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Stratocumulus: an introductory account

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Summary

This article on stratocumulus is one of a series of teaching papers on mesoscale meteorology developed at the Meteorological Office College. It describes the important physical and dynamical aspects of stratocumulus formation and dissipation, highlighting the roles of radiation, turbulence, subsidence and cloud microphysics. The aim is to provide simple conceptual models which will help meteorologists develop an understanding of this type of cloud.

1. Introduction

Stratocumulus is very common around the United Kingdom and usually occurs in large sheets, sometimes covering areas of about 10^6 km^2. Fig. 1 shows how often stratocumulus of some sort is present in the sky.

The presence of low-level layer cloud significantly affects the radiation balance of the lower atmosphere, thereby modifying both the structure of the boundary layer and the surface energy balance. Consequently, forecasts of boundary-layer phenomena, such as fog formation and dispersal, maximum and minimum temperatures, surface conditions, etc. are highly sensitive to the presence of stratocumulus.

It is difficult to forecast accurately its disperal and possible re-formation after a temporary clearance. In fact relatively little progress has been made towards developing reliable forecasting techniques, making it all the more important that forecasters should understand the physical and dynamical processes occurring in sheets of stratocumulus.

The object of this paper is to provide this physical insight without obscuring basic understanding with too much detail.

2. General features

Most data on the structure of stratocumulus have been obtained in the mid-latitudes from single cloud layers (e.g. stratocumulus near high pressure regions). Subtropical and arctic stratocumulus, as
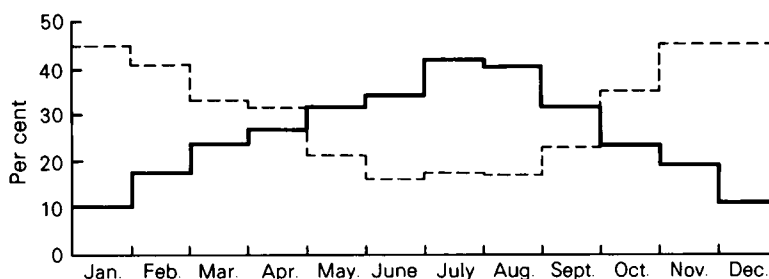
Figure 1.   Frequency of occurrence of stratocumulus (pecked line) and stratocumulus mixed with cumulus (bold line) in daytime observations for Boscombe Down 1960–69.

well as multiple layers of stratocumulus, have been less well studied so some caution must be exercised in applying the present results to such cases.

Stratocumulus formation is usually associated with either (a) the cooling or moistening (or both) of the boundary layer, or (b) the spreading out of cumulus beneath an inversion. The general features are best illustrated by reference to an example. Fig. 2(a) shows vertical structure measured by the Meteorological Research Flight Hercules aircraft during a slow descent (solid lines) together with a simplified representation (dotted lines). There are five regions of interest, namely: just above cloud (region A), cloud top (region B), within cloud (region C), cloud base (region D) and below cloud (region E).

Region A – just above cloud

In this region the air is warm and dry, often through subsidence. The air is stable and there is little or no turbulence.

Region B – cloud top

At the top of the cloud layer there is a marked inversion and hydrolapse. This is particularly well defined by the temperature profile. The boundary between the cloud layer and the subsiding air (which is several degrees warmer) has been observed to be as little as a few metres thick, but more generally it is a few tens of metres. The consequent large temperature, and hence density, gradient makes the atmosphere very stable and local perturbations are strongly damped, so that the cloud top is usually fairly flat, although small-amplitude gravity waves are often present.

Wind shear is usually confined to the inversion layer at the cloud top, where it may be large.

Region C – within cloud

Within cloud the air is well mixed, as shown by the temperature profile in Fig. 2(b), (and hence there is little wind shear) and has a constant wet-bulb potential temperature. Since in this example there is negligible precipitation, the total water content of a parcel of air rising through the cloud is conserved.

In discussing the water content of the atmosphere there are two important quantities: the amount held as vapour and the amount held as cloud water. The relation between them is best seen by an example. Consider a parcel of air at the surface at 10 °C with 6 g kg^{-1} of water vapour. Lift this parcel of air, without entrainment, without loss of water through precipitation and without any exchange of heat to or from the environment, from 1000 mb to 800 mb. The cloud base is at 945 mb.

