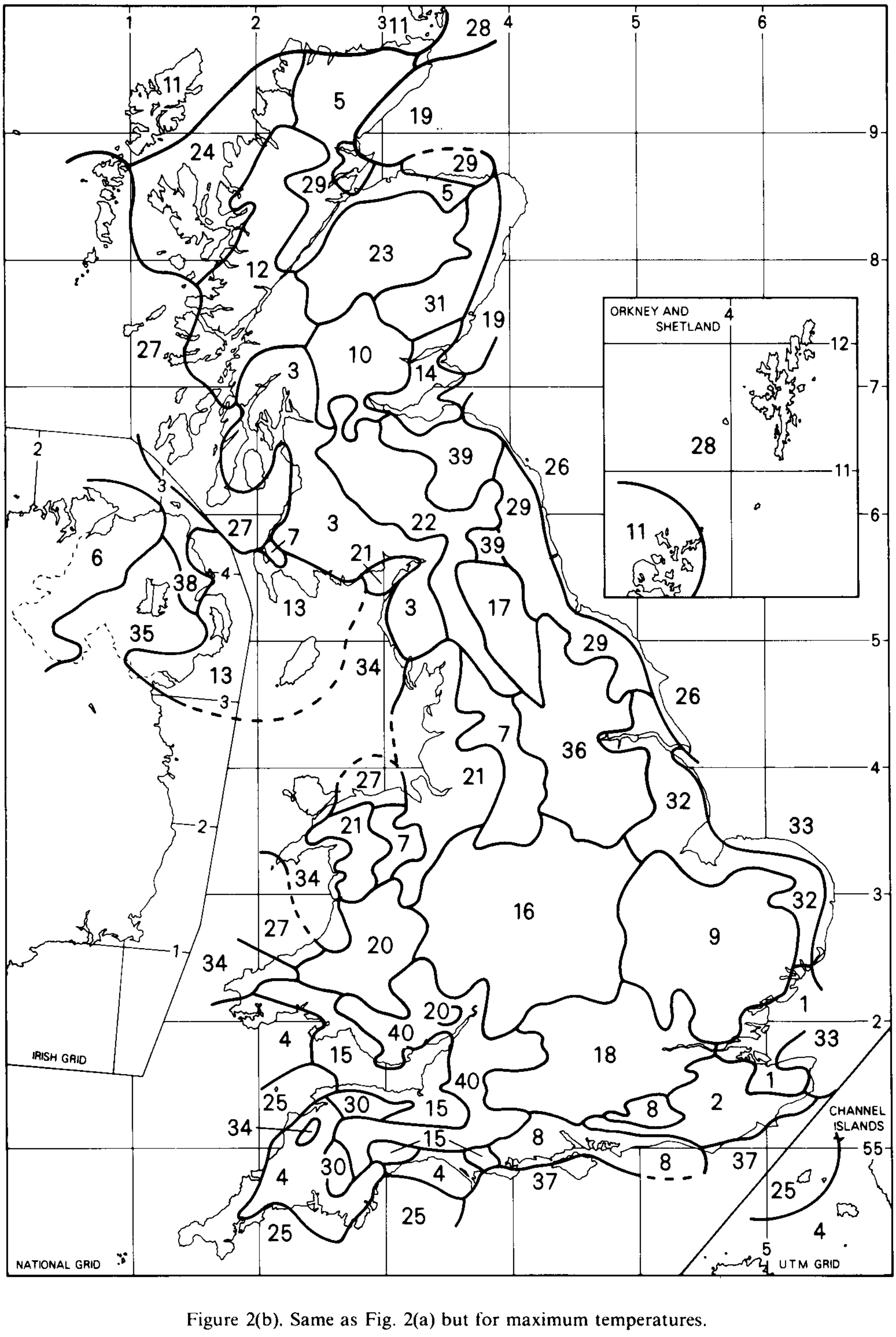

Figure 2(b). Same as Fig. 2(a) but for maximum temperatures.

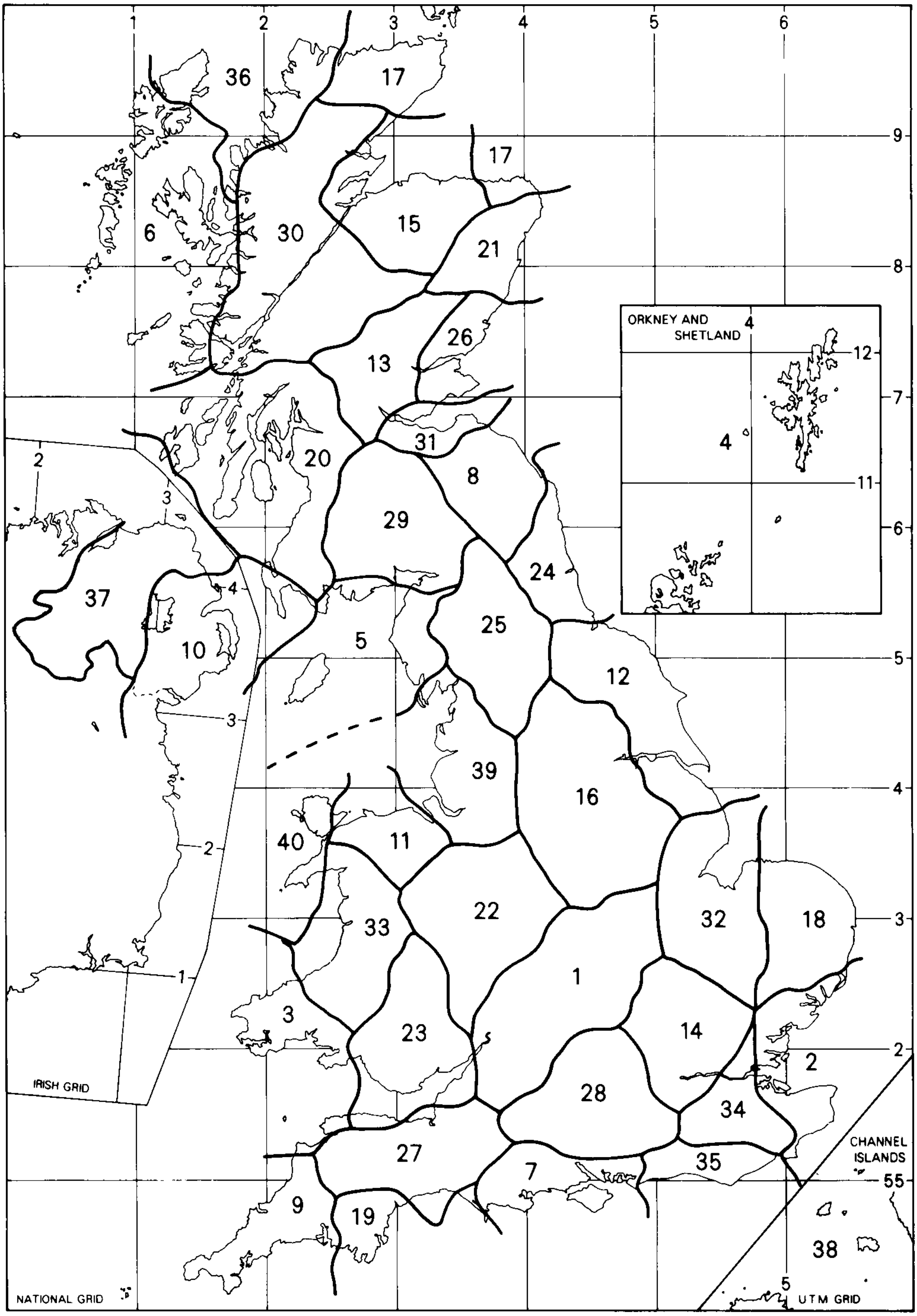

Figure 2(c). Same as Fig. 2(a) but for daily sunshine.

