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A review of three long-term cloud-seeding experiments

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Summary

The results of three long-term, randomized cloud-seeding experiments, carried out in Tasmania, Florida and Israel, are analysed and assessed. All three experiments carry claims to have increased the precipitation reaching the ground by an average of more than 15 per cent, statistically significant at the 5 per cent level. The present analysis does not support these claims for the Tasmania and Florida experiments. In the case of the Israeli experiment the statistical evidence for a positive seeding effect is strong, but needs to be reinforced and interpreted in terms of the observed microphysical and dynamical evolution of the clouds. Since this is one of the very few well-designed experiments that has produced consistently positive results over several years it is important to determine why the Israeli cloud systems should be more responsive to seeding than apparently similar clouds in other parts of the world.

1. Introduction

After 30 years of effort involving some hundreds of projects in many countries, and despite many confident claims and optimistic official reports, there is in fact very little convincing evidence that it is possible, by seeding clouds with artificial nuclei, to induce economically significant increases in precipitation that can be distinguished from the natural variations of rainfall. This unsatisfactory state of affairs has been recognized by the World Meteorological Organization which is investigating the possibility of establishing a long-term international experiment with a good chance of producing a definite, statistically significant result that will command the confidence of the world meteorological community and form the basis for judging the potential and cost-effectiveness of such projects, especially in semi-arid regions.

Although many cloud-seeding operations have not been designed as scientific experiments and are therefore not susceptible to proper scientific analysis and evaluation, a number of responsible long-term national experiments have been conducted in recent years, all based on statistical designs incorporating randomization between target and control areas and/or seeded and unseeded periods and employing similar techniques of statistical evaluation including tests of significance.

In this study I review, assess and compare the results of three recent major long-term experiments carried out in widely separated parts of the world—Tasmania, Florida and Israel. All three experiments have several important features in common. They were all directed by highly reputable scientists very experienced in the fields of cloud physics and cloud seeding. They all commanded considerable resources. They were all randomized experiments, operated over at least five years, and were designed and evaluated with the help of highly competent statisticians. They were all concerned with the seeding of moderately supercooled, mostly convective clouds with silver iodide dispersed from aircraft. They carry claims to have increased the precipitation reaching the ground by an average of more than 15 per cent, statistically significant at the 5 per cent level, although, in the Tasmania experiment, this was made only for the autumn season.

My analysis does not find strong support for these claims except in the case of the Israeli experiment where the statistical evidence is strong but will need to be reinforced and interpreted in terms of the observed microphysical and dynamical evolution of the clouds.

2. The Tasmania experiment (1964–70)

2.1. *Objective.* The objective of the Tasmania experiment (Smith *et al.* 1977, 1979) was to determine whether seeding cloud systems with silver iodide smoke released from an aircraft could increase the precipitation in a hydroelectric catchment area in Tasmania and to determine the circumstances under which such increases could be achieved.

2.2. *Experimental plan.* The experiment was conducted over the six-year period 1964–70 but seeding was carried out only on even-dated years in order to minimize any persistent effects, i.e. the carry-over of seeding effects from one year to the next. The experimental years were divided into periods of about 12 days and consecutive periods were arranged in pairs, one member of each pair being selected for seeding at random, the other member being used as an unseeded control period.

The target area of about 1000 mile^2, located on a plateau, 2500–3000 ft above sea level, in the centre of Tasmania, has a mean annual rainfall of about 40 in and was equipped with 16 rain-gauges read daily. The rainfall in the target area, mainly associated with the frontal systems of mobile depressions is fairly evenly distributed through the seasons, about 10 per cent of the total falling as snow in winter.

There were three control areas, one to the north (NC), one to the south (SC) and one to the north-west (NWC) of the target and these were used in various combinations in the analysis of the results. The NC area had a mean annual rainfall of 45 in and 18 rain-gauges, the SC area a mean annual rainfall of 35 in and 12 rain-gauges and the NWC area a mean annual rainfall of 55 in and 8 rain-gauges.

Assessment of the seeding operation took the form of a comparison between the rainfalls in the target area during the seeded periods with estimates of the rain that would have fallen in this area in the absence of seeding. The latter was estimated by correlation with rainfalls in the control regions measured in both seeded and unseeded periods, the correlation coefficients between historical values of the rainfalls in the target and control areas exceeding 0·9.

Seeding took place only when the clouds were judged suitable, i.e. if their tops were colder than −5 °C for stratiform clouds and only when the cloud depth exceeded half of the terrain clearance. Additionally cumuliform clouds were deemed suitable for seeding only if they were compact and solid in appearance with tops vertically above their bases indicating the absence of strong vertical wind shear. Seeding was carried out at cloud base wherever possible and upwind of the target area, allowing time for the clouds to drift over the target before precipitating.

The effects of seeding were judged not just in terms of the ratio T_s/T_u of the rain falling in the target area during the seeded and unseeded periods as in FACE (see section 3) but rather in terms of the double ratio $(T_s/T_u)/(C_s/C_u)$, where C_s and C_u refer to the rain falling in the control areas during the seeded and unseeded periods. Use of this double ratio is intended to compensate for the fact that the rainfall everywhere (in both T and C areas) may turn out to be either abnormally high or abnormally low in the seeded periods compared with the unseeded periods relative to the long-term averages, and therefore to make some allowance for conditions during the operating period not being representative. For example, if T_s/T_u turns out to be < 1, this might be interpreted in terms of seeding producing an actual *decrease* in rainfall but if C_s/C_u is also < 1 this might imply that the rainfall was naturally low everywhere, in both target and control areas, during the seeded periods compared with the unseeded periods even though these were designated at random and interleaved; in this case use of the double ratio would help correct for this and it is now widely used in weather-modification experiments including the Israeli experiment reviewed later.

2.3. *Assessment of the results.* Table I shows that the total rainfall in the target area during the 54 seeded periods of the 4-year trial was less than that in the 54 unseeded periods, the ratio being 0·92. Whilst more rain fell in the target area during the seeded than in the unseeded periods in autumn and spring, the contrary was the case in the winter and summer seasons. When allowance is made for unequal numbers of seeded and unseeded periods, making comparisons on the basis of the average rainfall per seeded or unseeded period, the ratios of seeded to unseeded rainfalls are autumn (0·84), spring (1·28), winter (0·81), and summer (0·68). On this basis one might conclude that seeding led to a decrease in the target-area rainfall over the four years as a whole; indeed only 19 out of 54 seeded periods produced more than the average value for the 108 operational periods. One might also infer that seeding produced positive results only in spring.

Table I. *Tasmania—rainfall analysis for seeded years*

										Double ratios $= \frac{T_s}{C_s}\Big/\frac{T_u}{C_u}$		
		n	T *inches*	C_1 *inches*	C_2 *inches*	T/C_1	T/C_2	$T/\frac{1}{2}(C_1+C_2)$	T_s/T_u*	$C = C_1$	σ	$C = \frac{1}{2}(C_1+C_2)$
Totals all four years	S	54	84·76	85·84	66·95	0·99	1·27	1·11	0·92	1·04		1·06
	U	54	92·15	97·47	79·31	0·95	1·16	1·04				
Autumn	S	14	20·46	19·06	14·47	1·07	1·41	1·22	0·84	1·25	0·05	1·25
	U	11	19·21	22·43	17·36	0·86	1·11	0·97				
Winter	S	14	22·03	26·11	19·82	0·84	1·11	0·96	0·81	1·02	0·5	1·07
	U	14	27·28	33·11	27·46	0·82	0·99	0·90				
Spring	S	16	30·67	30·09	22·99	1·02	1·33	1·16	1·28	0·98	0·6	0·99
	U	18	27·02	25·99	20·40	1·04	1·32	1·17				
Summer	S	10	11·60	10·58	9·67	1·10	1·20	1·15	0·68	0·94	0·8	0·93
	U	11	18·64	15·94	14·09	1·17	1·32	1·24				

T = rainfall over target area. C_1 = rainfall over control area 1 (= (NWC + SC)/2).
C_2 = rainfall over control area 2 (= (NC + SC)/2).
σ = statistical significance level for $C = C_1$.
S = seeded period. U = unseeded period. n = number of periods.

* calculated per period.

However, the picture changes markedly when comparisons are made with the rainfall in the control areas. Computation of the double-ratios $(T_s/T_u)/(C_s/C_u)$ suggest that seeding was most effective in autumn with an indicated increase of 25 per cent significant at the 5 per cent level, there being no significant increase in any other season or over the years as a whole. Moreover, in the intermediate years during which no seeding took place (Table II), the total rainfall in the target area was equal to the average totals for the three control areas but, in autumn, the target area rainfall was higher than the control value by 8 per cent. If we now use these unseeded years instead of the unseeded periods in the seeded years as a control, the double ratio indicates an increase of only 13 per cent due to seeding in autumn.

Table II. *Tasmania—rainfall analysis for unseeded years*

	T inches	C_1 inches	C_2 inches	T/C_1	T/C_2	$T/\frac{1}{2}(C_1 + C_2)$
Totals all three years	99·37	111·53	87·85	0·89	1·13	1·00
Autumns only	31·57	32·01	26·24	0·97	1·20	1·08

T, C_1 and C_2 as defined in Table I.

These calculations demonstrate how one can arrive at quite different conclusions about a seeding experiment depending upon experimental design, methods of analysis and evaluation, and especially on the criteria adopted for success or failure.

In the case of the Tasmania experiment the evidence does not provide strong support for a positive seeding effect. Taking the three operational years together, there is no season in which a T_S/T_U* ratio greater than unity is confirmed by comparison with the control-area rainfall through application of the double ratio. Only in autumn of 1968 were both ratios greater than unity (see Table III) but, in view of the small number of operational periods, the result is not significant.

Table III. *Tasmania—rainfall analysis for autumns of seeded years*

		n	T inches	C_1 inches	C_2 inches	T/C_1	T/C_2	$T/\frac{1}{2}(C_1 + C_2)$	T_S/T_u*	$\frac{T_S}{\bar{C}_S} \Big/ \frac{T_u}{\bar{C}_u}$
1966	S	4	4·62	3·91	2·80	1·18	1·65	1·38	0·61	1·41
	U	3	5·68	6·60	5·07	0·86	1·12	0·97		
1968	S	4	8·53	9·05	6·81	0·94	1·25	1·08	1·44	1·26
	U	4	5·94	7·05	6·87	0·84	0·86	0·85		
1970	S	5	6·08	4·93	3·72	1·23	1·63	1·41	0·57	1·13
	U	3	6·45	6·10	4·24	1·06	1·52	1·25		

T, C_1, C_2, S, U, n as defined in Table I. $\bar{C} = (C_1 + C_2)/2$.

* calculated per period.

Moreover, there is no independent evidence that the structure, evolution and constitution of the clouds was so significantly different in autumn as to make them more responsive to seeding.

3. Florida Area Cumulus Experiment (FACE) 1970–76

3.1. *Objective.* The object of the experiment was to determine whether seeding with silver iodide pyrotechnic flares from aircraft could be used to augment convective precipitation over a substantial area ($1{\cdot}3 \times 10^4$ km^2) in southern Florida by promoting the growth and amalgamation of supercooled cumulus clouds.

3.2. *Experimental design.* This was a statistically designed experiment without a control area in which seeding of the clouds over the target area was carried out on only half of the 'suitable' days selected at random, the other half being unseeded and used as controls.

Three different types of silver iodide flare were used in the course of the experiment. In the early years a seeding operation involved dropping more than 60 rather low-yield flares into clouds over the target area but, during 1975–76, larger (NEI) flares each producing about 1000 times as many active ice nuclei as the earlier types, were used on the last 17 seeding operations of the experiment.

The response to seeding was judged mainly in terms of comparing the quantity of rain falling in the target area on the seeded (S) days with that falling on the unseeded (U) days. The total rainfall in the target area was estimated by using a rather old 10 cm radar, the radar estimates being adjusted after comparison with a small network of conventional rain-gauges.