As the parcel rises through the atmosphere above the cloud base the amount of cloud water increases (roughly linearly) while the amount of vapour decreases. In fact the amount of cloud water increases at a value of about 0.7 g kg^{-1} km^{-1} or 1.0 g m^{-3} km^{-1} (the density of air at 1000 mb is about 1.2 kg m^{-3}). This

value is referred to as the adiabatic liquid water content. In practice the liquid water content of stratocumulus is always slightly below this value owing to the entrainment of dry air at cloud top (this is

Height (mb)	Humidity mixing ratio of air (g kg⁻¹)	Cloud liquid water content (g kg⁻¹)	Total (g kg⁻¹)
800	3.9	2.1	6.0
850	4.6	1.4	6.0
900	5.3	0.7	6.0
950	6.0	0.0	6.0
1000	6.0	0.0	6.0

revealed in Fig. 2(a) by the departure from the adiabatic value, shown by the dotted line, in the upper part of the cloud). Precipitation would also lower the liquid water content.

Icing on aircraft can be a major hazard in stratocumulus. This will occur with subzero temperatures (below about 10 °C if carburettor icing is considered) and high liquid water content. The latter reaches its maximum value near the cloud top. When temperatures fall below -20 °C most of the water is in the form of ice particles which bounce off the aircraft, i.e. there is little danger of icing. The main danger is in the temperature range 0 to -15 °C when there are many supercooled water droplets which freeze on impact with an airframe.

Region D − cloud base

The transition to clear air at the base of the cloud layer is poorly defined. In contrast to cloud top, the cloud base region has no strong temperature gradients and stability to vertical motion is weak. In consequence, the cloud base is diffuse and large perturbations can grow, as is evident from the rolls that are frequently observed at the base of stratocumulus sheets.

Region E − below cloud

Below cloud the air is also well mixed, with the same wet-bulb potential temperature as the cloud layer. In fact on many occasions the within-cloud and below-cloud regions may be treated as one, even though the potential temperature profile shows a discontinuity at the cloud base.

3. What controls the development of stratocumulus?

Stratocumulus results from interactions between processes having widely differing length and time-scales, in particular:

(a) Synoptic-scale subsidence maintains the inversion and tends to lower the cloud top.
(b) The stratocumulus lifetime of several days implies that radiative effects are important.
(c) Turbulent mixing raises the cloud top. ((a) and (c) are often in near balance.)
(d) The detailed structure of the cloud is defined by the microphysical processes.
We shall consider these four processes separately, then discuss their interaction.