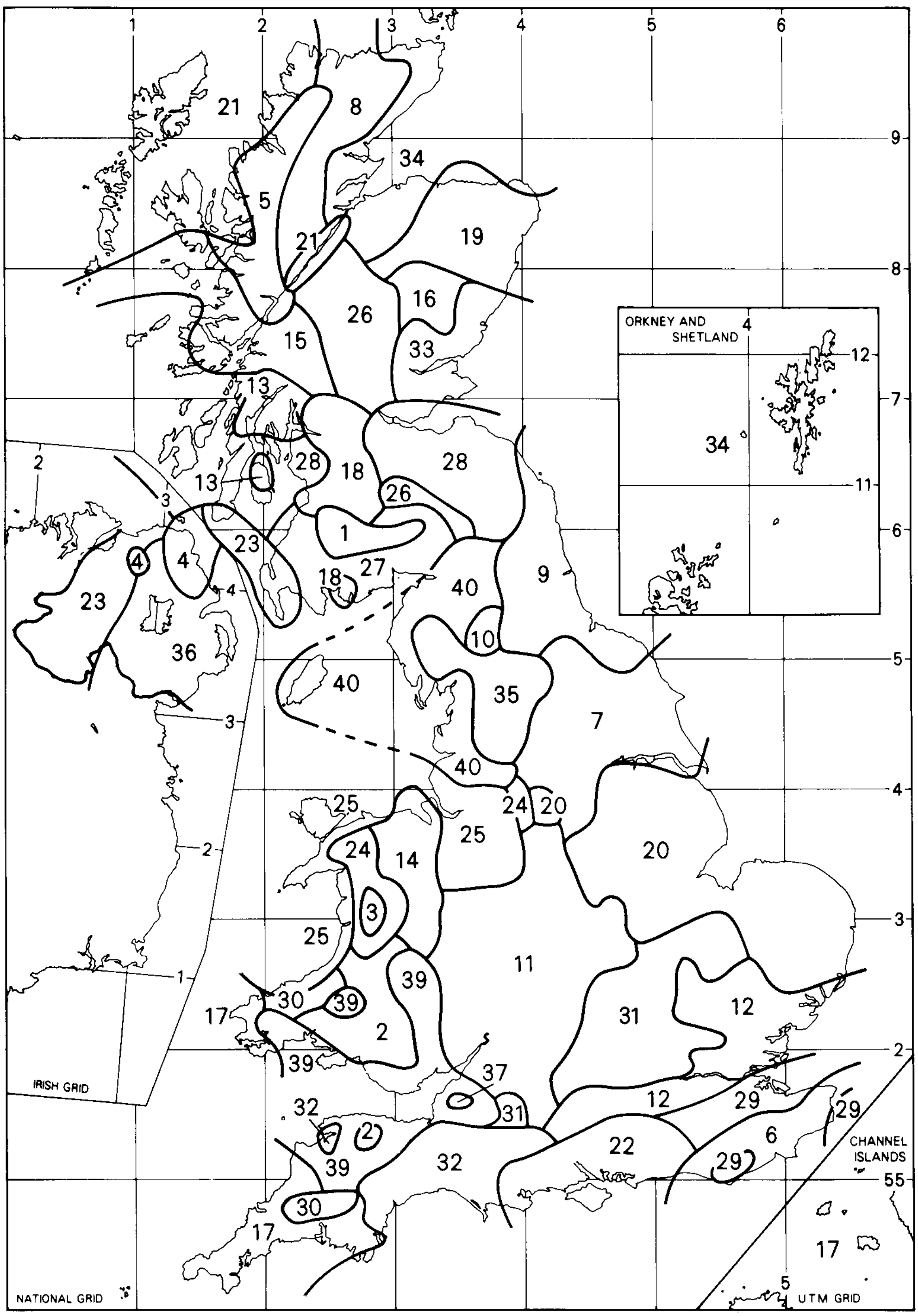

Figure 2(d). Same as Fig. 2(a) but for daily rainfall.

different elements depends partly upon the number of stations with data available for the study and partly upon the effects of topography on the element in question. From these maps it can be seen that while some quite large areas can be defined as being climatologically homogeneous for one element or another there are other areas where the patterns are complex and where topography is very important. Figs 2(a), (b), (c) and (d) also show that areas where the patterns are simple for one element may be complex for another and, therefore, that areas climatologically homogeneous for one element are not necessarily homogeneous for another.

The approach of trying to define climatologically homogeneous areas by means of factor analysis was therefore discarded, mainly because it was impossible to define a unique set of areas for all elements. However, it should be noted that for individual elements it might be expected that network requirements could be defined on the basis of one station per 1000 km^2 in each area of the maps in Figs 2(a), (b), (c) and (d). Some rounding up would be necessary so that each area, however small, would have at least one station, an area between 1000 km^2 and 2000 km^2 at least two, an area between 2000 km^2 and 3000 km^2 at least three stations and so on. This assumes, of course, that there are sufficient data to define the areas adequately in the first instance. In view of the coverage in some parts of the United Kingdom this is patently not the case. The use of the analysis to determine network requirements for single elements can thus only be practicable in areas where there is a large enough number of stations to determine the cluster groups.

Use of factor analysis to determine climatological complexity

Because, as has been shown above, one set of climatological areas cannot be defined for all elements an alternative approach depending upon the definition of the climatological complexity of fairly large predefined geographical areas was examined. For simplicity it was decided to use areas based upon the national grid, partly because the selection of areas and boundaries between stations can be made objectively and partly because this simplifies the writing of computer programs for such purposes as listing numbers of climatological stations in the various areas and analysing their height distributions. Other possibilities considered included using the four countries of the United Kingdom with their respective regions, or topographically defined areas such as the lowlands, highlands, coastal regions and so on. These were discarded as being either too subjective a definition or too complex for the purpose of this work and with no consequential perceivable benefits. The areas chosen are shown in Fig. 3. In order to avoid small land areas with few stations, contiguous grid squares or parts of grid squares were grouped as shown. The size of each area and the number of stations used for the analysis in each area are shown. Apart from Orkney and Shetland the smallest area of land was grid square SH with 4500 km^2 and the minimum number of stations in any area was 13. The minimum density of stations for any area was in square NN with 1.4 stations per 1000 km^2. In no area, therefore, was the station density less than the WMO recommended minimum for geographically simple areas although it should be pointed out that station distributions are by no means uniform within any particular area. The results of the clustering exercise for minimum and maximum temperatures are shown with the number of cluster groups recorded in each area. Extreme temperatures were chosen since these gave the most complex patterns and, rainfall apart, the largest quantity of data. (The analysis of rainfall used only the climatological stations and not the 6000 or so stations of the rainfall network.)

The smaller the number of groups represented in any one area then, presumably, the simpler is that area climatologically, while higher densities of groups indicate increasing climatological complexity. The simplest areas are Northern Ireland, where there are some 14 400 km^2, a station density of 4.6 stations per 1000 km^2 and only 3 (4) distinct groups for minimum (maximum) temperatures and the mainland area TL/TM (part of eastern England and East Anglia) with 13 100 km^2, a station density of 3

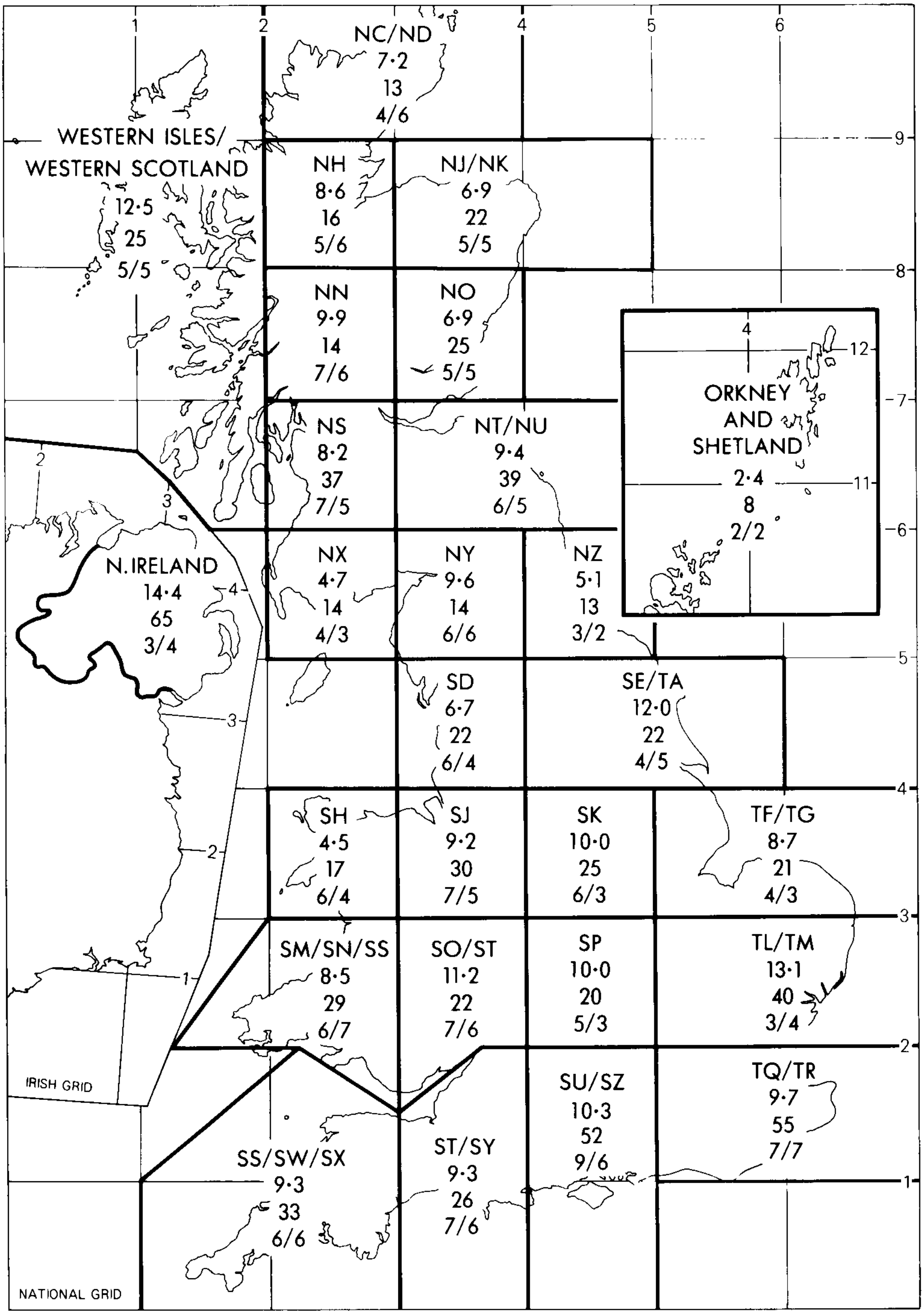

Figure 3. Areas and national grid squares showing code letters and size of land area (in units of 10^3 km^2) together with the number of ordinary climatological stations and cluster groups for minimum/maximum temperatures within each area.

stations per 1000 km^2 and only 3 (4) cluster groups. One of the more complex areas is central southern England, grid squares SU/SZ, with 10 300 km^2, a station density of 5 stations per 1000 km^2 and 9 (6) cluster groups.