The target area was defined in two different ways and separate analyses made for each. The Floating Target (FT) comprised the radar echoes of all the seeded clouds and those which merged with them so long as they remained in the target area. This may be regarded as the most intensely treated target. The Total Target (TT) comprised *all* the radar echoes including the FT echoes in the fixed target area. The rainfall was measured and analysed over a 6 h period following the first seeding and for the interval between the first seeding and 1 h after the last seeding.

The experimental sample consisted of 39 seeded and 36 unseeded days over the 6-year period but 4 days of disturbed weather ('naturally rainy days') were excluded from the analyses.

3.3. *Working hypothesis.* The main working assumption was that massive injections of silver iodide nuclei would liberate large quantities of latent heat through the induced freezing of supercooled cloud droplets and the deposition of water vapour on to the ice crystals. This latent heat could be expected to increase the natural buoyancy of the clouds, enhance their growth and promote their amalgamation into larger cloud systems which would produce more rain than the individual clouds on their own.

3.4. *Claims.* The authors (Woodley *et al.* 1980) claim that over the period as a whole the ratio of the average rainfall on seeded days to that on unseeded days was about 1·5 ± 0·4 for the TT area, these figures being significant at the 5 per cent level. The differences on seeded and unseeded days are said to be greater and of greater statistical significance on days with light winds, when the cloud radar echoes were mobile, and on days when the more efficient NEI flares were used. The authors admit, however, that the apparent increases in rainfall on the seeded days were due largely to heavy rains on only 4–7 of the seeded days.

3.5. *Assessment of FACE results.* The principal results of the experiment are summarized in Table IV, those for the floating target (FT) and the total target (TT) being listed separately.

Taking all the operational days together, with no stratification, we find that the average rainfall per seeded day exceeded the average per unseeded (control) day by a factor of 1·62 (FT) and 1·27 (TT)

Table IV. *Summary of FACE rainfall results*

			Floating Target				Total Target			
		n	T	$\bar{R} = T/n$	$\bar{R}_s/\bar{R}_u$	σ	T	$\bar{R}$	$\bar{R}_s/\bar{R}_u$	σ
All days	*S*	38	165·9	4·37	1·62	0·03	246·8	6·49	1·27	0·12
	U	33	88·9	2·69			168·5	5·10		
All days except 7 wettest S days	*S*	31	93·3	3·01	1·11		154·7	4·99	0·98	
	U	33	88·9	2·69			168·5	5·10		
All days with echo motion	*S*	28	113·6	4·06	1·75	0·02		6·13	1·57	0·02
	U	17	39·4	2·32				3·90		
Days with no echo motion	*S*	10	52·3	5·23	1·37	0·14		7·63	1·07	0·37
	U	17	65·1	3·83				7·14		
Days with > 60 low-yield flares	*S*	22	84·4	3·84	1·08	0·39		5·81	0·89	0·29
	U	19	67·4	3·55				6·54		
Days with NEI high-yield flares	*S*	17	87·1	5·12	2·06	0·008		7·43	1·72	0·01
	U	18	44·8	2·49				4·32		
Exclude 4 wettest S days	*S*	13	46·3	3·56	1·43			5·40	1·25	
Days with echo motion and high-yield flares	*S*	12	62·0	5·16	4·41	0·005		7·34	2·87	0·008
	U	8	9·38	1·17				2·56		
Exclude 4 wettest S days	*S*	8	21·2	2·65	2·26			4·48	1·75	

n = number of days.
T = total rainfall ($m^3 \times 10^7$).
$\bar{R}_s$ = average rainfall per seeded day.
$\bar{R}_u$ = average rainfall per unseeded day.
σ = statistical significance level.

but these results are heavily weighted by very heavy rains falling on 7 of the 38 seeded days. If these are excluded, the $\bar{R}_s/\bar{R}_u$ ratios drop to 1·11 and 0·98 respectively.

The authors claim that clear-cut positive effects of seeding are apparent only on days when the radar echoes from the clouds were mobile but, in fact, though the $\bar{R}_s/\bar{R}_u$ ratios were greater on those days, the actual average daily rainfalls were greater, both on seeded and unseeded days, when the echoes were stationary.

Although greater positive seeding effects are claimed for the high-yield NEI silver iodide flares, the actual average daily rainfalls (excluding the four wettest days) were considerably *lower* than on the days when low-yield flares were used despite the fact that during the 1976 large-flare campaign the radar rainfall totals were adjusted upwards by 32 per cent for the seeded days and by only 10 per cent for the unseeded days. However, because the rainfall on the unseeded days was also a good deal lower in 1976 than in previous years when the low-yield flares were used, the $\bar{R}_s/\bar{R}_u$ ratios for the trials with NEI flares come out higher at 1·43 (FT) and 1·25 (TT) even if the four seeded days of heaviest rain are excluded.

The highest $\bar{R}_s/\bar{R}_u$ ratios were obtained when high-yield flares were used on days of radar echo motion but again the results are heavily weighted by the four days of heavy rain. But, in any case, the high ratios are the result of the rainfall being abnormally low (about half the overall average) on the unseeded (control) days rather than the rainfall on the seeded days being abnormally high.

The authors also claim that rainfall increases attributable to seeding were of greater magnitude and statistical significance on days with light winds ($\leqslant$ 6 kn), when the clouds (radar echoes) were mobile, and when the high-yield flares were used. In fact, on only two of the seven days of heavy rain, which were largely responsible for the apparent positive effects of seeding, were all three criteria satisfied and, on these, the radar estimates of rainfall were multiplied by factors of 3·0 and 2·2 to adjust them to the rain-gauge data.

It is questionable whether a sample of fewer than 40 pairs of seeded and unseeded (control) days spread over six years is large enough to be stratified into several groups and produce results that are statistically significant. Moreover, we have to note the low accuracy of the rainfall measurements, the large adjustment factors applied to them, the distortion of the results by the fact that 44 per cent of the total rain fell on only seven (18 per cent) of the seeded days, and that when these are excluded there is little difference between the rainfall on the seeded and unseeded days.

The authors' basic physical premise that seeding promotes the growth and amalgamation of the clouds which then produce more rain than the individual clouds would do on their own receives little support from the data. Although the report mentions a few observations (not connected with seeding) of merged radar echoes producing heavier rain than isolated shower echoes, and opines that such mergers require strong surface-wind convergence for at least one hour beforehand, there is no evidence that seeding of isolated cumulus can lead to enhanced low-level mesoscale convergence. As indirect evidence for seeding leading to cloud mergers the authors cite the fact that the ratio of the FT to the TT rainfall on seeded days was greater (0·67) than on unseeded days (0·53) which they associate with a greater tendency for radar echoes to merge with the seeded clouds. However, the figures of Table IV are less favourable to this thesis on echo-motion days than on days of no motion; moreover, there is no difference between occasions when high-yield and low-yield seeding flares were used. The evidence is strongest for the few occasions when high-yield flares were used on days of echo motion but again this is strongly biased by the four wettest seeded days.

It may be that seeding on these four days led to considerable cloud growth and amalgamation but there is no direct evidence for this and if it occurs so rarely it can be of little practical significance.

Again we come to the conclusion that if these few days are excluded from the analysis there is no convincing evidence of any kind that seeding during the FACE operations produced a significant increase in rainfall.

After this analysis was completed, there appeared an important paper by Nickerson (1979) which comes to similar conclusions. His careful examination of hourly rainfall records reveals that prior to the introduction of the high-yielding NEI flares the average rainfall *outside* the target area was slightly greater on seeded days than on unseeded days. During the period when the NEI flares were used the average rainfall outside the target area on seeded days exceeded that on unseeded days by 60 per cent even in the 3 h period before seeding commenced, whilst during the 6 h period after the first flare was released, $\bar{R}_s/\bar{R}_u$ ratios in the outside (control) area as high as 3 were recorded. Nickerson also found that the large $\bar{R}_s/\bar{R}_u$ ratios that occurred over the target area during the NEI-flare period were *not* associated with anomalously high rainfall on seeded days but rather with abnormally low rainfall on unseeded days. Indeed when he used the control area data to compute a double ratio (as described for the Tasmania experiment) he obtained a value of only 0·82.

Nickerson accordingly concludes that the statistically significant differences between area-wide rainfall on seeded and unseeded days during FACE was due to natural variability rather than to seeding and also draws attention to the dominating effect on the statistics of a few 'outlier' days of heavy rainfall.

4. The Israeli experiment (1969–75)

4.1. *Objective.* The objective of the Israeli experiment as described by Gagin and Neumann (1980) was to examine the possibilities of enhancing rainfall in the catchment area of Lake Kinneret (Tiberias or Sea of Galilee) in Israel by seeding winter continental cumuliform clouds with silver iodide smoke released from aircraft supplemented by ground generators, and to determine the optimum cloud conditions for achieving a positive result.

4.2. *Experimental plan.* The experiment was conducted during the six winter seasons of 1969–75 following the encouraging results obtained in a preliminary experiment carried out from 1961–67 and described by Gabriel (1970), Gagin and Neumann (1974).

The total target area of 3775 km², subdivided into eight sub-areas, covering much of northern Israel including most of the Lake Kinneret catchment, has a mean annual rainfall of 630 mm, about two-thirds falling in the winter months. This rainfall was measured by about 55 rain-gauges read daily. A control area lying to the west and upwind of the target area, between it and the Mediterranean coastline, contained 25 rain-gauges, the correlation coefficient between the historical values of the rainfalls in the complete target and control areas being about 0·9 whilst that between the Lake Kinneret Catchment (LKC) and the control was 0·85.

The operational period was divided into seeded and unseeded days allocated at random but these counted as experimental days only if more than 0·1 mm of rain had fallen at any one of three specified stations in an unseeded buffer zone to the south of the target area. Each winter operation consisted of about 60 experimental days, about half of these being seeded. The clouds were mostly clusters or bands of cold cumuliform clouds associated with cold fronts and post-frontal systems moving in from the Mediterranean. The cloud-base temperature was typically −5 to −8 °C with tops extending frequently to the −15 to −20 °C levels. Aircraft seeding was carried out at cloud-base level along a north–south line located some 35 km west of the centre of the target area and was supplemented in the extreme eastern part of the target by ground generators located on the windward sides of hills.

The effects of seeding were judged in much the same manner as for the Tasmania experiment by comparing the average daily rainfalls in the target and control areas on both seeded and unseeded days selected at random in terms of the double ratio $(T_S/C_S)/(T_u/C_u)$, its standard error and its statistical level of significance.

4.3. *Assessment of the results.* Table V shows that the mean daily precipitation on the days randomly allocated for seeding exceeded that on the days designated to be unseeded by 16 per cent over the target area as a whole and by 21 per cent in the more limited Lake Kinneret catchment. Rainfall in both areas significantly exceeded the longer-term (1949–60) average values on both seeded and unseeded days. In the control area the average daily rainfall was only 3 per cent higher on seeded than on unseeded days so that increases, on computed double ratios, of 13 per cent and 18 per cent were ascribed to the effects of seeding in the total and LKC target areas respectively. The excess of the double ratios over unity were at least twice the standard error and both results are statistically significant at better than the 3 per cent level. These results are in rather good agreement with those obtained in the preliminary (1961–67) experiment which indicated rainfall increases of 15 per cent overall due to seeding.

Furthermore the eight sub-target areas all received more rain on the seeded than on the unseeded days as indicated by double ratios ranging from 1·06 ± 0·04 to 1·27 ± 0·10. The latter high value, significant at better than the 1 per cent level, was for the central part of the target area.

Table V. *Israeli experiment* (1969–75)—*rainfall analysis*

		Mean daily precipitation *millimetres*	T_s/T_u	$\mathrm{DR} = \frac{T_s}{T_u}\Big/\frac{C_s}{C_u}$	σ
Total target area	*S*	8·81 ± 0·74	1·16	1·13 ± 0·06	0·028
	U	7·59 ± 0·68			
	H	6·81 ± 0·36			
LKC area	*S*	8·89 ± 0·76	1·21	1·18 ± 0·08	0·017
	U	7·32 ± 0·68			
	H	6·33 ± 0·37			
Control area	*S*	8·30 ± 0·68	(C_s/C_u) 1·03		
	U	8·05 ± 0·70			
	H	7·64 ± 0·37			

H = long-term average (1949–60).
DR = double ratio.
LKC = Lake Kinneret catchment.
Other symbols as in Table I.