(a) Motion at the cloud top

The cloud top is not an impenetrable surface — it merely marks the boundary between clear air and air containing drops. When cold air sinks away from the cloud top some air is drawn down from above the cloud and mixes with the cloudy air. In particular, the downdraughts formed at cloud top must entrain some warm dry air from above the inversion some of which would be replaced by air from within the cloud. It is difficult to observe this process (but see Fig. 2(a), humidity mixing ratio) as it takes place
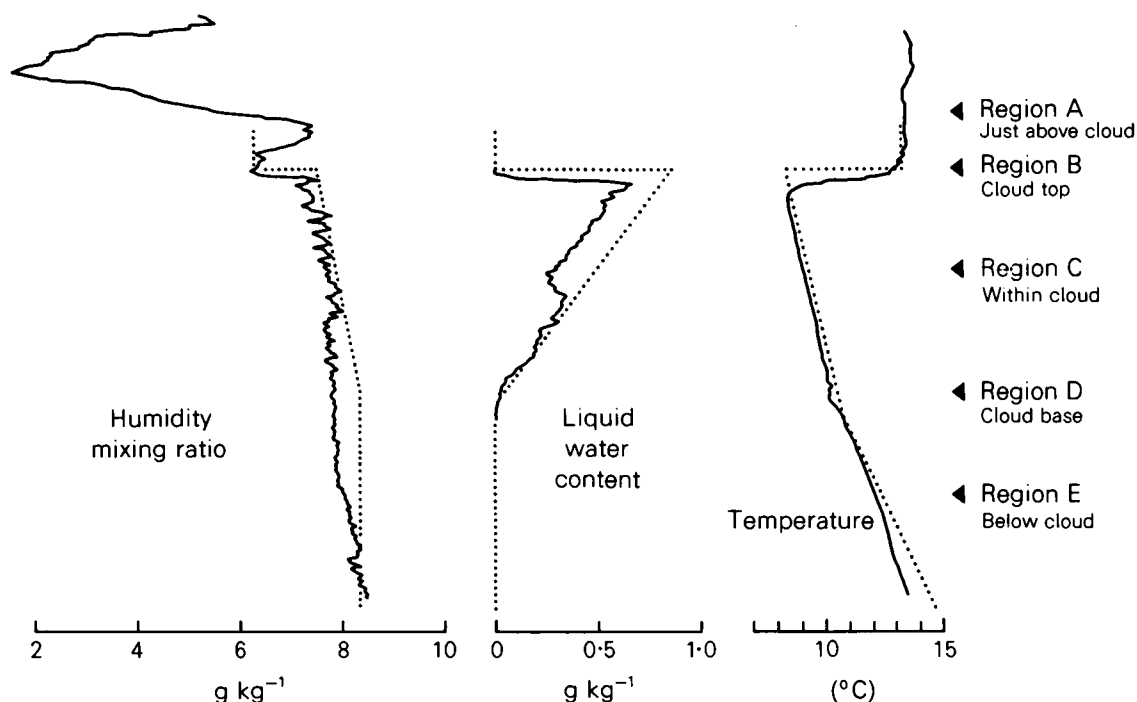
Figure 2(a).   An example of the humidity mixing ratio, liquid water content and temperature profiles in stratocumulus. The solid lines show the structure as measured by the Meteorological Research Flight C130 aircraft. The dotted lines show an idealized representation for stratocumulus.
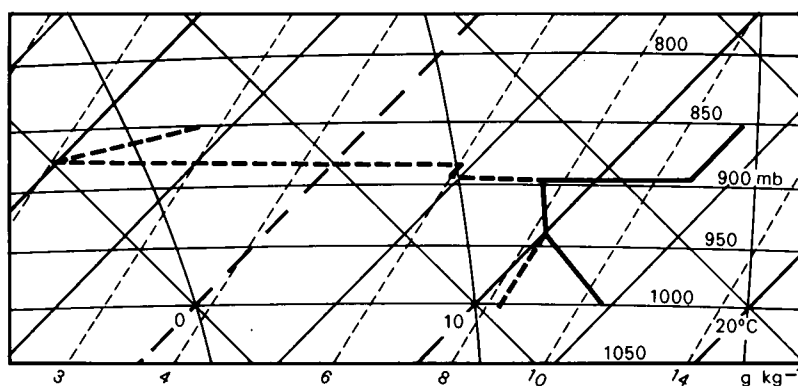

Figure 2(b).   Plotted ascent corresponding to the idealized profiles in Fig. 2(a).

within a few tens of metres of cloud top, but over a period of time the effect is to deepen the mixed layer and the cloud top rises. Initially, the entrainment of dry air into the cloud top may decrease the liquid water content of the cloud while the injection of cloudy air into the above-cloud region will produce little visible difference. However, on a longer time-scale the process moistens the region just above cloud top

and eventually, given a steady supply of moisture from the ground, the region will reach saturation and the cloud thicken. This effect is opposed by the large-scale anticyclonic subsidence, though the two need not be in balance. In consequence, the cloud layer will locally rise and fall, depending on whether one is stronger than the other. Aircraft observations show that frequently cloud top (and cloud base as well) slopes by 50–100 m per 100 km.

(b) *Radiative effects*

In general, radiative transfer takes place at all wavelengths but in the atmosphere we are primarily concerned with long-wave radiation (4–40 μm) and short-wave radiation from the sun (0.3–3 μm).

(i) Long-wave radiation

Once the cloud is sufficiently deep, typically about 150 m around the United Kingdom, the cloud layer acts approximately like a black body. The main long-wave properties can then be described by considering the radiative balance at cloud top, cloud base and within the cloud layer.

At cloud top, the cloud radiates (loses) energy according to its temperature (about 275 K) but receives very little from the overlying 'transparent' layers of the atmosphere. Cooling rates are therefore large, about 5–10 K per hour, and occur within the top few tens of metres of the cloud. Within the cloud there is little net radiative transfer as all the cloud droplets have a similar temperature, thus energy radiated away from a given volume inside the cloud is almost exactly balanced by that received from surrounding regions. At cloud base, since the ground temperature is usually a few degrees higher than cloud temperature, there is slight warming. Long-wave radiative transfer continues throughout the day and night, and its effect is summarized in Fig. 3(a).