An empirical measure of climatological complexity can be defined as the number of cluster groups per unit area. Taking the higher value of the maximum and minimum temperature cluster groups represented in each area then examples of 'complexity values' are 4/14.4 for Northern Ireland, 4/13.1 for TL/TM, 9/10.3 for SU/SZ, 6/4.5 for SH, and 7/8.2 for NS.

The quantitative effects of differing station density are difficult to ascertain and it is not possible to estimate how many more groups would have been produced in any particular area by increasing the number of stations. For Northern Ireland and those areas of the mainland with 30 or more stations it is fairly unlikely that many more groups would have resulted. For those areas with fewer than, say, 20 stations then it is quite possible that more groups would have resulted, particularly had different types of topography and a wider range of heights been represented by the climatological stations used in the analysis. The fact that fairly large areas of the Scottish highlands can apparently be homogeneous for maximum and minimum temperatures may simply be because many of the stations reporting are in glens, and the climate of one glen is similar to that of its neighbours. It is difficult to draw any really objective quantitative conclusions about network requirements simply because of the differing station densities and differing degrees of representativeness of the station network from area to area. In other words the 'complexity values' are somewhat uncertain in the more data-sparse areas.

Starting from the basis that Northern Ireland and grid squares TL/TM seem to be simpler climatologically than anywhere else in the United Kingdom then the climate of these areas could probably be adequately represented by the WMO minimum of one station per 1000 km^2, assuming that is that these areas comply with the WMO definition of being geographically fairly uniform. In other words, if the WMO guidance is correct then 14 stations evenly distributed over Northern Ireland or grid squares TL/TM should be sufficient to define the cluster groups derived from the analysis described above. It is not too much to argue that areas of greater geographical (or climatological) complexity require more stations to define the cluster groups deduced from the analysis described. To determine the nature of the relationship between station density required and climatological complexity would necessitate an experiment starting with many more stations than at present and repeating the clustering exercise with different numbers of stations. Future work could perhaps look at specific areas such as Northern Ireland for temperature and, perhaps more profitably, the whole of the United Kingdom for rainfall. For the time being, and pending such work, it is suggested that climatological station density-needs should be defined as being in direct proportion to the climatological complexity values derived above.

Table I shows the resultant numbers of stations and their densities for each of the areas on this basis. The application of this rule with an underpinning minimum of one station per 1000 km^2 gives some very high station densities in places, for example north-west Wales, square SH, would need 21 stations or about 4.7 per 1000 km^2. This, however, is a complex area topographically with coasts facing in all directions, coastal plains, valleys, mountains and plateaux. The calculated densities for some of the Scottish squares, NH and NN for example, could well be too low relative to some other areas because of underestimation of the number of cluster groups represented in NH and NN arising from the fairly low number of observations available for the cluster analysis.

The numbers of stations shown as a requirement makes no allowance for the uncertain future of many of the co-operating climatological stations. Even with 600 climatological stations there are relatively few with long periods of record. Some measure of redundancy is therefore desirable in the network and the actual requirement has been arbitrarily set at some 10% over and above the numbers shown.

Table I. *Number of ordinary climatological stations (OCS) and their height distribution relative to the height of the ground within the area, and the OCS requirement and density in direct proportion to the complexity value of the areas shown in Fig. 3*

Area or national grid square	Number of OCS			Station density (Number of OCS per 10^3 km^2)		Percentage of OCS at a level lower than 25, 50, 75 and 95% of total ground			
	Required	Actual	Deficit	Required	Actual	25%	50%	75%	95%
Orkney and Shetland	7	5	2	2.9	2.1	20	60	80	100
Western Isles/ Western Scotland	18	23		1.4	1.8	83	100	100	100
NC/ND	21	12	9	2.9	1.7	62	92	100	100
NH	21	15	6	2.4	1.7	73	93	93	100
NJ/NK	18	19		2.6	2.8	63	84	95	95
NN	25	10	15	3.0	1.2	90	100	100	100
NO	18	19		2.6	2.8	58	79	100	100
NS	25	34		3.0	4.1	68	82	97	100
NT/NU	21	28		2.2	3.0	39	75	100	100
NX	14	15		3.0	3.2	47	87	100	100
NY	21	11	10	2.2	1.1	45	73	82	91
NZ	11	10	1	2.2	2.0	45	80	100	100
SD	21	13	8	3.1	1.9	46	85	92	100
SE/TA	18	18		1.5	1.5	17	56	78	100
SH	21	13	8	4.7	2.9	61	92	100	100
SJ	25	26		2.7	2.8	27	54	81	100
SK	21	20	1	2.1	2.0	22	55	80	100
TF/TG	14	15	–	1.6	1.7	40	53	73	93
SM/SN/SS	25	25	–	2.9	2.9	60	84	92	100
SO/ST	25	14	11	2.2	1.3	57	78	86	100
SP	18	17	1	1.8	1.7	56	89	100	100
TL/TM	14	30		1.1	2.3	13	42	80	94
SS/SW/SX	21	37		2.3	3.5	59	70	79	94
ST/SY	25	21	4	2.7	2.3	43	62	81	95
SU/SZ	32	43		3.1	4.2	51	62	78	96
TQ/TR	25	43	–	2.6	4.4	36	60	84	99
N. Ireland	14	64	–	1.0	4.4	No height data on data set			
Total	539	600							

Monitoring the climatological network

The data given in Table I can be used to give a first indication of those parts of the United Kingdom where there are either too many climatological stations or not enough. It is, of course, also necessary to take into account the actual locations and spatial distribution of the stations and, in particular, the height distribution which is currently by no means ideal. Where there are deficiencies in the network then positive action can be taken by the Meteorological Office to recruit co-operating observers in order to open new stations or to ensure the continuation of existing ones. The data can also be used as an aid to decisions regarding the siting of automatic equipment for climatological purposes. Table I shows, for each of the areas of Fig. 3, the actual number of climatological stations, and the height distribution of those stations relative to the heights of ground within each area. It can be seen that the total number of climatological stations exceeds the total requirement. However, the distribution is by no means ideal, even when considered simply as numbers of stations in areas as large as those in Fig. 3 and without regard to the spatial distribution within each area. Similarly, the height distribution of stations leaves a lot to be desired. Some 20% of the land surface of the United Kingdom is above 300 metres but only 3% of the climatological stations are above that height.

Some areas have a satisfactory height distribution of stations, for example area SK with 80% of stations situated at locations representing the lowest 75% of the ground and 22% of the stations the lowest 25% of the ground. Other areas have a poor distribution, for example area NN with 90% of the stations situated at locations representing the lowest 25% of the ground and all stations the lowest 50% of the ground. (Note: areas with an adequate number of stations may have a poor height distribution, for example area NJ/NK where 63% of the stations are situated at locations representing the lowest 25% of the ground.)

The station densities given as requirements in Table I may, of course, be incompatible with the demand for data. In some areas it may not be sensible to try to achieve the prescribed coverage when considered in terms of cost to benefit ratios. What is scientifically or meteorologically desirable may not be economically necessary. Conversely, in some areas the demand for data to answer queries regarding weather details on special occasions may entail having a greater density of stations than is necessary just to determine climatological parameters. For example, an area may need a certain number of stations to define the rainfall climatology but many more to define rainfall associated with specific convective situations.

Conclusions

The use of factor analysis can lead to increased objectivity regarding the definition of climatologically homogeneous areas for individual elements and, as such, can be used to determine requirements for specific instruments. This could be of value in helping to decide optimum dispositions of new sensor systems to replace existing ones. Factor analysis does not define areas that are homogeneous for all climatological parameters. It can, however, be used to help define network densities in predetermined geographical areas of the United Kingdom. This information is of use in introducing some objectivity to the allocation of resources to the network as a whole and to maximize the benefit of any such expenditure.