These statistical results provide much more convincing evidence for the positive effects of seeding than those for either the Tasmania or FACE experiments although the basic Israeli data have not yet been published in sufficient detail to facilitate a full independent assessment. It is, however, unlikely that the results and conclusions are strongly biased by the occurrence of abnormally heavy rains on only a few seeded days as in FACE because, as Table VI shows, the largest percentage increases in rainfall attributed to seeding were obtained on days of light or moderate rainfall with rather little contribution from days when the rainfall exceeded 15 mm.

Further support based on physical arguments comes from an analysis of the rainfall data stratified according to the modal value of the daily distribution of cloud-top temperatures as shown in Table VII. When the modal value of the cloud-summit temperatures lies within the range −15 to −21 °C the indicated increase of rainfall due to seeding is 46 per cent, significant at the 0·5 per cent level. On other days, when the cloud-top temperatures are either above −10 °C or below −21 °C, the seeding effects are either nil or statistically insignificant. Gagin and Neumann give this result the following plausible (but over-simplified) physical interpretation. In clouds warmer than −5 °C the growth of ice crystals nucleated by seeding is so slow that they have neither the time nor space in which to grow into rimed

Table VI. *Israeli experiment—correlation of seeding effect as measured by double ratio with precipitation amount in control area*

Control precipitation amount (millimetres)	Number of days	Double ratio	σ
All the data	388	1·13 ± 0·06	0·028
0–30	367	1·12 ± 0·06	0·047
0–25	358	1·13 ± 0·07	0·038
0–20	345	1·14 ± 0·07	0·031
0–15	319	1·23 ± 0·08	0·005
0–10	275	1·17 ± 0·09	0·047
0–8	241	1·24 ± 0·12	0·034
0–6	217	1·20 ± 0·14	0·079
0–3	158	1·32 ± 0·16	0·053
0–1	94	1·67 ± 0·27	0·030
0–0·5	62	1·96 ± 0·38	0·056

Table VII. *Israeli experiment—correlation of seeding effect as measured by double ratio with cloud-top temperature*

Cloud-top temperature (modal value in degrees Celsius)	Number of days	$\mathrm{DR} = \frac{T_s}{T_u} \Big/ \frac{C_s}{C_u}$	σ
$-15 \leqslant T$	85	1·22 ± 0·13	0·087
$-26 \leqslant T < -11$	112	1·19 ± 0·09	0·017
$-26 \leqslant T < -15$	77	1·24 ± 0·11	0·017
$-21 \leqslant T < -11$	77	1·29 ± 0·11	0·008
$-21 \leqslant T < -15$	42	1·46 ± 0·16	0·005
$T < -26$	87	0·94 ± 0·11	0·629
$T < -21$	122	0·96 ± 0·09	0·492
$-26 \leqslant T < -21$	35	1·01 ± 0·15	0·503
$-11 \leqslant T$	50	1·31 ± 0·20	0·602

precipitation elements before either the cloud dies or they are carried up into the tops of the clouds reaching much colder levels. In any case, the silver iodide generators produce only a very low yield of nuclei active at −5 °C.

In clouds with summit temperatures below −21 °C the concentration of natural ice nuclei is probably sufficient to initiate the growth of solid precipitation elements in such numbers and sizes that they consume the cloud liquid water as fast as it is condensed in the updraught. In this case, the supply of additional artificial nuclei is unlikely to have much effect and this may explain why seeding did not apparently augment the heavy rains which presumably fell from deep clouds.

It is at intermediate temperatures that seeding is liable to have greatest effect since the ice crystals, growing at the maximum rate by diffusion at about −15 °C, are most likely to grow into precipitation elements before the cloud dies or before they are carried up to higher levels where they would have to compete with increasing concentrations of natural crystals.

Apparently the Israeli clouds do not contain the high concentrations of natural ice crystals that are frequently observed in only slightly supercooled clouds of maritime origin and cannot sustain an ice-crystal multiplication process such as that described by Hallet and Mossop (1974). This may be a consequence of Gagin's (1975) observation that these clouds consist of high concentrations of small droplets with a narrow range of sizes but this is unlikely to be the only reason. It is therefore important to determine any microphysical and/or dynamical differences that may account for these clouds being more responsive to seeding than those in many other parts of the world, if only to guide the choice of location and design for other experiments.

5. Conclusions

Examination of the results of three recent major long-term cloud-seeding experiments carried out in widely separated parts of the world reveals how different conclusions can be drawn depending upon the experimental design, methods of analysis and evaluation and on the criteria adopted for success or failure. In the case of the Tasmania and Florida experiments the evidence does not provide strong support for a positive seeding effect. Statistical evaluation of the Israeli experiment provides much more convincing evidence for average increases of rainfall due to seeding of about 15 per cent, but why these convective clouds should be more responsive to seeding than rather similar clouds in other parts of the world is not clear. It is therefore important to make comparative studies of the microphysical and dynamical evolution of these and other apparently similar cloud populations in an attempt to resolve these questions.

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The Meteorological Office archive of machinable data

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Summary

This paper describes the general layout of the contents of the Meteorological Office archive of machinable data. The principles adopted to quality control the data are discussed together with methods of storage, cataloguing and use. Some indication is given of the future development of the archive.

Introduction

The Meteorological Office has maintained a collection of machinable data for more than 20 years, but an organized archive of data to be retained permanently has emerged only during the last 10 years. The purchase of an IBM 360/195 computer early in the last decade acted as a catalyst because it provided improved peripheral devices such as magnetic discs as well as increased processing power.

General purpose access routines for the proposed archive were developed by the Systems Development Branch of the Meteorological Office and written in IBM assembler code. This approach demanded that certain key parameters were located in particular positions in all data sets in the archive. This minor disadvantage was outweighed by the power of the access software, which included a number of index search and match routines, and the ability of any programmer, who had been trained to use the access method, to access any data set designed to this specification.

The first data sets which were created contained climatological data. This was a logical choice because many of the data already held on magnetic tape were in this class, and pressure generated by enquiries and investigations indicated that they should be considered first. A little later, synoptic data were also archived permanently in a data set complying with the general guidelines. However, these data were not accessed frequently because the format did not match that used by the Central Forecasting and Forecasting Research Branches. Demand for these data is now increasing, but since they are not required for forecasting, storage in synoptic order has proved to be inconvenient and the data are now being re-sorted and archived in a more suitable order.

The priority allocated to the development of any section of the archive was dictated by the operational requirement for the data rather than by a rigid pre-arranged schedule. A manuscript catalogue of machinable data was produced listing all data sets in the machinable archive plus all collections of data which have been declared by individual branches. There was limited effort available for cataloguing because priority was given to producing master lists of observing stations which were more urgently required.

The number of data sets, both inside the archive and maintained parochially by individual Meteorological Office Branches, has increased to the point where lack of adequate cataloguing has become an embarrassment. It has also become evident that some data sets were ill-suited for their intended roles and others no longer necessary. A rationalization exercise has been carried out and the results are now being implemented. The remainder of this paper will attempt to describe the planned final state of the machinable archive, and to indicate what has already been achieved.

A general description of the archive of machinable data

The archive of machinable data can be conveniently divided into a number of logical sections as shown in Figure 1. DATAMAST, the proposed on-line catalogue of machinable data is shown as the top level of the archive since it would be the logical starting point for a user. Apart from the various master indexes, data are stored in four different orders as follows:

(a) *Synoptic order.* All data for a particular hour are stored together. Within the hour, the data are organized in station or location order.

(b) *Periodic order.* All data for one station or location for a nominated period are stored together, followed by the next station for the same period. Each station record is stored chronologically.

(c) *Climatological order.* All data for a particular station or location for all times are stored chronologically.

(d) *Regional order.* All data from a nominated geographical region are stored in any of orders (a) to (c) above.

The individual data sets do not always stand alone; there is sometimes a flow of data between them. Such data flows are indicated in context in the following descriptions of each of the elements of the archive.

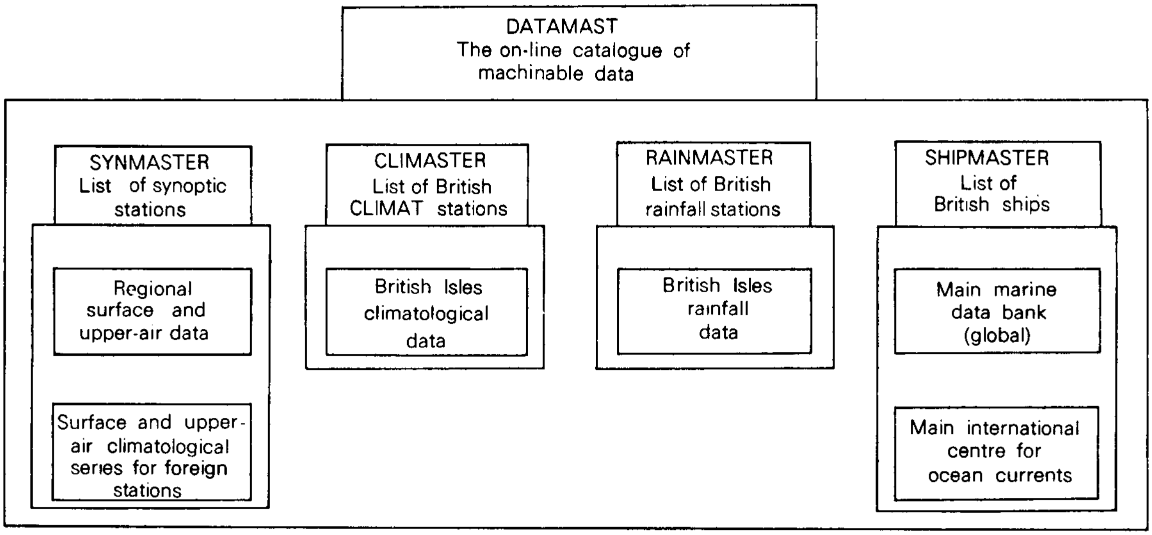

Figure 1. A schematic representation of the archive of machinable data.

1. DATAMAST—an automated catalogue of machinable data

The manuscript catalogue of machinable data is produced manually and updated at the end of each year. Entries are often out of date, and very few details are included because manual amendment is so laborious. The present catalogue is not effective, much staff time being wasted in searching for the appropriate data to answer enquiries. There is also evidence that the best answer is not always given because the person concerned is not aware of the existence of specific data sets. As the number of data sets increases this problem will grow and the difficulties experienced in updating the present catalogue will multiply.

As part of a major review to determine the number and range of data sets held in Meteorological Office Branches, it was found necessary to produce a preliminary version of the catalogue of machinable data as an on-line data set (DATAMAST) which could be accessed via a visual display unit (VDU) using the Time Sharing Option (TSO). If it is decided to release a complete operational version of the data set for general use, only minor improvements will be required to the software to make it a little more user orientated. The access routines would display a series of 'menus' to the operator, together with comprehensive instructions, allowing him to specify various parameters such as area, data type, frequency of observation, etc. The access routines would be flexible, and would allow for the whole range of searches from the very general to the specific. Finally the operator would be presented with a short list of data sets enabling him to inspect the attributes of each in turn. The level of information in DATAMAST would depend on the originating Meteorological Office Branch; for instance some branches might wish to withhold volume serial numbers for parochial data sets. A loose-leaf-format volume would also be produced and issued to Branches. This volume would be referred to by entries in DATAMAST and would eventually give the formats of all data sets in the catalogue.

Initially DATAMAST would refer only to machinable data, but eventually it might be extended to manuscript data and linked to the library index system. A considerable amount of work has been done on such data dictionaries in the United States of America, where the philosophy has been developed that all data should be catalogued in one place regardless of the storage medium or location. This is essentially a practical approach which admits that all data can never be converted into machinable form but the whereabouts of non-machinable data is important.