(ii) Solar radiation

It is more difficult to summarize the role of solar radiation because of its variation with time of day, latitude, season, etc. In addition, the albedo of the cloud layer (i.e. the percentage of the incident flux reflected back to space) varies from 40–90%, depending on cloud thickness, drop size, solar elevation, etc. Of that which penetrates, some is absorbed by the cloud (13–15%) while the remainder reaches the ground. Another feature of the solar radiation is that, since it has a shorter wavelength, the depth over which it is absorbed by the cloud is much greater than that for long-wave radiation. Fig. 3(b)
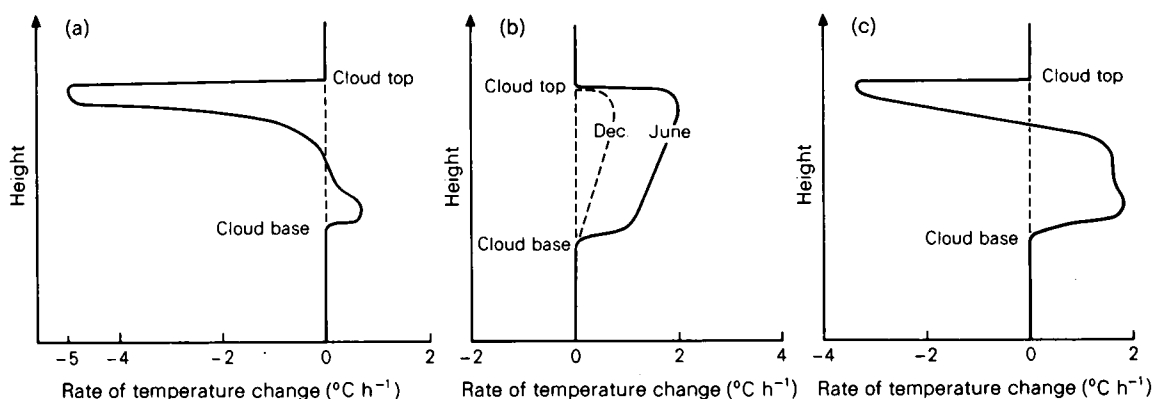

Figure 3. Typical rate of change of temperature profiles for stratocumulus showing (a) the net effect of long-wave radiation, (b) the net effect of solar radiation in the United Kingdom in June (solid line) and December (dashed line) and, (c) the combined effect of long-wave and solar radiation in the United Kingdom in June.

shows the net warming of the cloud in June at midday in the United Kingdom (latitude 52 °N). In winter this would be reduced by a factor of about four owing to the low elevation of the sun (dashed line in Fig. 3(b)) and at night would vanish. The combined effect of long-wave radiation and insolation (for the United Kingdom in June) is shown in Fig. 3(c). Note that in June at midday in the United Kingdom the amounts of solar radiation absorbed and long-wave radiation emitted by the cloud are nearly equal, although their spatial distribution is different. In consequence, stratocumulus may be expected to display significant diurnal changes, especially during the summer months.

(c) *Turbulence and entrainment*

The distribution of radiative heating and cooling, either by day or night, would, by itself, generate convective instability. This is released through turbulent motions which are observed to take the form of cold downdraughts descending from the vicinity of cloud top, with associated warm compensating updraughts. Thus cold air is brought down further into the cloud from the cloud top while warm air ascends. Since the rate of transfer of heat depends on the temperature difference within the cloud the system is self-regulating and, unless the cloud is dissipating or forming, effectively spreads the temperature changes due to radiation throughout the cloud.

However, as the long-wave cooling and solar heating will rarely be exactly in balance, in general the cloud experiences a net cooling. This will be discussed later, in more detail.

(d) *Microphysical structure*

As already stated, the liquid water content within stratocumulus increases roughly linearly with height at slightly below the adiabatic value. However, aircraft measurements show that there is usually little variation of droplet concentration with height (i.e. the number of cloud droplets stays the same but the drops become bigger towards the top of the cloud). The deeper the cloud layer, the larger the drops that form within it, and therefore there exists some critical depth at which drizzle (droplets more than about 100 μm) can form. It would be useful to derive a simple expression for this critical depth.

