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METEOROLOGICAL OFFICE

INVESTIGATIONS DIVISION TECHNICAL NOTE NO 9

R N HARDY

Rates of fall of snow, mixed precipitation and freezing rain

1. Introduction

A knowledge of likely frequencies of high rates of snowfall, sleet* and freezing rain or drizzle is of interest in specifying design standards in the field of aviation. This note primarily deals with snow, but it is believed that the results can be extended to cover sleet and freezing precipitation.

The requirement is to specify probability levels for very high rates of precipitation. It is not sufficient, even if it were possible, to estimate an all time extreme value, because the penalties in weight, cost or efficiency involved in combatting such an unlikely event would, when integrated over the lifetime of a fleet of aircraft, increase rather than reduce the accident risk.

Recording rain gauges have been in use in the Meteorological Office for some years and several stations compile routine statistics of hourly rainfall amounts (in tenths mm) and durations (in tenths hr). Many of these data have been transcribed to magnetic tape and the problem of assessing high rates of snowfall is approached through a computer analysis of these.

2. The Analysis Scheme

Because of difficulties of measurement there is little direct information on rates of snowfall. The Meteorological Office tilting-syphon rain recorder used at main observing stations includes a small heater (25W lamp) to protect it against frost; thus rates of sleet and slight snow at near freezing point may be measured to a good approximation. However, although procedures are laid down, large rates of fall of frozen precipitation over short periods cannot be determined accurately even by the most skilled and dedicated observer.

The total precipitable water in the atmosphere at a particular place has been found[1] to be highly correlated with the surface dew point, which when precipitation is falling is itself closely related to the surface air temperature. This explains why there is a fairly well defined, albeit not large, decrease with surface temperature in the proportion of precipitation falling at high rates (this is not true at the temperature extremes which probably mostly correspond to clear anti-cyclonic conditions). It is possible in view of this, to consider rainfall-rate statistics for a temperature band wherein it is known that a large proportion of the precipitation will have fallen as rain, and argue that this represents an upper envelope for snowfall rates. This is the approach adopted here.

Hourly precipitation amounts in tenths of mm and durations in tenths of an hour were considered for 23 locations in the UK over periods ranging from 6 to 23 years, 376 years' data in all. Initially frequency distributions of the duration of precipitation at various rates were computed for each 2.5 degC temperature band from -10 to +20 degC. The expected decrease in the proportion of large rainfall rates with temperature was evident, but it was also clear that small amounts of precipitation were reported at temperatures well below zero degC. The accuracy of these reports as regards rates of fall must be regarded with caution, but it was

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*Throughout this report sleet refers to a mixture of snow and rain, or snow and drizzle.

considered that they should be included. It appeared that by taking 2.5 degC as the upper temperature threshold, it was certain that a large proportion of precipitation considered would have fallen as rain, whilst most sleet, almost all snow and a little hail would also be included. Hence percentages of precipitation exceeding various rates with air temperature less than 2.5 degC were computed for each station. The few periods of precipitation at very high rates were individually checked against the reported weather, and cases of ice pellets or grapel excluded. This is because the processes of formation differ from those producing snow so that the two are not interchangeable. To be fully consistent rain from convective cloud should also have been excluded, but because such a very small part of precipitation at temperatures below 2.5 degC falls as rain showers such refinement is not essential.

3. Results

The cumulative percentages for each station were plotted on logarithmic graph paper and straight lines fitted by eye. In all cases the fit was quite good - indeed the three largest departures were found to be data errors when checked against the original records; examples are given in Figure 1 for London (Heathrow), Edinburgh (Turnhouse), Cardiff (Rhoose), Belfast (Aldergrove) and Lerwick. From the set of curves, rates of precipitation exceeded for 1 per cent and 0.1 per cent of the time were read off. These values are listed in table 1 and plotted in Figure 2; they are considered to represent realistic if slightly pessimistic estimates of rates of snowfall likely to be encountered within the lowest few hundreds of feet, for the given percentages of the time that the surface temperature is below 2.5 degC and precipitation is falling at a rate of 0.1 mm hr^{-1} or more. The isopleths in Figure 2 must be regarded as largely speculative, though the broad minimum over central England, coastal maxima and local maximum southeast of the Cheshire gap do not appear unreasonable.