2. Synoptic Data

(a) *Surface.* Once a day, surface synoptic data are extracted from the synoptic data bank and archived for permanent retention. The end product is a series of half-monthly synoptic data sets containing all synoptic information available from the Global Telecommunication System, and the British Isles and International data sets which contain extremes of temperature, sunshine, six-hourly rainfall and state of ground for the British Isles and north-west Europe respectively. A master list of station details called SYNMASTER controls the selection of stations which are archived. This master list should be checked annually against a reference list on magnetic tape, which is produced by the World Meteorological Organization. Software is being written which will incorporate any amendments which are necessary.

The synoptic extraction program is being rewritten to make it more robust and also to extract climatological information which will be available when the new synoptic codes are introduced in January 1982. The British Isles and International data sets could be discontinued from the inception of the new codes but existing enquiry software is based on these data sets and it is more cost-effective to continue to form them.

Very few enquiries are received which require data in synoptic order and therefore the synoptic data sets are to be reformated as shown in Figure 2. Only the regional monthly periodic data set and a climatological archive for selected overseas stations will be retained permanently. The climatological archive will be welcome for enquiry purposes although it will not contain all the parameters normally expected and the resolution of the data will not be as good as that derived from climate returns until the synoptic code changes in 1982.

When the new codes are available, monthly climatological data sets will be formed for British stations in the format currently used. At the same time a manuscript return will be produced which can be sent to the reporting station for quality control. Capturing climatological data from the synoptic data bank in this way will ease the work load of the data keying section.

(b) *Upper air.* An analogous system to that used for surface data is being developed for upper-air data. Once again synoptic ordering has proved inappropriate and regional monthly periodic data sets are to be formed for permanent retention. These data sets will be used to create a climatological series for selected overseas stations which will provide data to answer enquiries. The complete system is shown schematically in Figure 3.

3. British Isles climatological data

(a) *Surface.* Climatological data from official Meteorological Office stations will be captured from the synoptic archive as described above. Data from co-operating stations which are not connected to the telecommunication system do not appear in the synoptic data bank and will therefore continue to be keyed to magnetic disc or will be collected in some other way. The various options are discussed in detail in a later section on data capture. As shown in Figure 2 an increasing amount of data will be received on magnetic cassettes from field loggers such as DALE described by Burtonshaw and Munro (1977), the automated Sferics system, Lee (1980) and the proposed Meteorological Office Automatic Climatological Recording Equipment (ACRE).

(b) *Upper air.* All the main radiosonde stations in the United Kingdom are now equipped with the Mk 3 radiosonde system. The system copies a selection of data from each ascent on to a magnetic

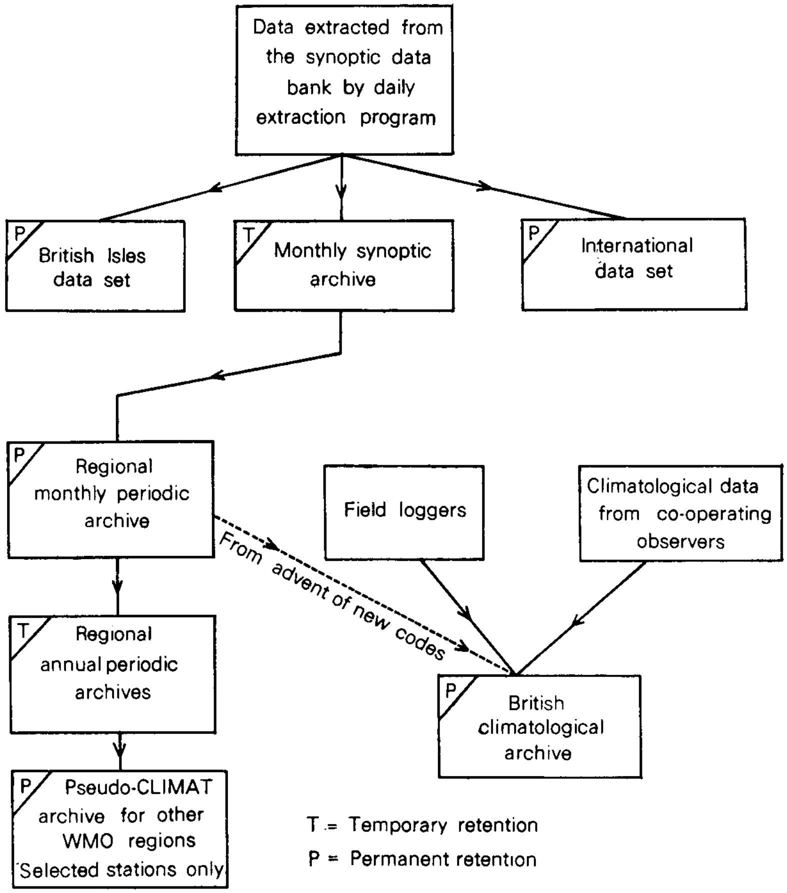

Figure 2. The surface data system.

cartridge cassette which is sent to Bracknell twice a month for processing. Since the necessary data for the climatological archives are retrieved from the cassette, manuscript returns are no longer completed except in cases of equipment failure. The standard-level data are extracted and added to the climatological upper-air archive; the special points which give fine structure are archived separately in the new detailed climatological archive. The main climatological archive is completed by retrieving data from the synoptic data bank as shown in Figure 3 when data are not available from the cassettes.

Balthum data are also received in manuscript form, keyed to disc and archived in a climatological series. The same data set has provision for MAST data at several levels.

4. The rainfall data system

RAINMASTER contains a wealth of information about rainfall stations and is probably the most frequently used of the master lists. It is now the practice to omit all station details except the station number from data sets to avoid the problems of multiple corrections; one correction to RAINMASTER suffices.

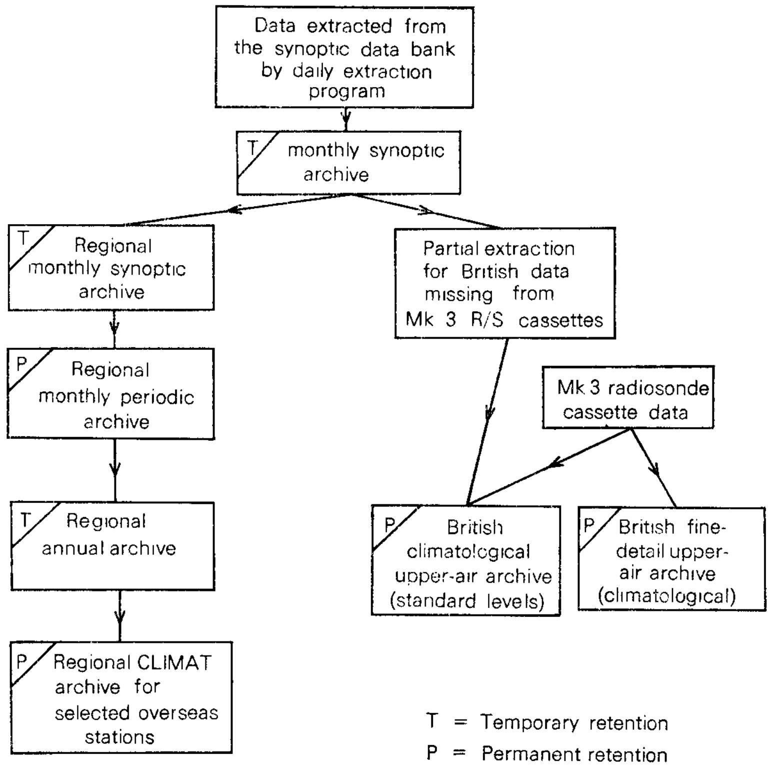

Figure 3. The upper-air data system.

Individual rainfall data sets are created for each different frequency of observation using either periodic or climatological order. Data from devices which measure rainfall with a fine time-resolution are assembled in one data set with markers which indicate the device or method of data extraction.

Data derived from the radar network are an exception and will be kept separately regardless of the frequency of observation. However, daily rainfall totals measured by radar will be combined with rain-gauge values to produce a data set containing daily areal rainfall totals. Storage facilities could not possibly cope with the enormous amount of data generated if rain-gauge data, radar-derived grid-point rainfall data, and the composite fields were all archived. Software will be developed to create composite fields in answer to individual enquiries as they occur.

The main data sets in the rainfall archive are shown in Figure 4. Daily rainfall totals are transferred from the climatological archive to the daily rainfall archive at regular intervals.

5. The marine data system

The marine data system does not yet have a master list in machinable form but the necessary information to create one is available on manuscript. The main marine data bank and its satellites, the ocean weather ship and the light-vessel data sets, are climatologically ordered. Data from the mobile ships are not put straight into the main marine bank; they are first stored in the annual periodic data set regardless

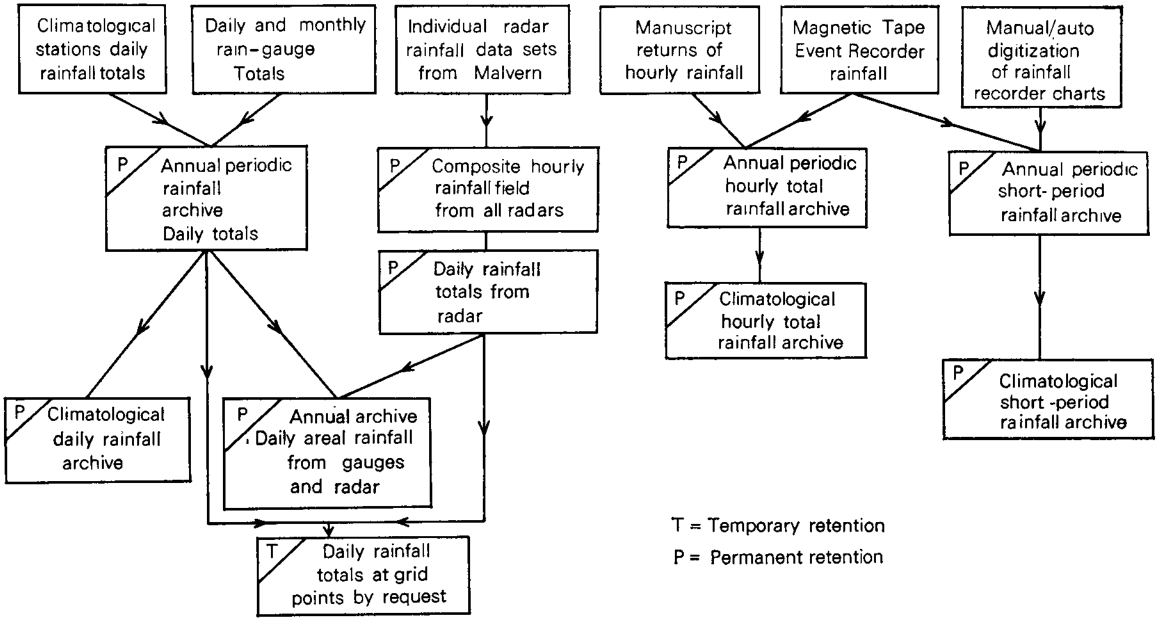

Figure 4. The rainfall data system.

of whether they have originated from the fleets of foreign countries or our own merchant ships. At this stage quality control is done and data recorded by our ships while in other regions of responsibility are reformated and dispatched to the appropriate centre in the International Exchange Format.

Many marine enquiries are received before data become available to answer them because there is a considerable delay between making the observation at sea and receipt of the ship's meteorological log-book at Bracknell. This problem is partially solved by creating an annual data set using data retrieved from the synoptic data bank as shown in Figure 5. Less than 50 per cent of the data eventually received can be captured in this way but it is useful to have even this limited information until manuscript returns are processed. When data from the manuscript returns exceed those from the synoptic data bank, the temporary data set is deleted.

The Meteorological Office is also the international centre for archiving ocean current data measured by mobile ships. A climatological data set has been created with a similar format to existing marine data sets and software is being developed to reformat the data for international exchange, as required.