References

Spackman, E. A. and Singleton, F. 1982 Recent developments in the quality control of climatological data. *Meteorol Mag*, **111**, 301–311.

World Meteorological Organization 1960 Guide to climatological practices. Geneva, WMO No. 100 (Currently under revision).

1981 Manual on the global observing system. Vol. 1 Global aspects. Geneva, WMO No. 544.

Ministry of Agriculture, Fisheries and Food 1976 The agricultural climate of England and Wales. Areal averages 1941–70. London. *Technic Bull* No. 35.

551.509.324.2:551.578.13:551.578.43(569.4)

A rain–snow discrimination study for Jerusalem

By L. M. Druyan and H. Berger

(Department of Geography, Bar-Ilan University, Ramat-Gan, Israel)

Summary

Rain–snow discrimination for Jerusalem is studied by examining upper-air meteorological variables observed over Israel, Cyprus and Lebanon. Scatter diagrams of snow events plotted according to pairs of variables observed usually 3–15 hours prior to the onset of snow show generally different distributions from rain events. The differences show the importance of local flow patterns, as well as the lower-troposphere temperature north-west and north of Israel, to subsequent snow. Interpretation of the snow frequency by area (on the two most successful graphs) as an indication of future probability suggests application of the results to rain–snow discrimination forecasting.

Introduction

Snowfall in Israel is confined mostly to the higher elevations of which Jerusalem (800 m) is the most populous. Jerusalem's mean minimum temperature for the coldest month (January) is a moderate 5 °C so that snowfall there requires the penetration of anomalously cold air. Although forecasting precipitation in general is by no means a trivial problem, rain–snow discrimination presents a particular challenge because a synoptic regime that provides efficient cold air advection will quite often bring rain or possibly sleet to Jerusalem and not snow.

There is considerable interest generated by the particular charm of Jerusalem, the Holy City, blanketed with the white of snow, for thousands of tourists and residents alike. The city is, however, also a bustling urban centre so that an accurate forecast of the infrequent snow event is of great importance to the municipality when preparing crews and equipment for snow removal.

The statistics of snow occurrence over mountainous and hilly regions in Israel are given by Bitan and Ben-Rubi (1978) and for Jerusalem in particular by Batz (1981). Batz shows, for example, that since 1948 snowfall has been observed, on average, in three out of four years. Moreover, although the snow depth once reached 50 cm, the median of maximum seasonal depths is only about 7 cm for this period. Both the studies review the synoptic weather patterns favourable for snow in Israel: a typical pattern shows cold advection from the north or north-east around the western side of a sharp trough or low of great vertical extent; the axis of the system usually extends toward the north-east from Israel. Precipitation can be initiated by low-level convergence within sea-level troughs, some of which are cold frontal zones, and is often enhanced by destabilization due to warm coastal waters and by the orographic influence of the Judean Hills.

A graphical method for rain–snow discrimination was previously based on upper-air observations from Israel's single radiosonde station (Druyan 1977, 1980). A summary of the second of these papers, which were published in Hebrew, is given in the Appendix. While results of the earlier work can provide useful forecast guidance, it is apparent that an important proportion of snow events are ambiguously predicted by the graph. This shortcoming prompted the present research.

No doubt conditions beyond Israel's borders are important in creating the environment that determines whether or not snow falls in Jerusalem during subsequent hours. The present study widens the search for predictors to include upper-air data from over Cyprus, Lebanon, Turkey and Syria.

Data

For the purposes of the study a snow episode is defined as a 12-hour period during which at least one observation of falling snow was made at the Jerusalem observatory atop the downtown Generali Building. This definition of course qualifies a maximum number of events. Although we did not examine the conditions for mixed rain and snow, we assume that they occur for borderline snow indications; here such situations are classified as 'snow'. Application of the above definition yielded 63 snow events from the meteorological archives for the period 1959–80. Control data consist of some 47 events during which only rain fell in Jerusalem on days when the surface temperature fell below 5 °C.

A search was made for the meteorological variables that best reflect differences in the atmospheric conditions preceding snow and rain respectively. These variables, which have potential as predictors, were chosen from synoptic upper-air observations made at least three hours before the initial snow observation and usually not more than 15 hours earlier; since radiosonde releases in Israel before 1964 were made only once per day, the data include 13 snow events for which the atmospheric conditions were observed 15–22 hours before the commencement of snowfall. The Israeli stations (Be'er Yacov before 1964, then Bet Dagan) are located in the central coastal plain near Tel Aviv. The variables over Israel included observations of 1000–500 mb and 1000–850 mb thicknesses, geopotential at 1000 mb, 850 mb and 500 mb, and 850 mb wind speeds and directions. Temperatures and wind directions were taken from operational 850 mb charts over the stations Nicosia (Cyprus), Beirut (Lebanon), Ankara (Turkey) and Latakia (Syria).

Results

The meteorological variables were tried in all possible combinations on scatter diagrams to examine which of them showed the most efficient rain–snow discrimination for subsequent precipitation over Jerusalem. As in Druyan (1980) the most important single parameter proved to be the Israel 1000–500 mb thickness (Z).

This parameter was previously used for predicting precipitation type (Wagner 1957) and is one of three predictors for automated rain–snow discrimination guidance provided for US cities (Glahn and Bocchieri 1975). The latter uses the so-called Model Output Statistics procedures and the predictors are therefore themselves derived from numerical forecasts.

The analysis showed that results are considerably improved by considering the 850 mb wind direction over Nicosia (D_N) simultaneously with Z. Fig. 1 shows all the events plotted according to their corresponding observations of Z (horizontal axis) and D_N (vertical axis). The scatter diagram shows that in the area labelled A snow followed the observation every time. The value of Z was here less than about 5350 which corresponds to a mean layer temperature of −9 °C. Although these are the conditions some 3–15 hours before snow onset, it is interesting to estimate the height of the 0 °C isotherm implied. For example, a moist adiabatic lapse rate with mean 1000–500 mb temperature of −9 °C intersects the 0 °C isotherm at about 850 mb. This pressure level is about 50 m above the ground over Jerusalem. We note, however, that the temperature structure over this elevated region is probably somewhat different from that of the free-air column measured by the radiosonde over the adjacent coastal plain. Glahn and Bocchieri (1975) found that a 50% probability of snow is indicated by thicknesses of 5360–5430 gpm over the US cities that are at approximately the same altitude as Jerusalem. Judging by the relative occurrence of snow and rain events for these thicknesses as shown in Fig. 1, the Jerusalem data are quite consistent with these findings.

It can be seen from Fig. 1 that the predictor D_N becomes important when Z is initially too high; a more northerly flow undoubtedly expedites the advection of cold air into the region. Thus, the proportion of snow events in area B_1 is 77% while in area B_2 41% of the events are snow; southerly or south-easterly flow over Cyprus, not uncommon before even 'cold' rain, seems to preclude subsequent snow in Jerusalem (events in area C). Reference to the characteristic maps for snow situations recalls the importance of a strong northerly wind component over the eastern Mediterranean Sea (Bitan and Ben-Rubi 1978, Batz 1981). We determined also that better discrimination is achieved by using the Nicosia wind rather than the wind over Israel, perhaps because the former is upstream from the forecast target area.

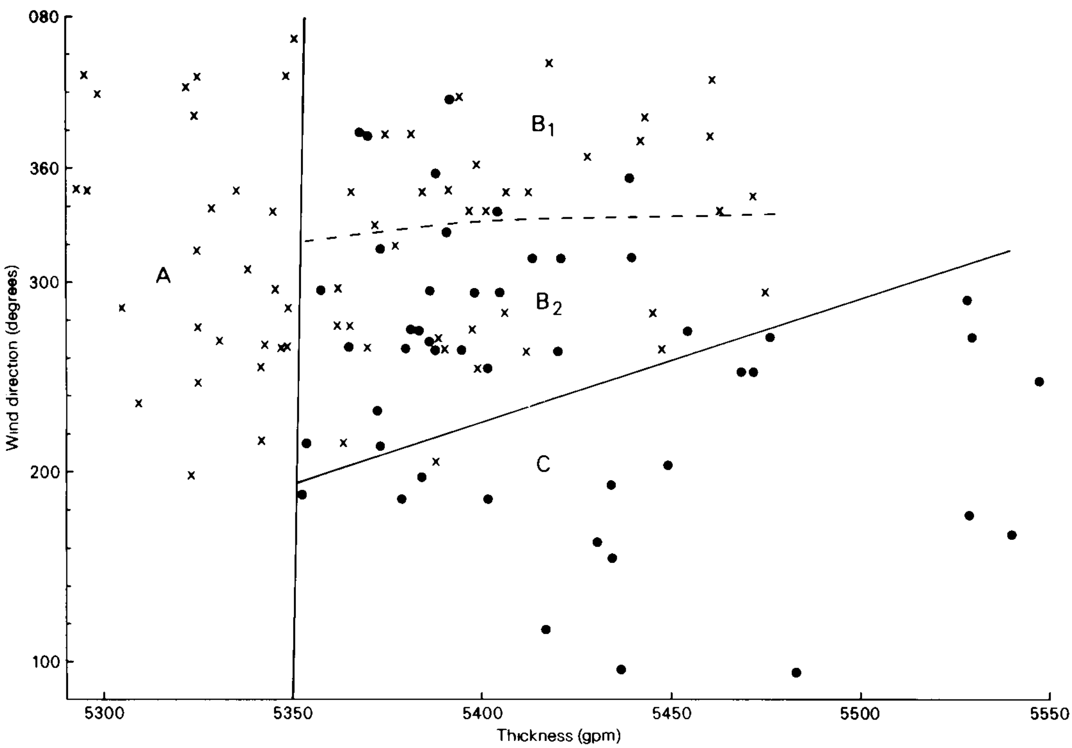

Figure 1. Distribution of snow (x) and rain events (dots) plotted according to earlier observations of 850 mb wind direction over Cyprus and 500–1000 mb thickness over Israel.