If it is required to estimate the likely frequency of encounter with snowfall at these rates, then it is necessary that they each be associated with a duration. The basic data have a minimum resolvable period of 6 minutes; consideration of the few very intense falls indicates that the 0.1 per cent rate can be associated with periods of typical duration 12 minutes, and the 1 per cent rate with rather longer falls averaging about 30 minutes (over the UK). In other words, in the course of 100 hours of precipitation at temperatures below 2.5 degC, one might expect two independent 30 minute falls at the 1 per cent rate, and an evens chance of a 12 minute fall at the 0.1 per cent rate (12 minutes being 0.2 per cent of 100 hours).

If overall probabilities are required, it is necessary to know the proportion of time that precipitation falls on average when the temperature is below 2.5 degC - factor A, and the proportion of total time that the temperature is less than 2.5 degC - factor B. These factors in percentage form are given for the 23 UK locations analysed in table 1 and plotted in Figure 3. It is emphasised that the isopleths drawn in Figure 3 must be regarded as highly smoothed estimates since local factors, particularly station altitude, play such a large part. As an example consider Stornoway:

i. From table 1 - given an air temperature below 2.5 degC and snow, we could expect an equivalent rainfall rate of 5.0 mm hr^{-1} for 1 per cent and 7.2 mm hr^{-1} for 0.1 per cent of the time.

ii. Using factor A and the above - given a temperature below 2.5 degC we could expect snow at an equivalent rainfall rate of 5.0 mm hr^{-1} for less than 0.082 per cent and at 7.2 mm hr^{-1} for less than 0.0082 per cent of the time. The 'less than' must be included because some occasions will be of rain and some of sleet at ground level.

iii. Over the year as a whole we would expect snow at the above rates for less than 0.0083 and 0.00083 per cent of the time (factors A and B), or about 1 hour in 10,000 and 1 hour in 100,000 respectively.*

From Figures 2 and 3 it is possible to assess probabilities of heavy rates of snowfall for any location in the UK.

4. Discussion

The assumptions, explicit and implicit, in the foregoing analysis have been mentioned earlier; this section will be concerned with tentatively extending the results in four areas by considering the following questions. Are the stations representative of the worst likely world-wide conditions? Can topography and altitude be taken into account? Can the results be extended to sleet? Is freezing rain covered?

4.1 An extension to world-wide conditions. There is no reason to associate heavy rates of snowfall with high latitudes. On the contrary, areas where very cold air occasionally crosses relatively warm stretches of water are most likely to be subject to the heaviest falls. In this regard the United Kingdom is more suitably situated than most countries, though parts of Japan, the Southern Alps, and areas bordering the Great Lakes of North America and the Caspian Sea can be expected to suffer more prolonged heavy snow under favourable circumstances. Not surprisingly data are sparse. The world record snowfall, discussed by Paulus[2], of 76 inches in 24 hours at Silver Lake, Colorado (10,220 ft AMSL) averages out at about 7.2 mm hr^{-1} water equivalent; this suggests that extreme falls may amount to exceptional durations of heavy snow, rather than exceptionally heavy rates of snowfall. Wiggin[3] describes other heavy falls near the Great Lakes; these have invariably been associated with large temperature differences between airstream and water of up to 15 degC, the storms tend to be localised and produce very low density lying snow - down to 0.03 g cm^{-2}, which contributes to the large snow depths.

It is considered that the results derived here for the UK will, when modified for the percentage of time at sub 2.5 degC temperatures elsewhere, tend to be on the pessimistic side for most areas subject to snow; however special situations in some areas are not catered for.

4.2 Topography and Altitude. It is necessary to distinguish between these two factors: high ground, particularly windward slopes, must be expected to experience a higher proportion of snowfall at high rates; above uniform terrain the rate of precipitation in a non-showery situation would be expected to increase slightly with altitude up to the cloud base (or, in the case of snow, up to that level below the cloud base at which the air is saturated with respect to ice) and to decrease above this level.