6. Quality control

It is beyond the scope of this paper to consider in detail the various quality control methods used on archive data but the general principles can be summarized. There are usually several levels in any quality control system starting with the simplest checks and becoming progressively more complex, and most systems incorporate human scrutiny at some stage. It is a general rule that data must never be destroyed by quality control action and the archive of machinable data obeys that rule. Separate cross-referenced data sets contain suspect data together with the reasons for the change; the original

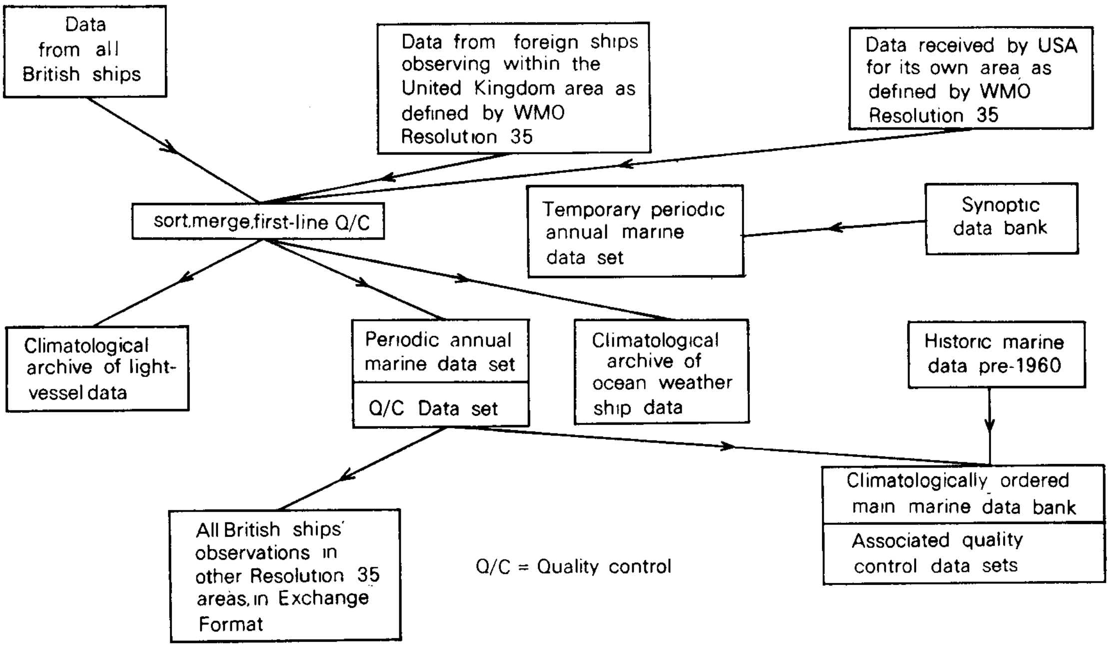

Figure 5. The marine data system.

data set will contain either missing data or, if possible, an estimated value, with a marker set in both cases. Software exists to restore the original data and display them together with the markers and estimated values on demand.

The levels of quality control applied to data in the machinable archive vary from virtually negligible for surface synoptic data through an average level for marine data to highly detailed for daily rainfall and climatological data. Table I summarizes the situation and indicates where improvements are in hand. The level of quality control is usually determined by the use to which the data will be put and the cost of processing them. Many of the climatologically ordered data sets contain data reformated from periodic data sets which are used to answer enquiries for data at a given location and time. Such data must be well quality controlled, therefore the climatological data receive a higher level of quality control than usual, of necessity. Much of the quality control is aimed at correction of random errors which occur after observation, but recently an attempt has been made to present summarized quality control information to rainfall station inspectors via a VDU. The inspector is then able to consider the performance of the rainfall station in the context of the data produced. A similar system has been requested for other climatological stations and is the first recognition of the fact that the quality of the machinable archive is dependent on the whole system which is used to produce it. The system of production may only be improved by encouraging feedback of information at all stages, including the observers.

7. Capture of data

The majority of climatological data, even from official Meteorological Office stations, is extracted from manuscript returns and keyed direct to disc by the data keying section. The whole operation is dependent on the staffing and workload of this part of the Meteorological Office. Some pressure of

Table I. *Quality control in the archive of machinable data*

Data type	Frequency	Quality control method	Status
Synoptic surface	Hourly	As in synoptic data bank	Results not included in permanent archive
Synoptic upper-air	6-hourly	As in synoptic data bank	Operational
United Kingdom climatological upper air	6-hourly	Comparison of standard and selected levels, hydrostatic equation, lapse rates, wind shears, comparison with forecast model input fields	Under development
United Kingdom fine-detail upper-air	6-hourly	Nil	Nil
United Kingdom climatological surface	Hourly to daily	Internal consistency, range checks, area means, comparison with neighbouring stations	Operational
Daily rainfall	Daily	Comparison with neighbouring stations	Operational
Short-period rainfall	Hourly to daily	Nil	Nil
Marine	Hourly to daily	Internal consistency and range checks	About to become operational

work has been removed by automating observing instruments such as the Mk 3 radiosonde system. However, it is likely that many other automatic observing systems will be used to fill gaps in the observing network rather than to replace existing stations.

The acquisition of climatological data from official stations via the synoptic data bank should be effective in reducing the amount of data to be keyed by approximately 20 per cent when the new codes are implemented in 1982. Even so, further reductions are desirable if keying staff are to cope with all the data which are awaiting keying. There are a number of alternatives which could be used to process data from co-operating observers both on land and at sea.

It is possible that an Optical Character Recognition (OCR) system with associated keying stations could be used. These mixed systems allow documents to be read by the OCR and unresolved characters from an earlier batch to be keyed simultaneously. The main problem with such a system is the unpredictable error rate; Meteorological Office forms are larger and more complex than those used in most other applications and the text is often less distinct which may result in higher error rates than those obtained commercially.

An alternative approach is to purchase a number of individual key-to-cassette systems and use these to record observations. The cassettes could be sent to Bracknell to be translated at monthly intervals, or at the ends of voyages for ships. Most systems currently marketed are used for stock control in large warehouses, or for remote ordering of goods using acoustic couplers and Post Office telephone lines. Such systems are too elaborate and much too expensive for the Meteorological Office.

There are indications that some manufacturers could use standard components to produce a compact keyboard and cassette tape drive for a fairly reasonable price (in the region of £200). It could then be a practical solution to issue these units to co-operating observers as inventory items.

8. Storage media

The Meteorological Office machinable archive is stored on magnetic tape, each tape having two back-up copies. There are about 4000 archive tapes and a further 11 000 tapes containing individual Branch data sets of one type or another. These tapes occupy valuable storage space and also make demands on staff and resources since they must be cleaned and respooled at regular intervals. Pressure on storage space has been eased by changing to higher density tapes and ensuring that each tape is full. Unfortunately, this means that some users have to read a greater length of magnetic tape to find the sections which they require and therefore are much more likely to encounter a tape error. This can be offset to some extent by reducing safety margins and allowing users to access the first back-up tape which is copied in reverse order.

Since the archive will continue to grow, a long-term solution must be sought to the problem of permanent retention of machinable data when any part of those data may be required at any time. Mass storage devices could be a practicable solution, but all of those currently available use magnetic tape technology and this is not acceptable for permanent retention of data. Research is being done on systems using laser holography on photographic film, and laser light on optical discs. The former is a sequential device with very long access times for a 1000-metre spool of film, although that film may contain the equivalent of 540 standard (1600 bpi) tapes. The latter is a direct-access device but has a lower capacity equivalent to about 20 magnetic tapes. Both devices have the disadvantage that data may not be amended; the entire film or disc must be rewritten. However, it is possible that this problem may be overcome by the use of laser light of differing wavelengths and photochromic materials whose response is wavelength dependent. Such devices could then be used for data of medium age (two to four years), where there is still the possibility of amendment, and also for updating long records.

9. Using the archive of machinable data to answer enquiries

The Meteorological Office archive of machinable data exists primarily to answer enquiries which vary in complexity from a simple request for data to a large-scale investigation taking many months and involving substantial resources. In general, the larger the task the less impact the storage media will have on the time taken to complete it. Many enquiries are received for small amounts of data, a substantial proportion by telephone. Even if the data are held on a permanently mounted disc, it is not possible to answer such an enquiry immediately because TSO is not designed for the purpose and response is too slow. A microfilm archive is now being developed to satisfy this need, containing data extracted from the machinable archive and printed on microfiche and jacketed 16 mm film. There is little co-ordination of the development, which is occurring simultaneously in most of the enquiry bureaux, and access methods are fairly crude and manually operated. However, these embryo systems have proved successful in answering simple data enquiries both by telephone and with confirmatory hard copy.

A study of available equipment has been made, for systems ranging from simple manually operated readers to fully automatic carousels accessed by minicomputer, such as the ARMS system (Hannum 1979). It is difficult to say what level of automation is justifiable because an expensive system such as ARMS would not be cost effective with the number of small enquiry bureaux which we have at present. Only, if a centralized enquiry bureau was set up, similar to that of the United States National Climatological Center at Asheville, North Carolina, which uses a mixed microfilm and computer data base system, could the capital outlay be justified. However, such a development is not thought to meet Meteorological Office circumstances, even though the addition of word processing facilities and automatic invoicing to such a system would further increase its effectiveness.

Conclusion

This paper has attempted to describe the growth of the Meteorological Office archive of machinable data and to indicate its future development. General purpose access software has been developed for the archive, and higher level accessing subroutines are now being developed for some of the component data sets so that application programmers need not be aware of the mechanics of the indexing used.

This activity together with the cataloguing of available data is the first step towards an automated data base perhaps using new mass storage technology. It is unlikely that the machinable archive alone will ever satisfy all the data enquiries which are received. It will probably be necessary to set up a hybrid machinable/microfilm data base and a true data dictionary to achieve a high success rate.

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Plotted synoptic charts and time-series graphs for research purposes

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Summary

This note describes a facility for the provision of a wide variety of plotted but unanalysed synoptic charts and graphs for use by investigators and research workers.

1. Charts

Data for meteorological research and investigation are normally presented as computer printouts, supplemented by either analysed operational charts or simplified versions of them which have been published. The researcher will usually want to reanalyse these charts, and is often prevented from doing so easily by the incompleteness of the data, by the presence of the existing, often simplified, analysis, or by the need to trace the chart to produce his own copy. A suite of programs has now been written which will give the investigator a plotted but unanalysed chart which he can analyse directly, and on which additional observations can be plotted by hand. The orography is not shown. A list of positions and heights can be provided for British Isles synoptic and UK climatological stations.

Data from the synoptic data bank on magnetic tape, which is retained for five years, are normally used to plot the chart on 35 mm microfilm. At present this can be enlarged at Bracknell either to A4 size or, preferably, to chart size (60 cm × 45 cm). The surface charts available are as follows:

(a) A standard Central Forecasting Office surface chart, such as the 1 in 2 million scale British Isles chart produced for facsimile transmission, the 1 : 3 million British Isles and North Sea chart, the 1 : 7·5 million western Europe chart or the two 1 : 10 million charts covering the northern North Atlantic Ocean. There are standard lists of stations for all these charts.

(b) A special 1 : 2·1 million British Isles chart with an augmented station list giving a rather more detailed coverage than the 1 : 2 million chart, and with ships' reports plotted also. A printout of the coded observations for stations which cannot be plotted because of lack of space can also be provided with this chart.