The mixture of snow and rain occurrences followed by the conditions prescribed by area B (Fig. 1) means that these two predictors sometimes cannot provide complete discrimination. The remaining predictors were tried via scatter diagrams for all the events appearing in areas B_1 and B_2. Fig. 2 shows the most successful of these plots; here the vertical axis gives the 850 mb wind direction over Beirut (D_B) and the horizontal axis the 850 mb temperature (T_B), also over Beirut. Many of the snow cases for which the first two predictors (Z and D_N) were not decisive are conveniently relegated to the cold left side of Fig. 2. The data show that $T_B < -2$ °C is a sufficient condition for subsequent snow in Jerusalem (area D of Fig. 2(a)). Rather surprisingly, there is strong evidence that at warmer values of T_B, rain, rather than snow, is favoured by north-westerly winds over Beirut (the events in area E of Fig. 2(a)) while snow is more frequent following south-westerlies (area F).

This indication becomes even more apparent when the data from the mixed-event area B_2 (of Fig. 1) are isolated on a similar plot (Fig. 2(b)). The slopes of the boundaries between areas E and F and H and J (Figs 2(a) and 2(b)) imply that the warmer T_B is, the more southerly the wind over Lebanon must be for eventual snow. Why should north-westerly flow virtually preclude snow at these warmer temperatures

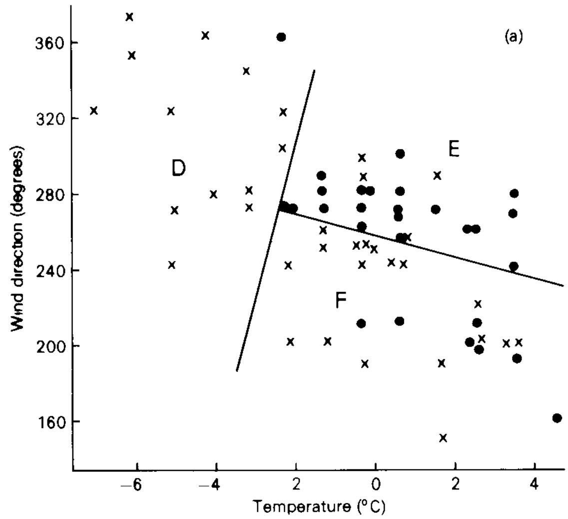

Figure 2(a). Snow (x) and rain events (dots) from areas B_1 and B_2 of Fig. 1 plotted according to earlier observations of 850 mb wind direction and temperature both over Beirut.

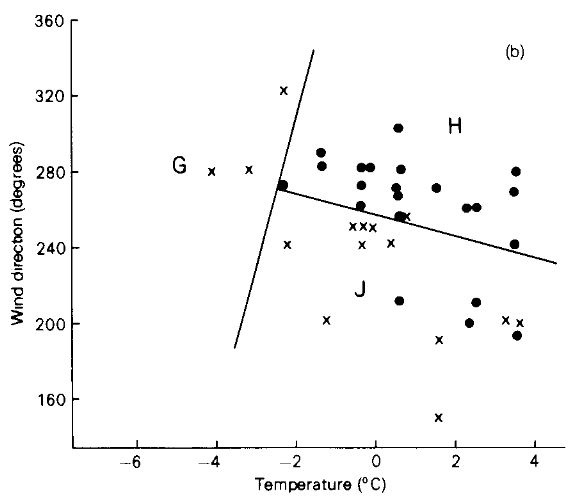

Figure 2(b). Same as Fig. 2(a) but for events from area B_2 of Fig. 1 only.

while south-westerlies presage a high snow frequency? By way of explanation we point out that north-westerlies indicate a likely trough position downstream (to the east) of both stations and it is possible that in these situations the coldest air has already reached the Israel–Lebanon longitude. North-westerlies at both stations may also reflect a too-shallow trough with insufficient advection from the cold air reservoirs of northern Europe. This situation is depicted schematically in Fig. 3(a). On the other hand, a veering of wind direction from Lebanon to Cyprus implies a trough upstream of Israel and a likelihood of an additional surge of air, cold enough for subsequent snow in Jerusalem, as depicted schematically in Fig. 3(b).

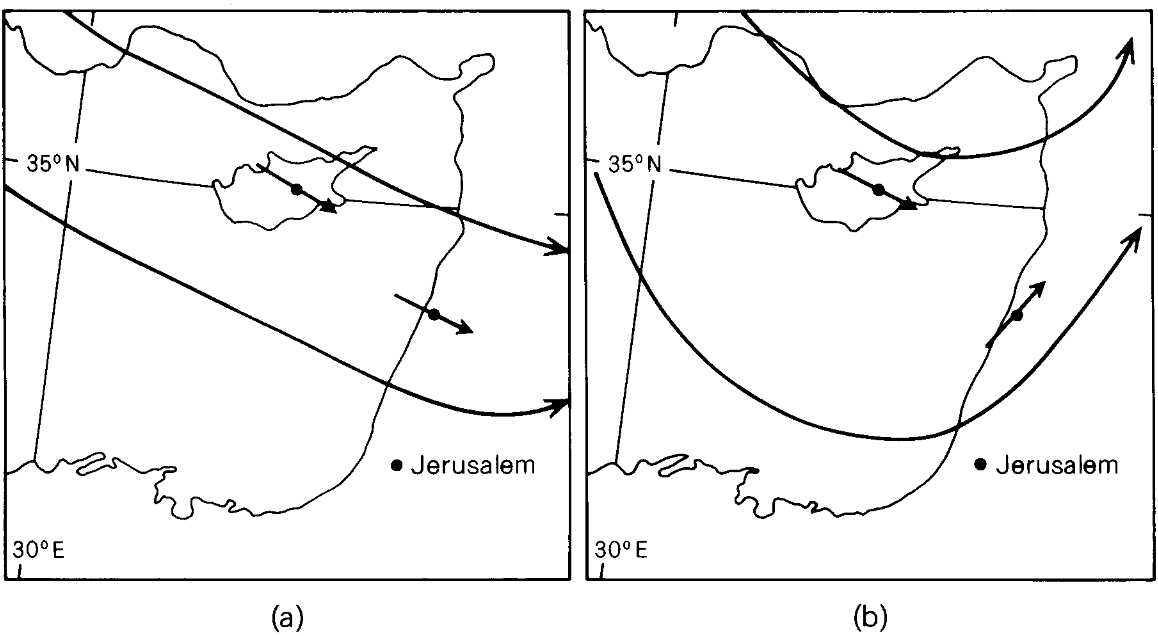

Figure 3. Schematic representation of 850 mb flow for north-westerlies over Cyprus and Lebanon (a), and for south-westerly flow over Beirut (b).

Application

The results suggest the following procedure for assigning a probability (conditional on the expectation of precipitation and surface temperature below 5 °C) of snow in Jerusalem. Observations of Z and D_N determine the primary category for use with Fig. 1:

observations qualifying for area A ... 100% probability of snow,
observations qualifying for area C ... 5% probability of snow,
observations qualifying for area B_1 ($T_B < -2$ °C) ... 100% probability of snow,
observations qualifying for area B_1 ($T_B > -2$ °C) ... 77% probability of snow, and
observations qualifying for area B_2, refer to Fig. 2(b) where:

area G ... 100% probability of snow,
area H ... 5% probability of snow, and
area J ... 73% probability of snow.

By way of comparison we note that during the period January 1976–March 1980, Jerusalem experienced 63 precipitation days during which the local surface temperature fell below 5 °C. On 16 of these at least one observation of snow was reported, implying a climatological expectation of only 25.4% for cold precipitation days; for precipitation days in general, the climatological expectation of snow is, of course, much lower.