A crude assessment of the probability of heavy snow at different altitudes can be made by assuming a mean temperature lapse rate of 2 degC per 1000 ft / and using a modified B factor. For example we may regard a surface temperature of less than 2.5 degC as corresponding to snow in the lowest 1250 ft, 2.5 to 5.0 degC to the 1250-2500 ft altitude band and so on. The mean annual percentage time that the surface temperature lies below the chosen threshold can then be used instead of the tabulated B factor; Figure 4 gives curves for four locations which probably encompass almost all areas of the UK. The amount by which the proportion of precipitation at high rates increases with surface temperature is countered by the loss of that part which forms below the

*Whilst extrapolation to higher rates can hardly be justified, it is interesting to note that at Stornoway the 0.01 per cent level is a rate of 9.5 mm hr^{-1}, and that this might be expected for less than 1 hour in 10^6 or around 30 seconds per year on average.

/ The ICAN atmosphere has a lapse of 19.8 degC from 0 to 10,000 ft.

altitude of interest; nevertheless, probabilities calculated this way should only be regarded as order of magnitude assessments.

The problem of correcting for mountainous terrain is rather different and, although attempts will be made to analyse the only suitable data available, i.e. 10 years of hourly readings from Ben Nevis around the turn of the century, the outcome cannot be awaited with optimism. Possibly the best simple adjustment where possible, is to scale the percentages of precipitation at high rates at the nearest low level station for which data are available, by the ratio of the annual average rainfall in the area of interest to that at the low level station.

4.3 Sleet. The analysis described earlier included sleet implicitly, as mixed precipitation most often occurs between zero and 2.5 degC. Since it is reasonable to suppose that the part of sleet in the form of water drops constitutes less of a problem to aviation than the snow content, then sleet can be regarded as being included in the foregoing analysis.

Standards for snow and supercooled water have also been requested. Supercooled water droplets and ice crystals coexist in most clouds between about -10 degC and -40 degC. The concentration of ice crystals increases rapidly as temperature decreases, and the survival of supercooled water droplets depends both on the concentration of ice crystals and the rate at which water vapour is made available for condensation - i.e. the ascent velocity of the air. Broadly speaking two stages of precipitation growth are involved. Initially ice crystals grow rapidly at the expense of the water droplets due to the lower equilibrium vapour pressure over ice than over water - the Bergeron process. In layer clouds the small vertical velocities usually result in the evaporation of all the supercooled water and further growth to precipitation then occurs by the aggregation of ice crystals to form snow flakes. In clouds with lower crystal concentration and higher vertical velocities the supply of supercooled water droplets can be maintained and further growth of the ice crystals takes place by the accretion of droplets forming graupel and eventually hail. Although all combination of these processes can exist under varying conditions, it is generally true that heavy snow and supercooled water do not coexist. The remote circumstance of sleet falling through a freezing layer may be regarded as a less severe manifestation of freezing rain which is considered below.

4.4 Freezing rain or drizzle. Precipitation in this form requires a subzero layer underlying warmer air. Falling snow melts whilst traversing the warm layer and subsequently becomes supercooled; the resulting drops freeze on impact, producing a coating of clear ice. Sometimes rain or drizzle falls on to a surface cooled by radiation to below zero degC even though the ambient air is not. In this case the precipitation is not supercooled and the effect on aircraft surfaces is not usually important because the ice melts rapidly as soon as taxying commences; however runways become treacherous.

When freezing precipitation affects a layer above the surface the situation can be serious for aircraft in flight, though modern aircraft usually have sufficient power reserve to climb out of trouble. High rates of freezing precipitation are rare and short lived, because it tends to be self cancelling; the melting layer is cooled in supplying the latent heat to the snow flakes and the lower freezing layer is warmed by the reverse process. A slow build up of large ice accumulations over several days in the more usual severe manifestation, and this can cause severe damage to fixed ground installations; the well documented occasion in January 1940 when much of Southern England and Wales was affected, is a good example[4].