(c) A 09 GMT synoptic-type chart of the British Isles using data from climatological stations (see *Meteorol Mag*, **109**, 260) which gives a once-a-day mesoscale depiction of wind, total cloud cover,

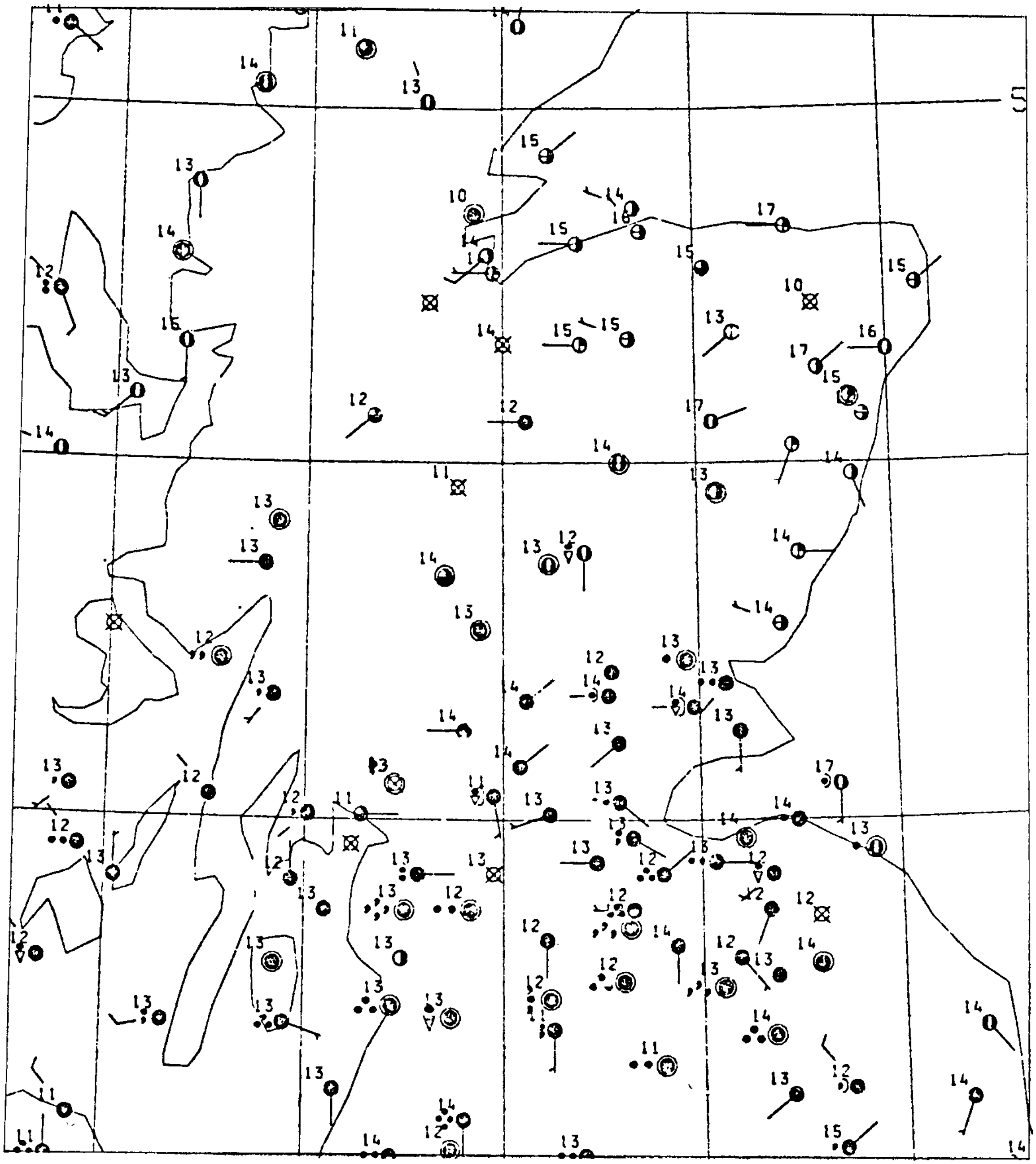

Figure 1. Detail of 09 GMT climatological stations chart for 19 July 1980, showing part of Scotland. Total cloud amount, wind, present weather and temperature are plotted.

present weather, temperature and dew-point, or a subset of these (Figure 1). In contrast to synoptic data bank data, the climatological data used are available for 1972 onwards. For such data, 1 : 1·5 million charts covering either England and Wales or Scotland and Northern Ireland are also available.

(d) A single-element British Isles chart of any of the daily or 09 GMT meteorological elements recorded by climatological stations, e.g. maximum temperature or 09 GMT temperature (units 0·1 °C), sunshine, snow depth, day of hail, 30 cm soil temperature.

(e) A surface chart centred on any given latitude and longitude in the northern hemisphere and for any scale in whole millions, e.g. 1 : 3 million, 1 : 11 million. There is a standard coastline, which is rather crudely drawn at the 1 : 1 million and 1 : 2 million scales, and a standard station list which is probably adequate in Europe, but which would not support detailed charts in other parts of the hemisphere. However, all ships' reports whose plots do not overlap are plotted.

Upper-air charts can also be produced for any of the standard levels or for 1000–500 mb or 1000–850 mb thicknesses and thermal winds. The main charts available are the 1 : 7·5 million western Europe (about 20°W to 20°E), the 1 : 10 million Europe (rotated, with vertical longitude 35°W) and the 1:20 million circumpolar North Atlantic chart covering Europe, the Arctic, Canada and the North Atlantic Ocean to about 35°N. Reports from aircraft can be plotted, but for 00 GMT they cover the whole period 00–12 GMT (for 12 GMT, 12–24 GMT), thus biasing these reports towards a later time than the nominal one. Satellite data can also be plotted if required.

There are several plotting options available, mainly dependent on which elements are required. The digit size can be altered; increasing it can result in the overlapping of plots, but more usually in the omission of some of the stations to avoid overlapping. On the 1 : 7·5 million upper-air chart, however, the digit size can be made large enough to be legible on A4 enlargements without affecting the coverage.

2. Graphs

A program has been developed to plot a month's climatological data for one station on a single frame of microfilm, in the form of a multiple time-series graph of weather elements observed hourly (or three-hourly). The graph consists of four rows containing eight days each, leaving 'day 32' for annotation. On enlargement to chart size, one hour occupies 0·1 inch horizontally, while 4 inches are available vertically for all the elements. (One inch = 2·54 cm; inches are still the basic unit of length in the plotting system.) One day's data extracted from the graph are shown in Figure 2(a) at approximately the real size. Most elements reported hourly are shown, either as a line graph or symbols or both, or as the coded values. Cloud base and visibility have a logarithmic scale, while hourly rainfall is presented as a histogram. Sunrise and sunset lines are drawn for each day.

A simplified version of the graph which may be suitable for the general public is shown in Figure 2(b). Only temperature, rainfall, relative humidity, wind speed, sunshine (this only for 1980 onwards) and a limited number of single or double letter codes for present weather and wind direction are plotted.

One version of the graph enables hourly climatological data for up to 31 stations for one day (or 15 stations for two days etc.) to be plotted on a single frame. This arrangement may be useful for case studies, when the stations can be arranged to be roughly in their geographical positions. Such graphs can be drawn for data back to about 1970, though the single-station monthly graph is available for a few stations as far back as 1949. Case-study graphs from the synoptic data bank can be produced, but are more expensive in computer time than the others, although they can be obtained immediately after the event, while a wait of two to six weeks may be necessary to obtain quality controlled climatological data.

Modifications to the formats of the graphs could be made if experience of their use showed a need for change.

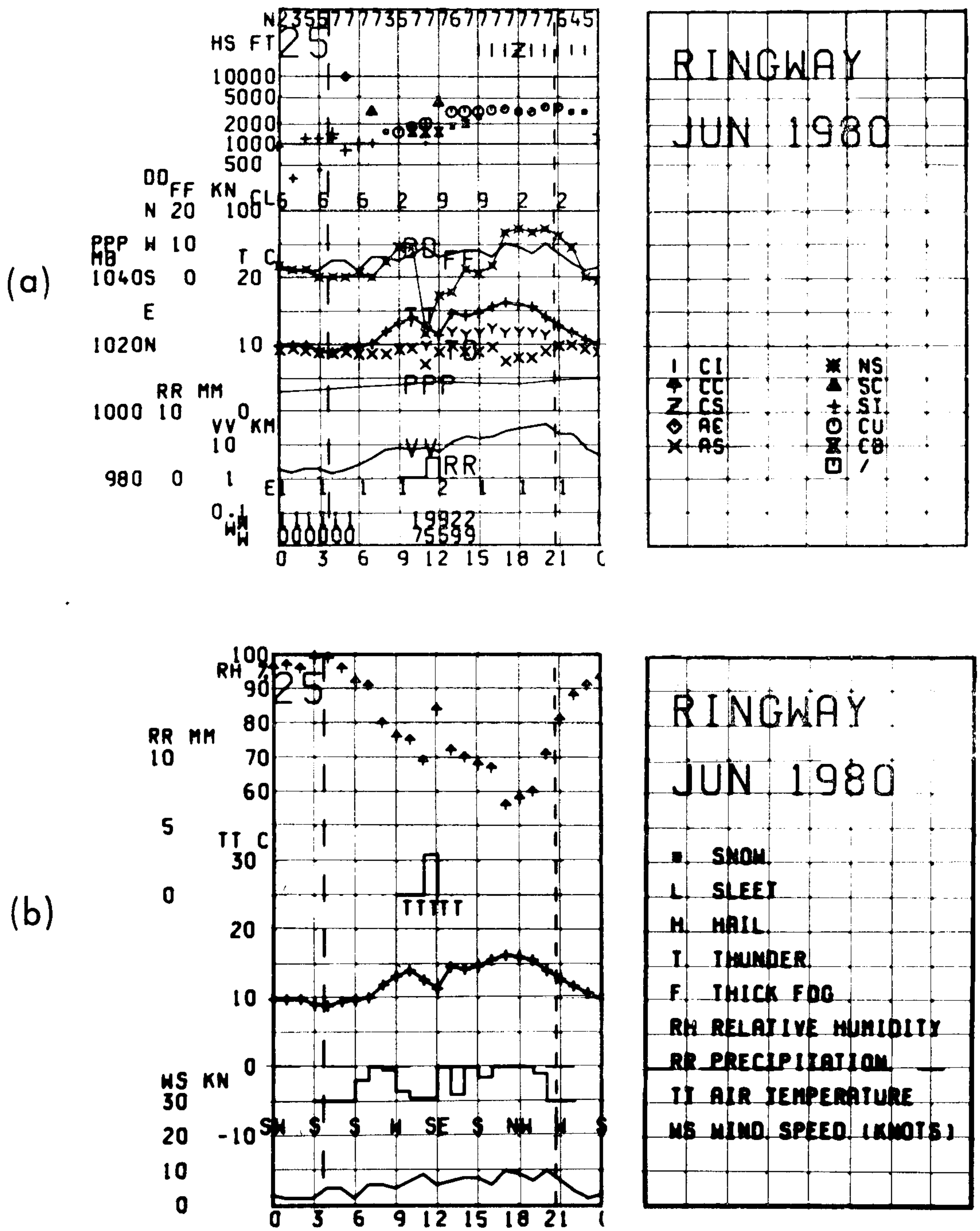

Figure 2. Time-series graphs of one day's weather, extracted from monthly graphs. (a) Standard version. (b) Simplified version.

3. Costs and enquiries

The cost of producing a chart or graph is comparable to that of printing out the data from the computer. A typical computer basic cost per chart might be 4 units (£5 to the general public at present), to which have to be added administration costs. The weight of paper is less than for a printout of the data it contains, and some customers may prefer to receive only the microfilm. The weather graphs can be inspected more quickly than can printouts, thus saving the customer time.

Enquiries about the charts and graphs from within the Meteorological Office should be addressed to Met 0 9, and from elsewhere to the Director-General, Meteorological Office (Met 0 3b), London Road, Bracknell, Berkshire RG12 2SZ.

4. Acknowledgement

The line drawers/chart plotters section of the Data Processing Branch wrote many of the programs which were used or modified to produce the charts and provided valuable assistance during the project.

551.589.6

A note on singularities

By D. G. H. Battye

(Meteorological Office, Bracknell)

Summary

The apparent tendency of short-period temperature fluctuations of like sign to recur at certain times in different years is investigated. Pseudo-random sequences of long-period mean daily temperatures are set up. The distributions of fluctuations over various time intervals are compared between random and real series. Differences are found to lack statistical significance.