Conclusion

We have considered 21 years of data and have used the most liberal definition of a snow event to maximize the data base. Differences have been documented between the atmospheric conditions which precede snow and rain in Jerusalem on cold days (surface temperature below 5 °C). During the period under study snow occurred following 1000–500 mb thicknesses over Israel less than 5350 gpm and was considerably more frequent than rain following even greater thicknesses whenever 850 mb winds over Cyprus were from the north through north-east. Rain without snow in Jerusalem was associated with 850 mb temperatures north of Israel warmer than −2 °C combined with west to north-west low-level flow over Cyprus and Lebanon.

The scatter diagrams which demonstrate the relative importance of selected upper-air variables in rain–snow discrimination at Jerusalem can be useful for prediction. They are, however, somewhat uncertain over certain ranges of several variables that occurred infrequently in the data set. To use the diagrams for forecasting, the indicated frequency of snow within appropriate ranges of the 'predictors' is interpreted as probability; the boundaries between radically different probability categories should be regarded as transitions representing intermediate probabilities.

The present study adds to the findings published in Druyan (1980) in that it considers upstream conditions. The results suggest that multiple regression or discriminant analysis could quantify the relative importance of each meteorological variable. Here the relationships between atmospheric conditions and rain–snow discrimination are shown qualitatively and in a graphical presentation which is suitable for operational forecasting.

References

Batz, U. 1981 Snow in Jerusalem. *Meteorologia B'Yisrael*, **16**, 31–44 (Hebrew).

Bitan, A. and Ben-Rubi, P. 1978 The distribution of snow in Israel. *Geojournal*, **2**, 557–567.

Druyan, L. 1977 Forecasting snow for Jerusalem with an objective method. *Meteorologia B'Yisrael*, **13**, 7–10 (Hebrew).

1980 A new graph for forecasting snow for Jerusalem. *Meteorologia B'Yisrael*, **15**, 5–6 (Hebrew).

Glahn, H. R. and Bocchieri, J. R. 1975 Objective estimation of the conditional probability of frozen precipitation. *Mon Weather Rev*, **103**, 3–15.

Wagner, J. 1957 Mean temperature from 1000 mb to 500 mb as a predictor of precipitation type. *Bull Am Meteorol Soc*, **38**, 584–590.

Appendix—Summary of Druyan (1980)

Fig. A.1. shows the distribution of snow and rain events in Jerusalem taken from the years 1959–77. These data have been plotted as in Figs 1–3 but here the observations that precede the events are the height of the 0 °C isotherm (vertical axis) and the 500–1000 mb thickness (horizontal axis), both over Israel's central coastal plain (Bet Dagan or Be'er Yacov). The symbols, the definition of snow and rain and the time interval between the upper-air parameters and snow onset in Jerusalem are the same as in the present study. The strong relationship between the height of the 0 °C isotherm and the 500–1000 mb thickness notwithstanding, the scatter of the events suggests that an advantage is gained by considering them in concert. The trend of increasing frequency of snow following low heights of the 0 °C isotherm and low thicknesses which is documented by the diagram undoubtedly offers useful information to the forecaster. Unfortunately, rain-snow discrimination remains ambiguous for certain intervals presumably because both predictors reflect only local conditions.

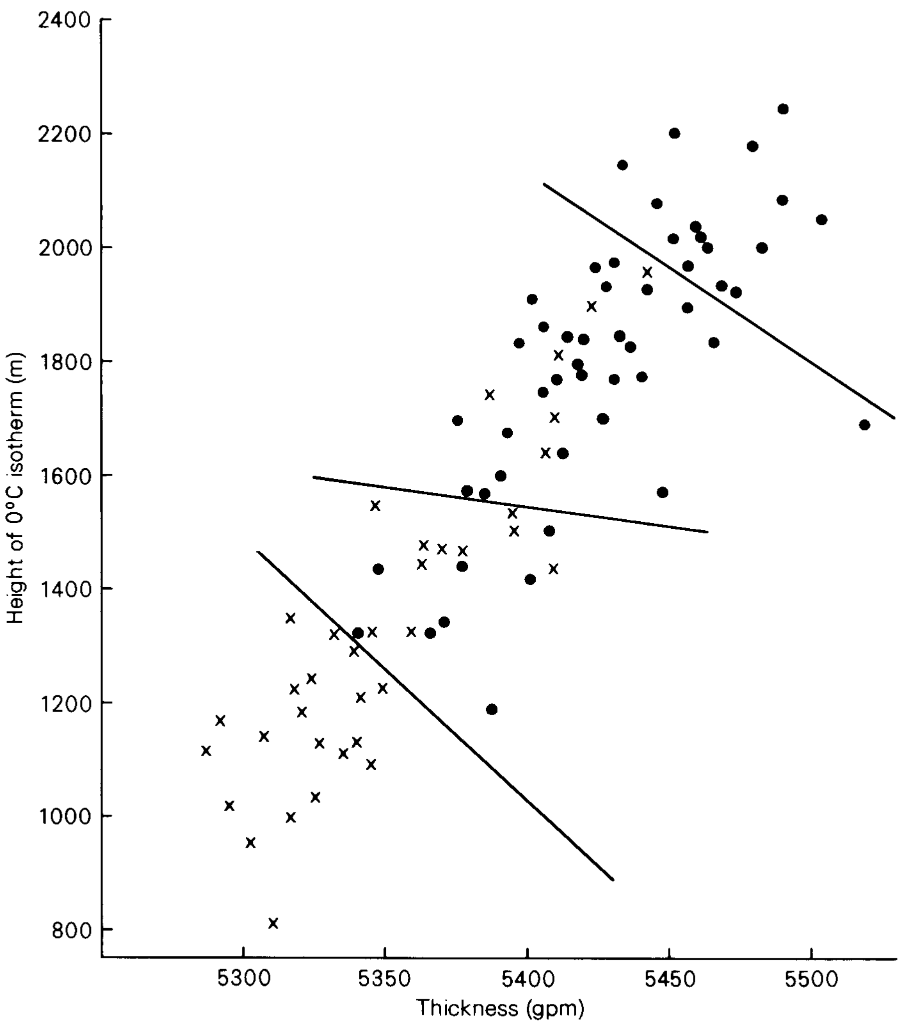

Figure A.1. Snow (x) and rain events (dots) from the years 1959–77 at Jerusalem plotted according to height of the 0 °C isotherm and 500–1000 mb thickness observed over Israel (from Druyan 1980).

551.511.3:551.541:551.553.3(414)

Oscillations of wind at Edinburgh due to travelling gravity waves

By K. J. Weston

(Department of Meteorology, University of Edinburgh)

Summary

Cases in which the surface wind exhibits periodic oscillations are examined to establish the conditions under which they are most commonly observed. All oscillations were found to occur at night in polar or arctic airstreams when a stable layer was present at about 850 mb above a layer of almost neutral static stability.

1. Introduction

Oscillations within a stably stratified layer of air — gravity waves — are extremely common at all levels in the troposphere. The most familiar type, and those which have been most intensely studied, are stationary gravity waves, or lee waves; but travelling gravity waves have also received attention. Travelling waves are commonly observed on microbarograph records as periodic pressure variations of amplitude up to about 1 millibar and periods generally between 5 and 15 minutes. Keliher (1975) analysed 280 gravity wave events and concluded that about half were shear-induced in layers where the Richardson number was small. Gedzelman and Rilling (1978) detected 88 examples of gravity waves during a two-month period using a network of four microbarographs. Their results also suggested that such waves are often generated by dynamic instability of the wind profile in the upper troposphere and that their pressure amplitudes are greatly enhanced by the presence of a layer of high static stability in the lower troposphere.

Rather less frequently observed are regular periodic oscillations of surface wind due to gravity waves. An early analysis of such events was performed by Gossard and Munk (1954), who analysed seven occasions of waves in California all of which occurred in the presence of a low-level stable layer with base at 300 m or below. The oscillations often followed a reversal of a land- and sea-breeze circulation. More recently Richner and Nater (1981) analysed observations obtained at sites near Zurich, Switzerland and compared observed phase velocities with theoretical values. The present article is a study of cases of oscillations of wind speed or direction, or both, over a five-year period at Edinburgh to establish the conditions most likely to give rise to such occurrences. Data from Shanwell radiosonde station are used to examine upper winds and temperatures on wave occasions.

2. Characteristics of the oscillations

During the period studied (1978–82 inclusive), nine occasions of well-defined oscillations of surface wind were identified, all occurring in arctic or polar maritime air masses. In addition to these, there was a similar number of identifiable, but minor, oscillations which were not included in the study. Fig. 1 shows the clearest example: there are pronounced oscillations that are in phase and have amplitudes of about 2.5 m s^{-1} and 40° respectively in speed and direction.

Table I summarizes observations from all nine cases. On six occasions there were clear oscillations in both speed and direction while the remaining three displayed regular variations only in direction.