A recent investigation[5] into freezing precipitation over the Eastern USA and Canada showed that freezing rain or drizzle occurs for about one ninth of the time of snowfall, and invariably at air temperatures between 26 and 32 degF (minus 3 to zero degC). This notional duration is compared in Table 2 with the actual duration of freezing precipitation at rates of 1 mm or more at a selection of UK stations. In every case the actual duration is less than would be expected if Bilello's findings applied to the UK, in most cases much less. This suggests either that a much greater proportion of freezing precipitation falls at rates of less than 1 mm hr^{-1} or that the relative frequency of freezing precipitation differs fundamentally between the UK and North America or, and this seems probable, both. The air temperature at the observations succeeding 25 (14.0 hours) out of the total of 61 (36.3 hours) occasions of freezing precipitation was above zero. The maximum rate reported was 2.0 mm hr^{-1} over 0.1 hr at Plymouth, but the difficulties of measurement should not be forgotten.

The limited evidence available suggests that probabilities of high rates of freezing precipitation may be rather less than one per cent of those for snow.

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Table 1

Station	Height AMSL (metres)	Period of data (inclusive)	Rate of ppn ($mm\ hr^{-1}$) exceeded for 1% *	0.1% *	A	B
Aberporth	133	1957-1971	4.0	6.0	4.95	6.83
Belfast (Aldergrove)	68	1949-1971	4.7	7.0	7.05	11.69
Birmingham (Elmdon)	96	JUN 1949-1971	3.7	5.5	5.55	14.52
Boscombe Down	126	1957-1971	3.6	5.4	4.10	13.50
Cardiff (Rhoose)	67	1957-1971	3.4	5.1	4.69	10.07
Dishforth	32	1957-SEP 1965	3.6	5.3	10.27	14.82
Leeming	32	OCT 1965-1971				
Edinburgh (Turnhouse)	33	1957-1971	3.8	5.6	4.80	15.00
Eskdalemuir	241	1957-1970	4.2	6.1	9.62	23.13
Glasgow (Renfrew)	8	1949-APR 1966	4.2	6.2	5.45	13.08
" (Abbotsinch)	5	MAY 1966-1971				
Kew	5	1957-1969	3.2	4.7	4.23	9.29
Kinloss	113	1959-1971	4.6	7.0	12.56	14.82
Lerwick	82	1957-1970	4.8	7.1	12.22	15.31
London (Heathrow)	25	1949-1971	3.5	5.2	3.72	11.42
Manchester (Ringway)	75	1949-1971	3.4	5.0	5.17	12.63
Manston	44	1961-1971	4.1	6,2	5.80	9.95
Mildenhall	5	1949-SEP 1969	3.2	5.0	4.07	13.84
Plymouth (Mount Batten)	26	1949-1961	4.5	6.6	2.94	5.01
Prestwick	16	1957-1971	4.1	6.1	4.57	12.00
Stornoway	3	1957-1971	5.0	7.2	8.15	10.18
Thorney Island	4	AUG 1958-1971	4.0	5.9	3.17	9.66
Tiree	9	1957 1971	4.9	7.0	5.20	4.65
Valley	10	1957-1971	4.1	6.0	4.24	5.73
Wick	36	1957-1971	4.8	7.1	9.64	12.83

A. For temperatures below 2.5 degC, the percentage of time during which precipitation fell at a rate of 0.1 mm hr^{-1} or more.

B. Percentage of time during which temperature was below 2.5 degC.

* These percentages refer to the period with temperature below 2.5 degC and precipitation falling at a rate of 0.1 mm hr^{-1} or more.

Table 2

Station	No. of years data	(i)	(ii)	(iii)
Aberporth	15	78.0	0.52	0.07
Belfast (Aldergrove)	23	238.9	1.04	0.04
Cardiff (Rhoose)	15	157.0	1.05	0.79
Edinburgh (Turnhouse)	15	118.1	0.79	0.21
Eskdalemuir	14	603.1	4.31	0.35
Lerwick	14	723.2	5.17	0.09
London (Heathrow)	23	177.3	0.77	0.16
Manchester (Ringway	23	225.1	0.98	0.39
Plymouth	13	19.4	0.15	0.06
Tiree	15	25.0	0.16	NIL
Wick	15	415.0	2.77	NIL

(i) Total duration of precipitation at 1 mm hr^{-1} or more with the temperature from -5.0 to -0.1 degC.