Introduction

From time to time, relatively large fluctuations of duration from 1 to about 10 days in period-mean daily temperatures at certain times of the year have excited interest because of their supposed predictive value, despite the absence of evident physical causes. This note compares such 'singularities' in a long-period series of mean daily Central England Temperatures (hereafter CET) with those in randomly generated equivalent series to determine whether they are likely to be chance variations due to sampling.

The value of singularities as noteworthy events in the climatological calendar is controversial. Brooks and Mirrlees (1930) noted that 'it has frequently been asserted that these warm and cold spells, or crests and troughs on the curve of temperature, are not strictly haphazard in their occurrence, but exhibit a definite tendency to cluster around certain days'. Lamb (1950) described a singularity as a 'typical short-lived but pronounced variation' and compiled a list of singularities through the year, although considering that their reality was not susceptible to testing by statistical methods.

McIntosh (1953) and Reynolds (1955) compared daily temperature series, from Edinburgh and Liverpool respectively, with harmonically smoothed curves. Their conclusions differed: McIntosh left the subject in doubt by considering such non-seasonal temperature variations to be very largely but not entirely random; Reynolds listed a series of 'warm and cold spells' which were thought to be 'worthy of publication', implying that they were notable singularities. Recently, from a more objective study, Aust (1979) has suggested that singularities are not all chance variations, but form an important part of the annual temperature progression.

The random-shift method

The main difficulty in testing the statistical significance of temperature deviations from a smoothed curve lies in the nature of the data involved. Each sequence of daily means is autocorrelated to an extent varying with time of year and, more important, weather type. Thus the number of degrees of freedom in the final sequence of long-period mean daily values is itself variable, and not amenable to simple analysis. This note presents the results from an approach designed to overcome this problem. Original yearly sequences of daily temperature values are unaltered, but before the obtaining of sequences of long-period daily means, each year is advanced or retarded by up to 5 days or not moved at all, the precise adjustment being randomly determined. The character and degree of autocorrelation is thus preserved in the constituent 365-day sequences and hence also in the means. Real singularities in the actual series of long-period daily means would be expected to be removed or considerably reduced by this process, which is analogous to smoothing by an 11-point running mean. On the other hand, if further apparent singularities are generated in the new sequence of long-period pseudo-mean daily values, such that statistically the frequency distribution of small-scale variations is unaltered, then this constitutes strong evidence that the original singularities are themselves a feature of chance variation in the sampling.

Results of the random-shift method

For this investigation 105 years of daily values of CET from 1871 to 1975 were used. Each daily temperature is one half of the sum of the daytime maximum and preceding night minimum averaged over a number of stations in England, the precise distribution varying with time; a full description is given by Jenkinson and Carr (1979). The curve of mean daily values through the year averaged from 1871 to 1975 is shown in Figure 1. Interesting apparent singularities can be seen at, for example, the cold period around 12 February, the warm period from 11 to 15 May and similarly the warmth near 15 December.

The 105 annual sequences of 365 daily temperatures were each subjected to a random time shift of between plus and minus five days, as already described. These were averaged to give pseudo-mean daily values through the year and this process was repeated 100 times. The frequency distribution was then found, over the complete set, of the temperature differences between all pairs of days from 1 to 10 days apart. The average distribution from these 100 runs of differences over periods of 1, 5 and 10 days is shown in Figure 2, together with frequencies of the sequence of actual mean daily values from 1871 to 1975. Because the simulated sequence of daily means is derived from 100 quasi-independent series, it may be regarded as chance expectation for the purposes of statistical testing. Table I gives values of chi-square (χ^2) for frequencies of temperature differences over all intervals from 1 to 10 days. It can be seen that only in the case of 5-day intervals is χ^2 significant at the 5 per cent level. This may well be a chance result when it is considered that 10 tests were carried out. Hence there is no evidence that 'singularities' in series of long-period daily means are other than chance superposition of similar temperature variations.

It may be of interest to see the scale of some generated 'singularities'. The examples of peaks, troughs and sharp gradients in Figure 3(a)–(f) were selected from the first 10 simulations. These may be compared with the actual sequence of daily means given in Figure 1.

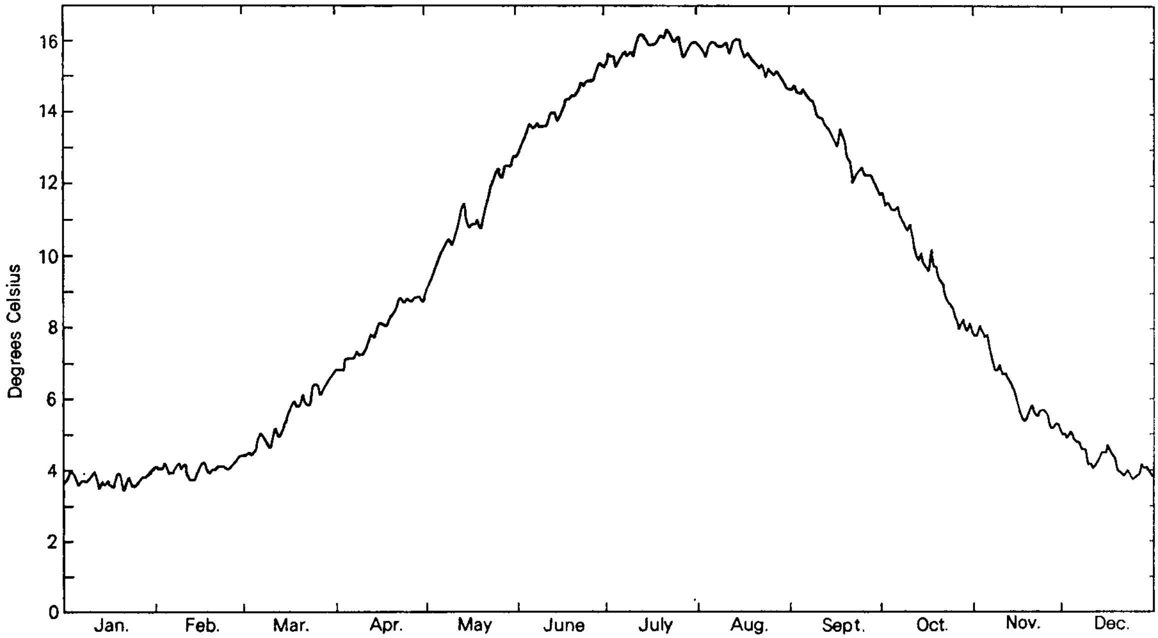

Figure 1. Mean daily CET, 1871–1975

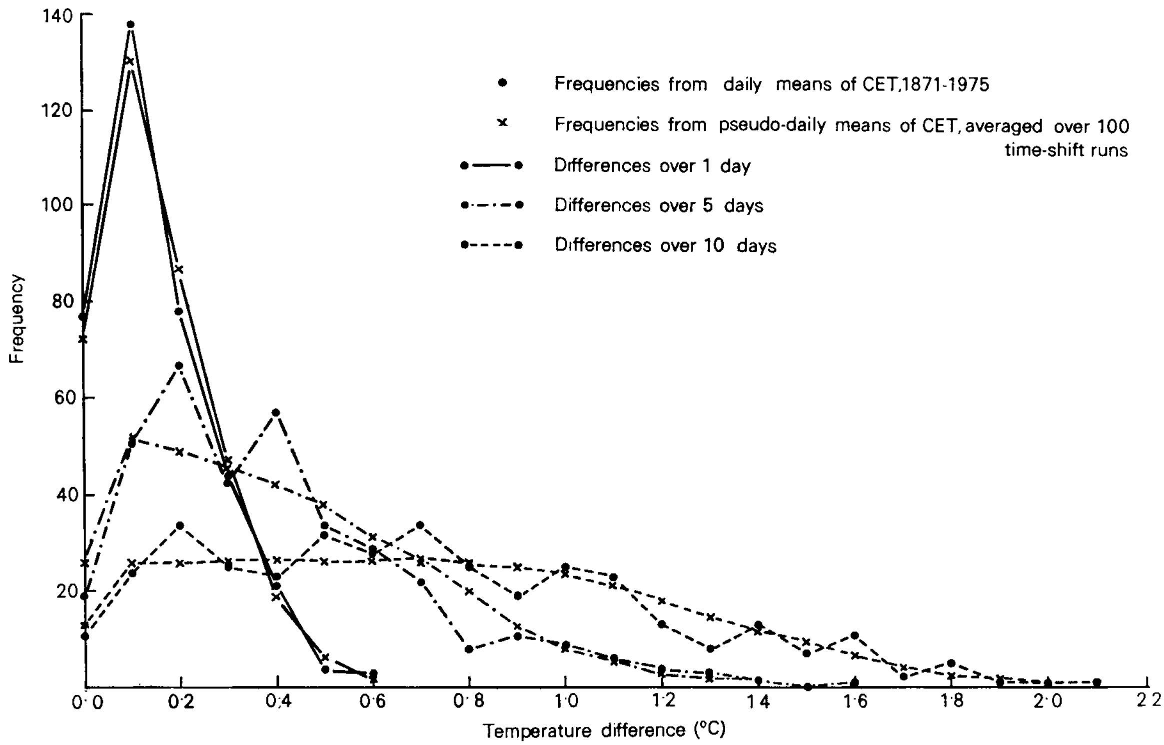

Figure 2. Frequencies of temperature differences at 1-, 5- and 10-day lags.

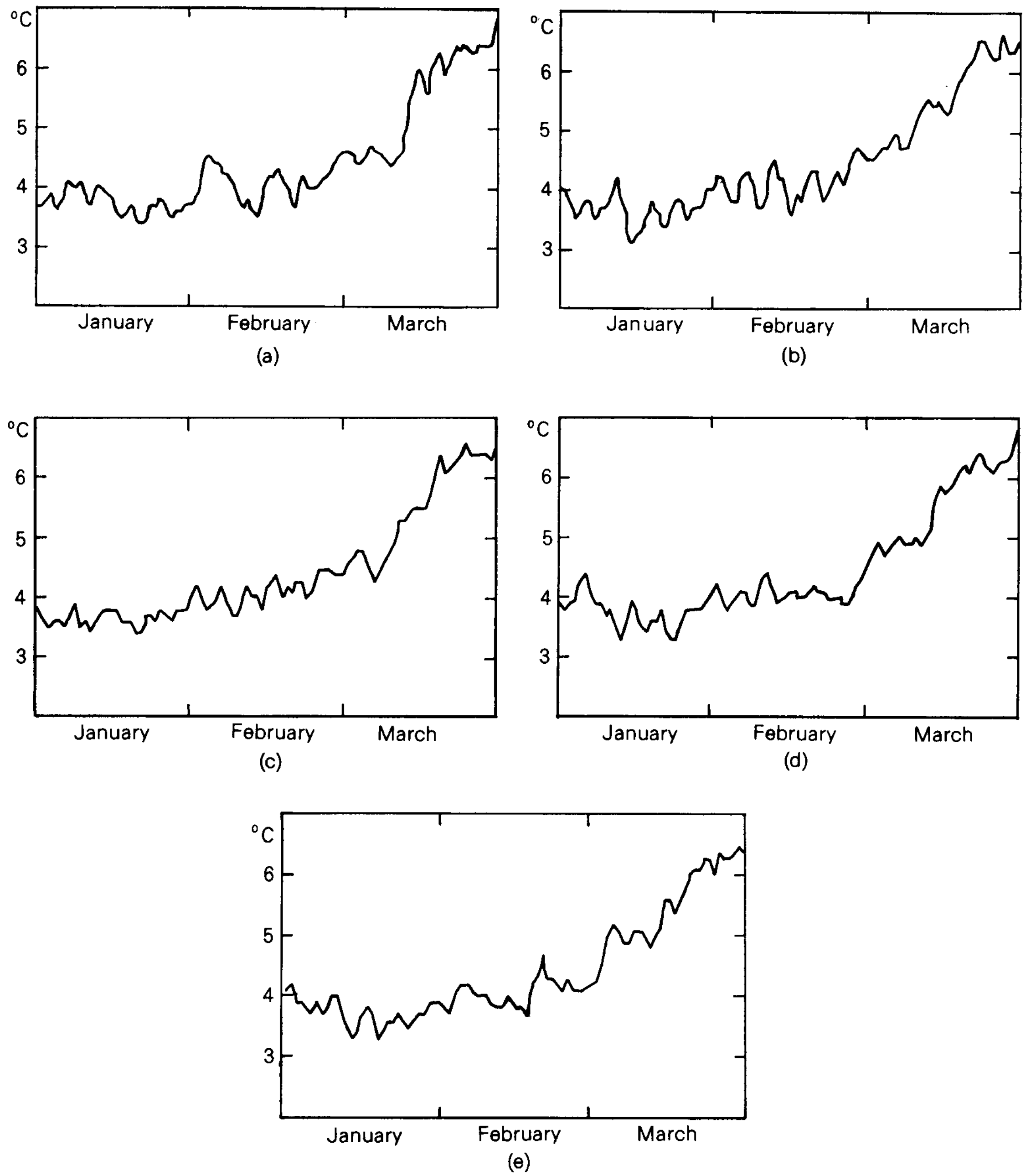

Figure 3. Examples of time-shift generated pseudo-mean daily CET series.