Fig. 2 shows a satellite photograph taken over Scotland at a time when oscillations of surface wind were occurring (same occasion as for Fig. 1). Two cloud layers can be seen, the levels of which can readily be identified from humidity and temperature soundings taken over Scotland. There is a layer of closed cells of stratocumulus at about 850 mb over and to the north of Scotland, and rather dense cirrus at about 400 mb over and to the west of Scotland; this cirrus is associated with a warm front approaching from the Atlantic. Waves can be seen in both these cloud layers over much of Scotland. Of particular interest are those in the stratocumulus over north-east Scotland where there are two sets of waves with different orientations. One set has an orientation approximately north to south, as have the waves downwind (eastward) of the Faeroes (F) and Shetland (S). All these waves are perpendicular to the wind at stratocumulus level and are likely to be stationary gravity waves. However, the second set of waves has an orientation approximately south-west to north-east with a distinct curvature and they are probably travelling gravity waves.

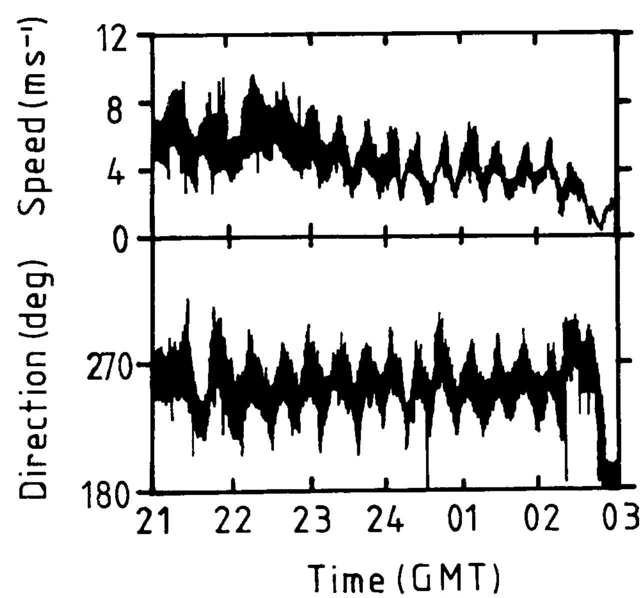

Figure 1. Anemogram for 22/23 March 1982 recorded at the University of Edinburgh.

Table I. *Amplitude and period of oscillations of surface wind at Edinburgh*

Date	Time (GMT)	Amplitude Direction (degrees)	Amplitude Speed (m s $^{-1}$)		Period (minutes)
30 Aug 1978	0300 - 0730	40	1.0	in phase	25
8 Feb 1979	0400 - 0800	90	2.0	in phase	26
18 Jul 1979	2000 - 2400	30			40
11 Sept 1979	1930 - 2200	30	2.0	in phase	28 (speed) 14 (direction)
21 Sept 1979	2130 - 0030	30			22
29 Feb 1980	2000 - 0100	60	3.0	in phase	irregular
3 Mar 1980	0000 - 0700	90	2.5	in phase	28
23 Apr 1981	0230 - 0530	40	–		29
22 Mar 1982	2130 -0330	40	2.5	in phase	20

Photograph by courtesy of Dundee University

Figure 2. NOAA 5 satellite picture, 0335 GMT, 23 March 1982; AVHRR infra-red image. The north arrow is aligned along the Greenwich meridian. Waves can be seen to the east of the Faeroes (F) and Shetland (S) and over much of Scotland.

All nine cases of pronounced wave motion occurred during night-time, as did all other cases of identifiable waves in this data set. Table I shows the time of occurrence of waves, as identified from anemograms. The non-occurrence during day-time is, no doubt, partly due to the greater difficulty of identification caused by a more variable wind with a higher gust amplitude; but this cannot be the whole explanation because many of the waves are of sufficiently large amplitude to stand out against this variability. Significantly, on all nine occasions, lee waves were visible on images from polar-orbiting satellites during the pass prior to the occurrence of the wind oscillations.

3. Thermal structure

As most of the waves occurred at or near midnight, the 00 GMT radiosonde soundings from Shanwell (about 50 km north-north-east of Edinburgh) are fairly representative of conditions during wave occurrence. Fig. 3 is an analysis of the thermal structure on wave occasions and shows the levels of stable layers in which the lapse rate is less than half that of the dry adiabatic. The figure represents stability in terms of the increase of potential temperature in °C per km. On all nine occasions there was a markedly stable layer between about 850 and 750 mb. Below these stable layers the lapse rates were close to the dry adiabatic, ranging between 7.5 and 9.3 °C per km, with an average of 8.4 °C per km.

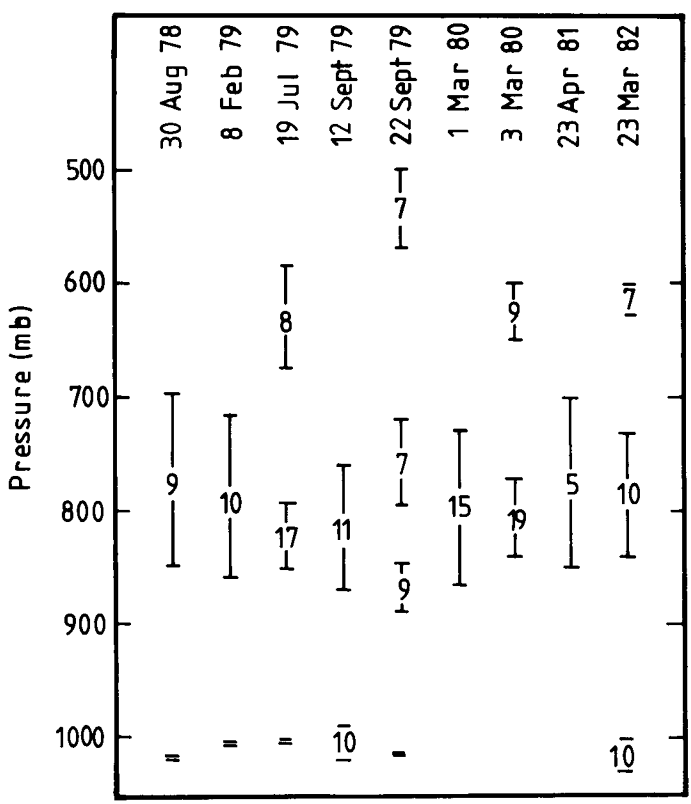

Figure 3. The extent of layers with a lapse rate less than half the dry adiabatic lapse rate. Figures show the increase of potential temperature in °C per km but values are not shown for very shallow layers at the surface.

It can be seen that there was only a small variation in height of the base of the stable layer so that a composite temperature sounding, with height normalized with respect to the height of this base, can readily be drawn; this is shown in Fig. 4. Thus the thermal stratification typical of wave occasions is a shallow stable layer at the surface with a layer above, in which the lapse rate is close to the dry adiabatic, which in turn is capped by an inversion.

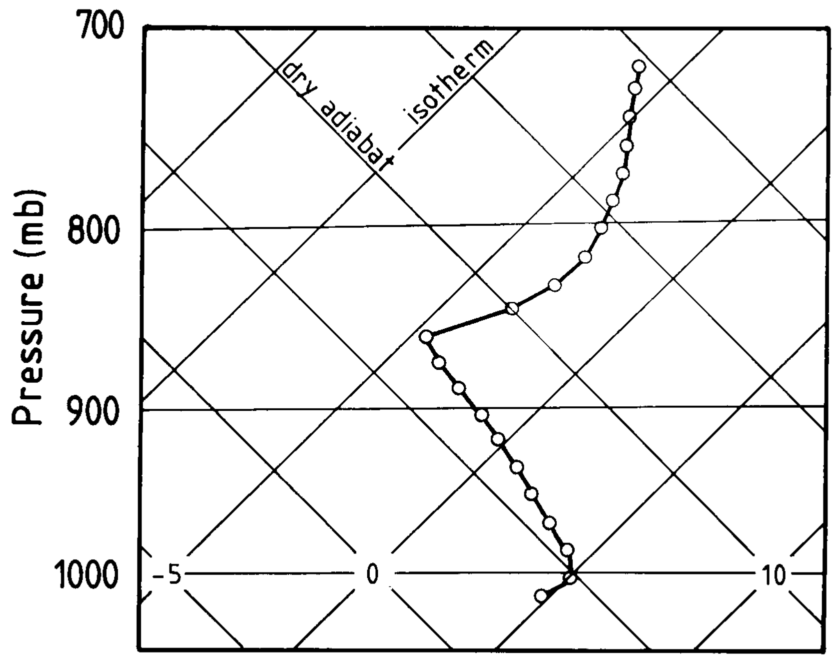

Figure 4. A composite sounding for nine occasions of gravity waves. Values of potential temperature were averaged at heights normalized with respect to the level of the base of stable layers near 850 mb. Isotherms and adiabats are shown at intervals of 5 °C.

4. Concluding remarks

Gravity waves in the lower troposphere of sufficient amplitude to give marked oscillations of surface wind appear to occur on occasions with a marked temperature inversion, beneath which there is a layer with a lapse rate close to the dry adiabatic. All cases in this study occurred at night in polar or arctic maritime airstreams, so that a shallow stable layer at the surface was probably present on all occasions. Lee waves were observed on all occasions prior to the oscillatory wind events.