(ii) Notional mean annual duration of freezing rain or drizzle at 1 mm hr^{-1} or more based on Bilello's findings (see text), i.e. one tenth of (i) divided by the number of years.

(iii) Mean reported annual duration of freezing rain or drizzle at 0.1 mm hr^{-1} or more.

All durations are in hours.

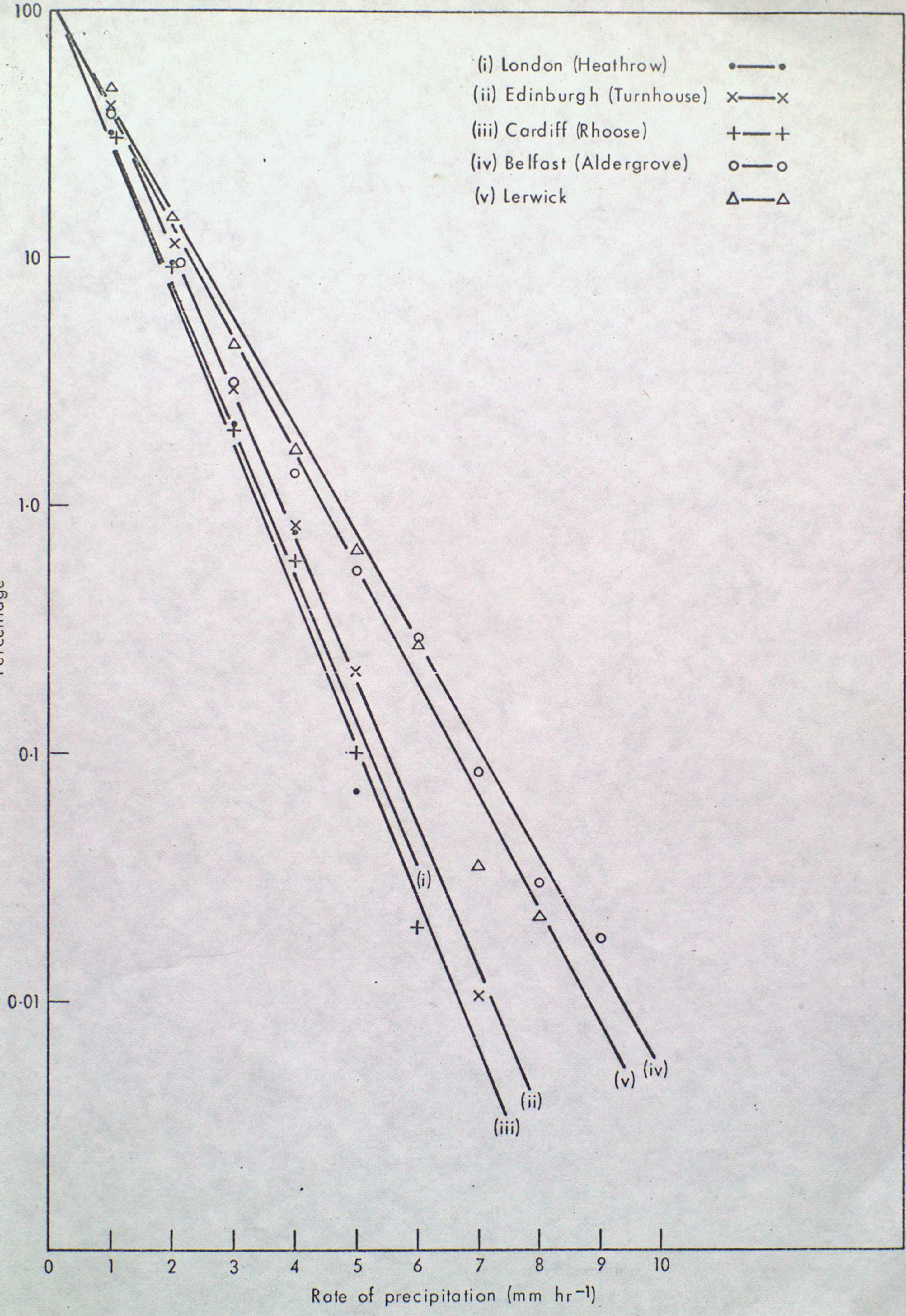

Figure 1 Percentage of precipitation at temperatures below 2·5°C exceeding given rates