Table I. *χ^2 values of temperature differences over* 1 *to* 10 *days*

Lag (days)	Degrees of freedom	χ^2 value	χ^2 at 5 per cent significance level
1	5	2·4	11·1
2	7	13·8	14·1
3	9	15·0	16·9
4	11	16·4	19·7
5	12	23·9	21·0
6	13	10·6	22·4
7	14	12·3	23·7
8	15	12·0	25·0
9	16	13·1	26·3
10	17	16·8	27·6

The degrees of freedom are equal to the number of classes in the comparison, minus one.

Conclusion

Sequences of daily values in the Central England Temperature series show no evidence of any consistent year-by-year variation on scales from 1 to 10 days that cannot be ascribed to seasonal trends or chance.

Acknowledgements

Thanks are due to Mr R. N. Hardy for suggesting this approach and for advice at various stages.

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Letter to the Editor

Hailstorm at Sevenoaks, 26 June 1980

On 26 June 1980, a large shallow thundery low covered the British Isles and most of northern Europe. This low had approached from the north-west and proved very persistent and slow moving; its effects were felt for seven days. Thundery showers and storms had been experienced during the previous four days.

Photograph by courtesy of Sevenoaks Chronicle

Plate I. Hailstorm at Sevenoaks, Kent, 26 June 1980.

Photograph by courtesy of Sevenoaks Chronicle

Plate II. After the hailstorm at Sevenoaks.

June 26 dawned fine and sunny in the Sevenoaks area and these conditions lasted until early afternoon. Cumulonimbus development then occurred and a storm was observed to the south over the Tunbridge Wells area. However, it remained dry with sunny periods and reasonably warm at Sevenoaks until late afternoon.

The storm over Tunbridge Wells moved away and it appeared that the threat was over. However, there was a rapid development of cloud just to the east of the town from about 1530 BST. This was the herald of a remarkable and highly localized storm which began at 1630 and lasted until 1800. The sluggish wind and configuration of the land at Sevenoaks probably account for the intensity and localized nature of the storm.

At 1630 it began to rain, spasmodically at first and then steadily with increasing intensity. The accompanying thunder was of moderate intensity and continued so throughout the duration of the storm. The rainfall was quite another matter; it increased to a continuous torrential downpour the like of which I have experienced only in the Tyrol. The rain became interspersed with bursts of hail. These became more frequent until, in an area centred around Sevenoaks School, hail fell continuously for over half an hour with such intensity that the ground was covered to a depth of up to 6 inches with occasional much deeper patches. The area thus affected was about half a mile across. I measured several hailstones and found a diameter of a quarter of an inch several times.

As will be seen from the accompanying photographs the scene resembled a January snowscape rather than the aftermath of a June thunderstorm. The lying hail was still largely unmelted the next morning and some patches persisted in gullies etc. more than 48 hours later, despite temperatures of 15 °C.

The almost stationary nature and incredible intensity of the storm can be seen from the following readings of the rainfall between 1630 and 1815:

(1) Sevenoaks School	4·50 inches
(2) Knole Road (1 mile distant)	2·02 inches
(3) Cramptons Road (2½ miles distant)	0·84 inches
(4) Otford village (4 miles distant)	0·11 inches
(5) Shoreham village (6½ miles distant)	Nil.

The reading at (1) above will probably figure in the records of short-period intensity for Great Britain (see Ingrid Holford. *The Guinness book of weather facts and feats,* Enfield, Middlesex, Guinness Superlatives Ltd, 1977, p. 139). It rivals the Hampstead storm of 14 August 1975. At (2) above, the temperature was observed to fall from 17 °C to 6 °C in 30 minutes.

B. R. Dixon

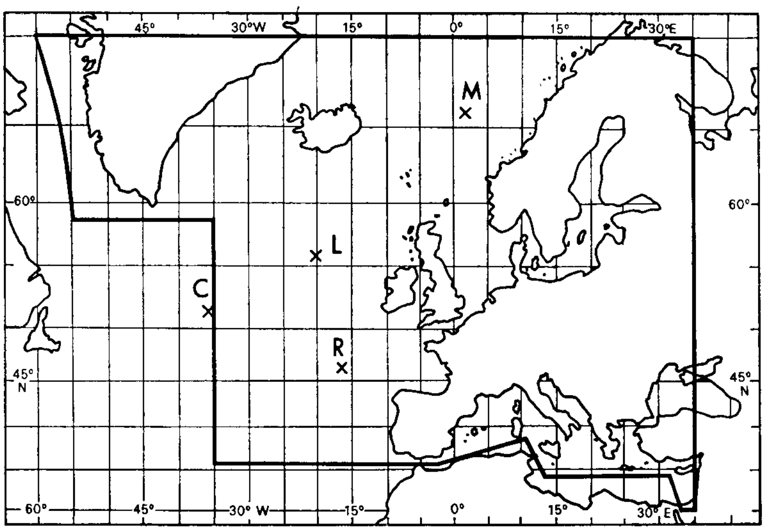
Sevenoaks, Kent.

Notes and news

Future plans for North Atlantic Ocean Stations

The fifth session of the Board established to administer the Agreement for Joint Financing of North Atlantic Ocean Stations met in Geneva in July 1980. The Board decided to maintain the present network beyond 1981, with some operational changes which might also reduce the network's present operating costs.

The most important operational change comprises a different way of manning the four ocean stations (see map). Furthermore, from 1982 onwards, the telex-over radio system of telecommunications will be used instead of the present Morse system.



Positions of the Ocean Stations in the NAOS network as from 1 January 1982. Station C is operated by the USSR and Station R is operated by France. Station L will be operated jointly by the United Kingdom and Netherlands and Station M will be operated by Norway.

The purpose of the Agreement, which was adopted on 15 November 1974 in Geneva by a Conference of Plenipotentiary Delegations, is to ensure the operation and financing of a network of four ocean stations in the North Atlantic for the purpose of making meteorological observations. Each station is permanently occupied by a ship specially equipped and staffed for carrying out surface and upper-air meteorological observations and for providing other services such as making oceanographic and other scientific observations and rendering safety services to other ships and to aircraft.

At present, the following 15 countries are parties to the Agreement:

Cuba	Norway
Denmark	Spain
Finland	Sweden
France	Tunisia
Germany, Federal Republic of	United Kingdom
Iceland	USSR
Ireland, Republic of	Yugoslavia
Netherlands	

A further six countries make annual voluntary contributions to the system.

WMO Press Release

Long-range monthly forecasts—cessation of publication

As one of the measures to reduce costs and manpower in the Civil Service, the Meteorological Office has announced that it is to cease to issue long-range monthly forecasts at the end of the year. The publication of *Monthly Weather Survey and Prospects* (which contain the forecast) will also cease.

The service of forecasts for up to a week ahead—for example the farming forecasts, broadcast on a twice-weekly basis—where reliability has increased recently with the extension of computer-based methods, will be maintained. Some research on long-term prediction will continue, as will the existing consultancy service for specific customers.

The task of producing the monthly forecast is closely integrated with the normal forecasting and research activities of the Office, and it is not possible to be precise about its full cost. However, as a result of cessation of publication and reduction in associated research, seven posts will be given up with a resultant saving of approximately £47 000 a year at 1980 pay rates.

Daily Weather Report—cessation of publication

Publication of the *Daily Weather Report*, the *Monthly Supplement* to the *Daily Weather Report* and the *Daily Aerological Record* will cease at the end of this year.

This step is being taken as a result of the Government's determination to reduce public expenditure and the number of civil servants engaged upon work that, although desirable, is not absolutely essential.

Daily synoptic charts covering much the same area are available in the form of the *European Daily Weather Report*, prepared and distributed widely by the West German Meteorological Service, Deutscher Wetterdienst, Zentralamt D 6050, Frankfurter Strasse 135, Offenbach am Main, Federal Republic of Germany. The price is comparable with that of the *Daily Weather Report* of the Meteorological Office.

An historical account of the *Daily Weather Report* will be given in a future issue of the *Meteorological Magazine.*

Symposium on Applications of Lidar to Atmospheric Radiation and Climate

This symposium is to be held on 20 August 1981 in Hamburg, Federal Republic of Germany, and will form part of the IAMAP Third Scientific Assembly—Radiation Commission (17–28 August 1982). The co-convenors are:

V. E. Derr	V. E. Zuev, Director
US Department of Commerce	Institute of Atmospheric Optics
NOAA/ERL/WPL R45X3	Siberian Branch of the Academy of Sciences
325 S. Broadway	Tomsk–29
Boulder, Colorado 80303	Gertsena Street 8
	USSR

Abstracts are due by 2 March 1981 and should be sent to V. E. Derr.

Meteorological Magazine—increase in price

As from January 1981 the price of an issue of the *Meteorological Magazine* will be £1.80 and the annual subscription will be £23.80 including postage.

Licences for reception of meteorological broadcasts

(This notice refers to broadcasts of technical data including radio-facsimile, not ordinary forecasts issued by public radio and television stations.)

The Radio Regulatory Department of the Home Office is responsible under the Wireless Telegraphy Act (1949) for the issue of licences for the reception of all telegraphy except sound broadcasting from authorized broadcasting stations or messages by telephony or telegraphy from licensed radio amateurs who have been exempted from licensing.

Licences for reception of meteorological broadcasts will be issued by the Radio Regulatory Department of the Home Office for an annual fee of £5 subject to the agreement of the Meteorological Office who, before giving consent, may levy an additional charge dependent on the use to be made of the data received. No additional charge will be levied on amateur meteorologists using the information for domestic and non-commercial purposes, on schools and colleges who use the information solely for instructional purposes or on most classes of shipping, provided that in each case an undertaking is given that the information will not be offered for resale in raw or processed form or otherwise be used in connection with the provision of any commercial service. In all other cases, the level of additional charge or waiver thereof will be decided in the light of information as to use given at the time of the licence application.

Any individual or organization wishing to be authorized to receive meteorological broadcasts from any source in the United Kingdom or in other countries should without delay address an application to:

Meteorological Office (Licensing)
London Road
Bracknell
Berkshire RG12 2SZ.

The application, in letter form, should give details of all broadcasts to be received, reception frequencies, reception apparatus to be used and where this is kept, and the purpose for which the information received is to be used. The level of additional charge or waiver thereof will be notified to each applicant. After any payment due is received by the Meteorological Office, the application will be forwarded to:

Home Office
Radio Regulatory Branch (R1)
Waterloo Bridge House
Waterloo Road
London SE1 8UA

who will issue the licence on payment of the £5 fee.

Correction

'A homogeneous rainfall record for the Cirencester area, 1844–1977' by P. D. Jones, *Meteorol Mag*, **109**, 1980, 249–258.

The units quoted on page 256 in the heading to the table forming Appendix 2 should be 'tenths of a millimetre' not 'tens of millimetres'.

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CONTENTS

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.

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

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