References

Gedzelman, S. D. and Rilling, R. A. 1978 Short-period atmospheric gravity waves: a study of their dynamic and synoptic features. *Mon Weather Rev*, **106**, 196–210.

Gossard, E. and Munk, W. 1954 On gravity waves in the atmosphere. *J Meteorol*, **11**, 259–269.

Keliher, T. E. 1975 The occurrence of microbarograph-detected gravity waves compared with the existence of dynamically unstable wind shear layers. *J Geophys Res*, **80**, 2967–2976.

Richner, H. and Nater, W. 1981 A comparison of gravity wave phase velocities calculated from the impedance equation and pressure data. *Geophys Astrophys Fluid Dyn*, **17**, 15–26.

551.521.16

Measurement of low levels of daylight on 6 August 1981

By P. J. Littlefair

(Building Research Establishment, Department of the Environment, Garston)

Summary

Armstrong (1983) has presented radiation data for 6 August 1981, a day when intense darkness enveloped much of southern England around midday. At Bracknell global irradiances were well below the 1% percentile for most of the day. At the same time daylight measurements were continuously being made at Garston, Hertfordshire, and these are reported briefly here.

Since February 1981 daylight illuminances have been recorded continuously at Garston, Hertfordshire (51.7° N, 0.4° W). Measurements are made on vertical external planes and inside model rooms, as well as the more usual measurements of horizontal total and diffuse external illuminance. The purpose of the work is to improve methods for predicting daylight availability and lighting energy consumption inside buildings (Littlefair 1983).

During normal working hours each illuminance is measured every minute; the variation with time of horizontal total illuminance on 6 August 1981 is plotted in Fig. 1. The overall outline of the graph is

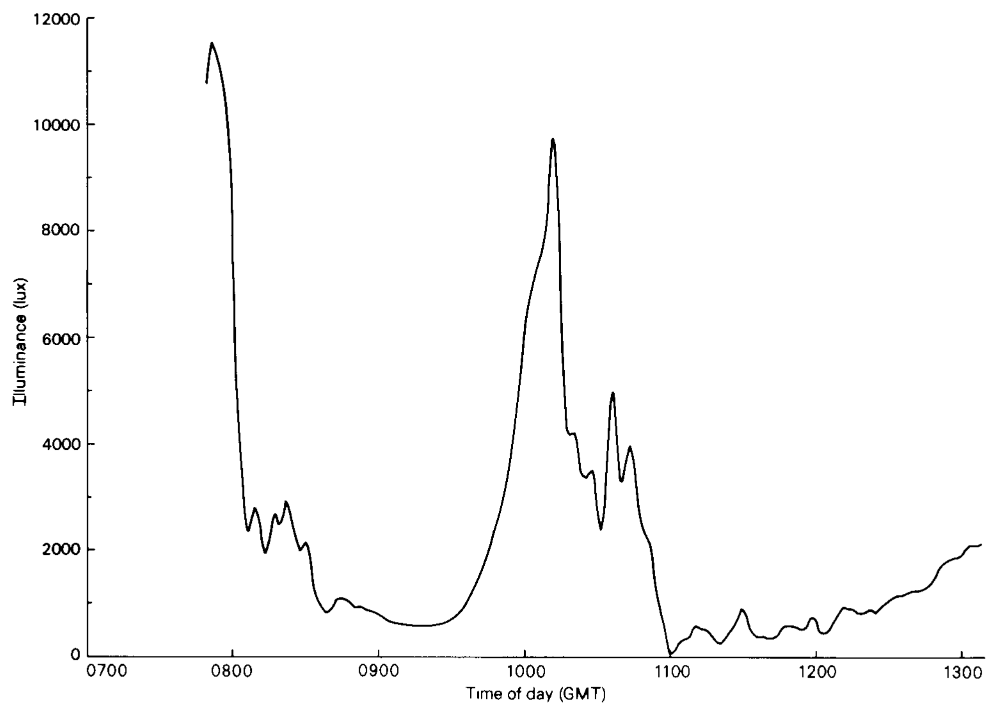

Figure 1. Horizontal unobstructed daylight illuminance under heavily overcast skies at Garston on 6 August 1981.

similar to the variation in irradiance presented by Armstrong (1983). However, the greater sensitivity and fast response time of the daylight sensors enable a detailed analysis of the lowest illuminance levels to be carried out.

This is presented in Fig. 2, which shows the variation in horizontal total illuminance between 1050 and 1210 GMT. The lowest value recorded was 89 ± 7 lux just after 1100 GMT. Between 1100 and 1200 GMT the unobstructed horizontal illuminance did not exceed 1000 lux. Under overcast skies 1 W/m^2 corresponds approximately to 115 lux (Krochmann and Seidl 1974).

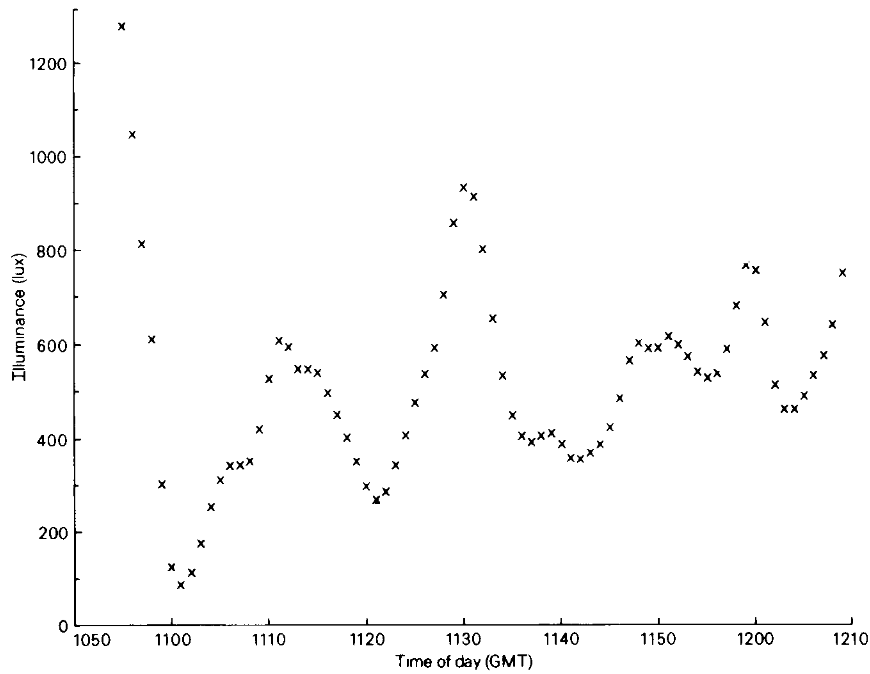

Figure 2. Minimum values of horizontal unobstructed daylight illuminance at Garston on 6 August 1981.

Krochmann and Seidl also give formulae for the average illuminance from an overcast sky; that due to Krochmann gives a value of 16 500 lux for this time of day and year.

Acknowledgement

The work described forms part of the research program of the Building Research Establishment of the Department of the Environment, and is published by permission of the Director.

References

Armstrong, R. J. 1983 Global solar radiation measurement on 6 August 1981. A day of midday darkness. *Meteorol Mag*, **112**, 200–207.

Krochmann, J. and Seidl, M. 1974 Quantitative data on daylight for illuminating engineering. *Light Res & Technol*, **6**, 165–171.

Littlefair, P. J. 1983 Daylight for lighting. Presented at Building Research Establishment seminar, 8 March 1983. Design and selection of lighting controls. Building Research Establishment, Garston.

THE METEOROLOGICAL MAGAZINE

No. 1341 April 1984 Vol. 113

CONTENTS

	Page
Climatological network design. F. Singleton and E. A. Spackman	77
A rain–snow discrimination study for Jerusalem. L. M. Druyan and H. Berger	90
Oscillations of wind at Edinburgh due to travelling gravity waves. K. J. Weston..	97
Measurement of low levels of daylight on 6 August 1981. P. J. Littlefair..	102

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

Applications for postal subscriptions should be made to HMSO, PO Box 276, London SW8 5DT.

Complete volumes of 'Meteorological Magazine' beginning with Volume 54 are now available in microfilm form from University Microfilms International, 18 Bedford Row, London WC1R 4EJ, England.

Full-size reprints of out-of-print issues are obtainable from Johnson Reprint Co. Ltd, 24–28 Oval Road, London NW1 7DX, England.

Please write to Kraus Microfiche, Rte 100, Millwood, NY 10546, USA, for information concerning microfiche issues.

Printed in England by Robendene Ltd, Amersham, Bucks,
and published by
HER MAJESTY'S STATIONERY OFFICE

£2.20 monthly **Annual subscription £26.50 including postage**

Dd. 736047 C15 4/84

ISBN 0 11 727232 9
ISSN 0026–1149