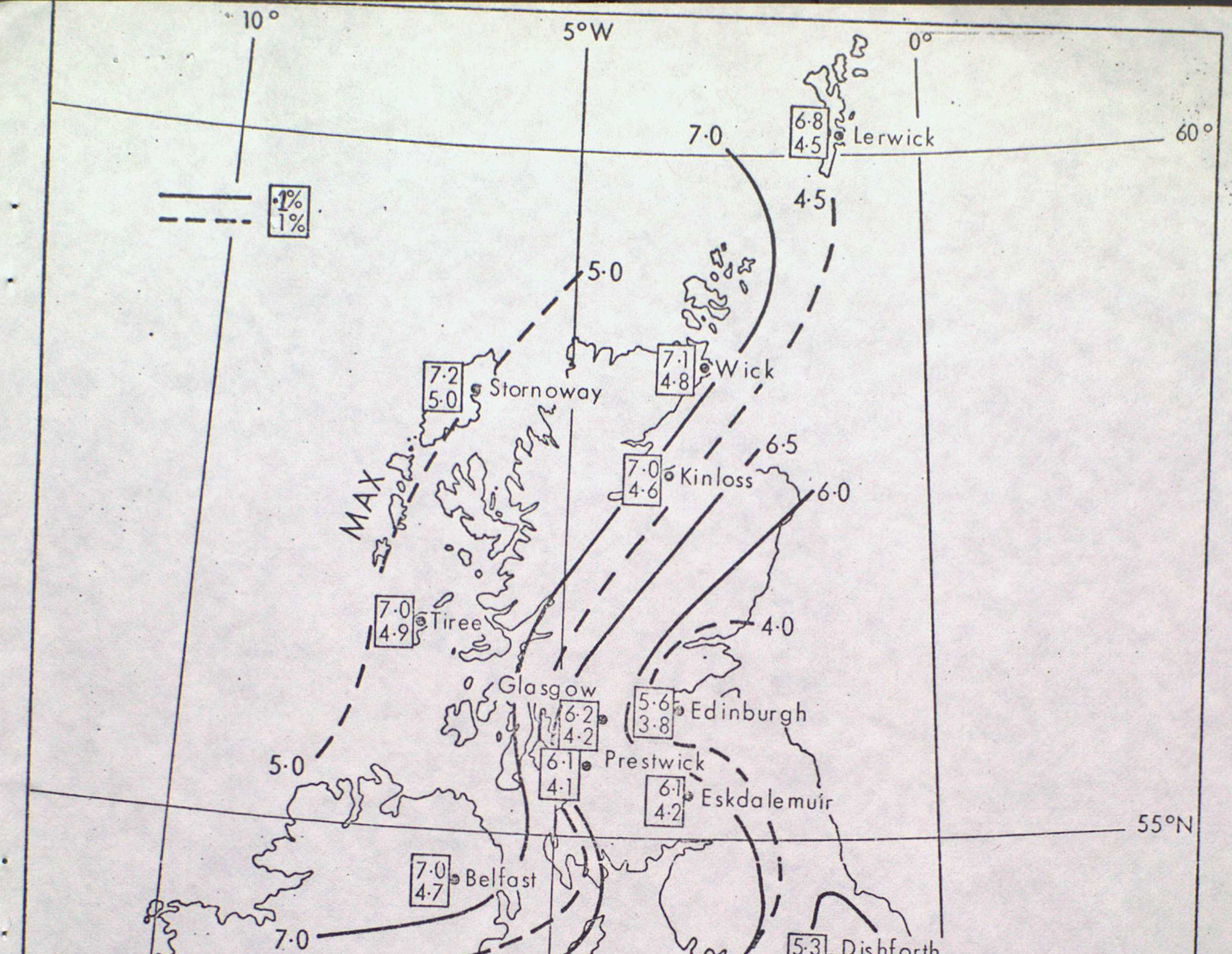

Figure 2 Rates of snowfall in mm/hr[-1] water equivalent, likely to be reached for 1% and 0·1% of the time snow falls at 0·1mm/hr[-1] or more

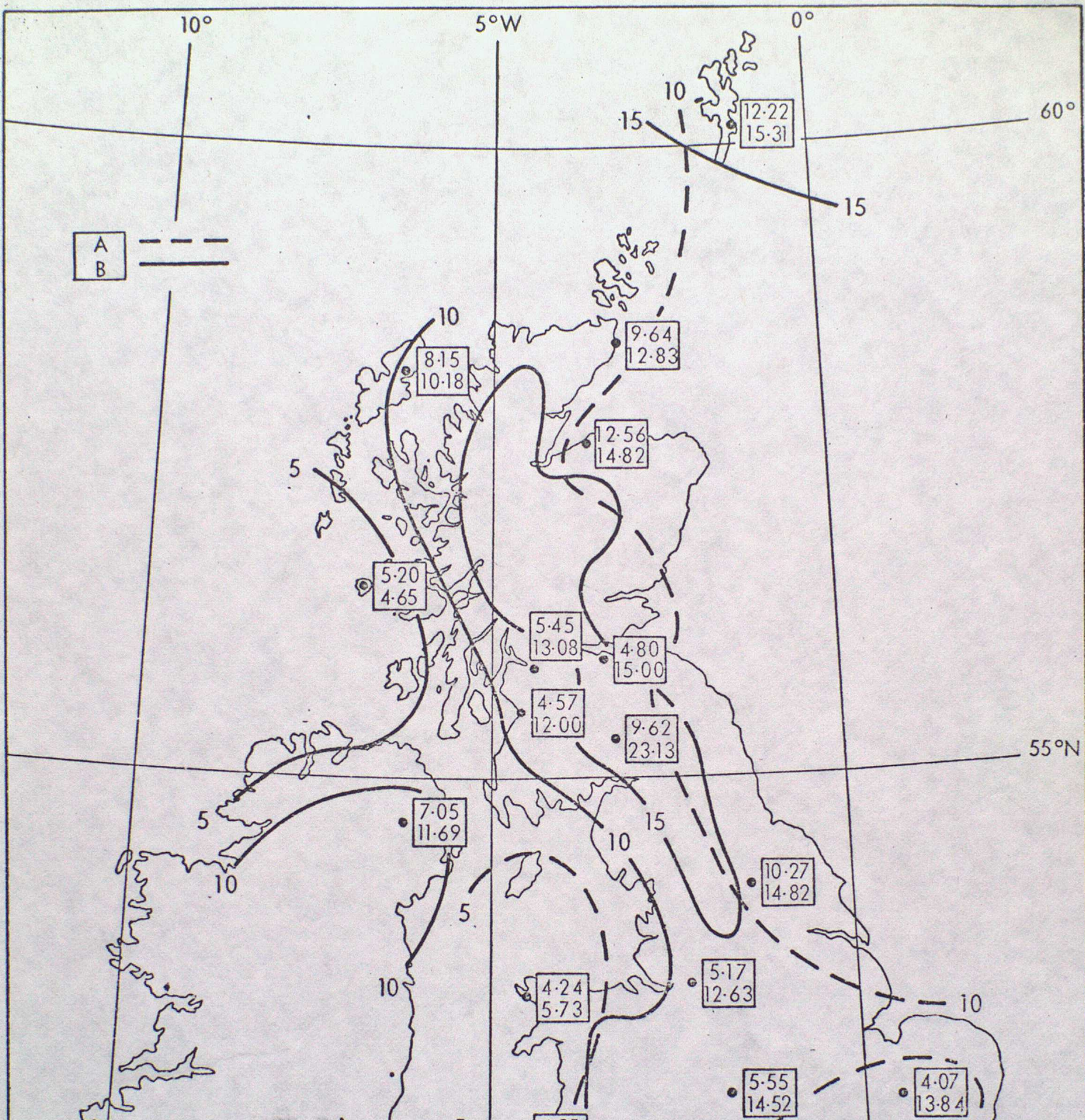

Figure 3

A. Percentage of time with temperature below 2·5°C during which precipitation fell at 0·1mm/hr^{-1} or mor

B. Percentage of time during which temperature was below 2·5°C

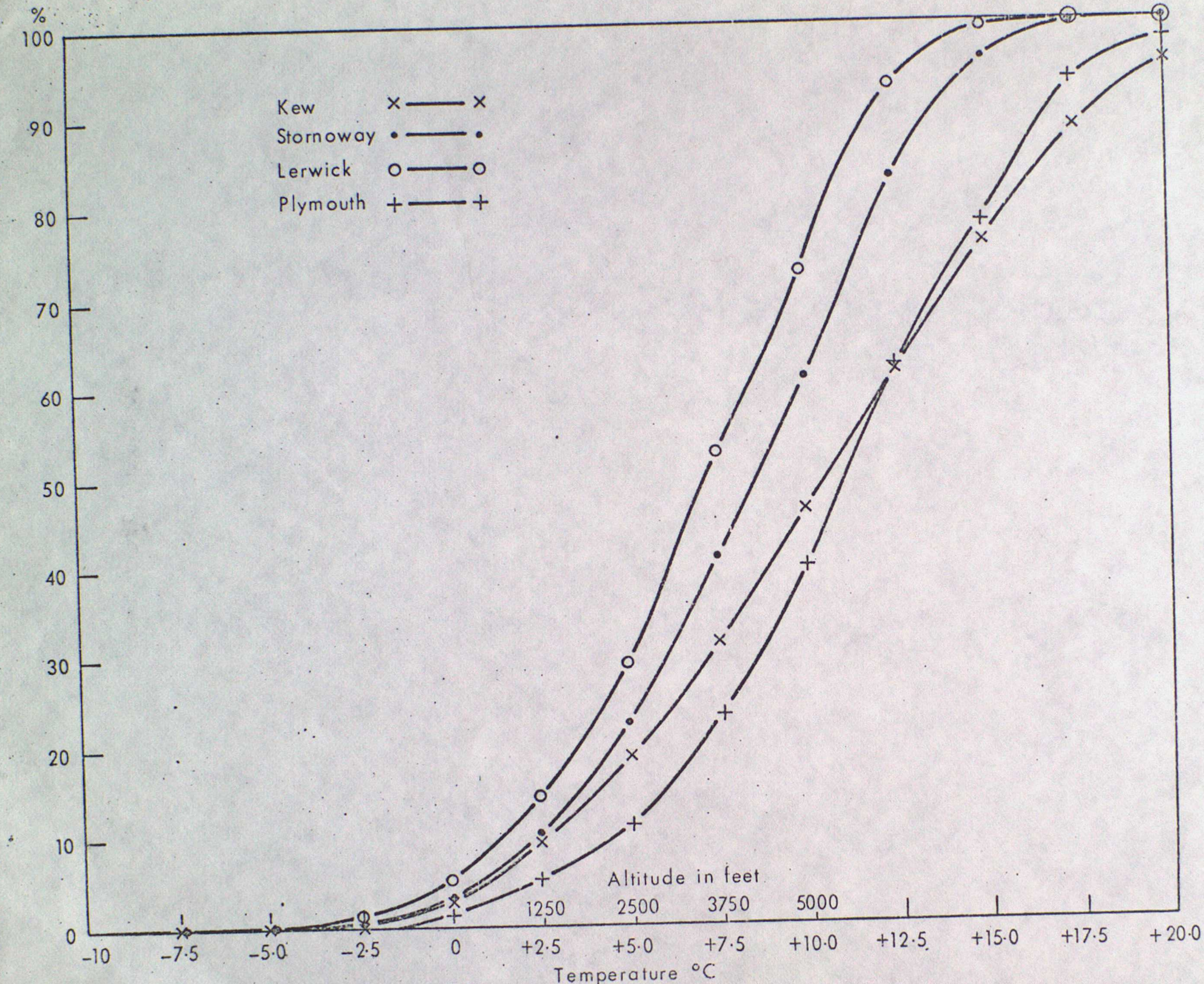

Figure 4 Percentage time with surface temperature below given value