From microphysical theory there are two relevant facts:

(i) droplets less than about 20 μm radius grow only by condensation, and

(ii) droplets more than about 20 μm radius can grow by coalescence provided they are surrounded by droplets of different size.

Therefore, to produce drizzle, a few droplets must first grow, by condensation, to 20 μm. Thereafter growth by coalescence to produce drizzle is relatively rapid, although the process is complicated by the random nature of droplet collisions. Neighbouring droplets are not all the same size so it is helpful to define a mean droplet radius and to consider a size distribution about that radius. For example, if the mean radius is 10 μm then in stratocumulus one would expect to find drops ranging in size from about 5 to 15 μm, although these limits are not rigid. Thus a few 20 μm particles appear when the mean radius is about 15 μm. Therefore, knowing the critical mean radius (15 μm) at which 20 μm droplets first appear (i.e. the critical mean radius from which drizzle can subsequently form) and the liquid water content, the critical depth of cloud can be calculated provided that we know the number concentration of the cloud droplets.

For example, let the number of droplets be N cm^{-3}. Then the liquid water within a cloud is given by $N \times$ (mean mass of the drops). Taking the mean radius as 15 μm the liquid water content equals

$$N \frac{4\pi}{3} \left(\frac{15}{10^6} \right)^3 \times 10^{12} \text{ g m}^{-3}. \qquad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (1)$$

Within stratocumulus the adiabatic liquid water content varies with height at a rate of about

1.0 g m^{-3} km^{-1} (section 2) therefore at the top of a cloud of depth d metres the liquid water content is:

$$d \, 10^{-3} \text{ g m}^{-3}. \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

Equating (1) and (2) we have (very roughly)

$$d = 10N \text{ m}.$$

This relationship is summarized in Table I. Aircraft measurements have shown that N ranges from about 50 for clean maritime air to greater than 500 for industrial areas in continental regions. There is no way of measuring N from synoptic data but a good estimate can be made by considering the source of an air mass and its subsequent trajectory.

Table I. *An estimate of the depth of stratocumulus containing water droplets only required to produce drizzle at cloud base in a layer with cloud-top temperature above about -5° C*

Air mass	Number of water droplets (N cm^{-3})	Minimum depth of cloud to produce drizzle at cloud base (m)
Very clean maritime	50	500
Maritime	100	1000
Continental	200	2000
Industrial continental	250	2500

Whether or not the drizzle reaches the ground will depend on the humidity of the air below cloud base and local orographic effects that result in increased vertical motion.

Table I refers to stratocumulus cloud containing only water droplets. It provides only a very rough guide since droplet coalescence is a statistical process which has been poorly represented in the above calculations. In real clouds some drops, by chance, grow faster than others; also the effects of turbulence can 'recycle' certain drops allowing them a larger than average time in which to grow. In reality, rainfall production is a very complex process which is difficult to represent simply.

If the stratocumulus layer has a cloud-top temperature below about $-5\,^\circ$C, ice processes can become important and greatly enhance the production of precipitation, thereby reducing the depths in Table I. However, whether or not ice is present, maritime stratocumulus is always more likely to produce precipitation than continental stratocumulus.

Fig. 4 provides a summary of the processes discussed so far as well as indicating energy input from the surface.

4. The interaction of different scales of motion

(a) *Nocturnal effects*

Consider a sheet of stratocumulus in steady state during the day, with a radiation balance as shown in Fig. 3(c). At dusk the solar radiation ceases and the structure of the heating/cooling changes to that

SYNOPTIC ANTICYCLONIC SUBSIDENCE

Turbulent
entrainment
at cloud top

CLOUD TOP

INVERSION

Region A

Region B

Solar radiation heats the body of the cloud

Long-wave
radiation
producing
cooling at
cloud top
and heating
at cloud base

Cold
downdraught
from cloud top

Warm
updraught
from
cloud base

Downdraughts and
updraughts produce
mixing

LATENT
HEAT RELEASE

Microphysical
interactions
produce
precipitation

CLOUD
BASE

CLOUD LAYER

Region C

Region D

Surface fluxes of heat and moisture

GROUND
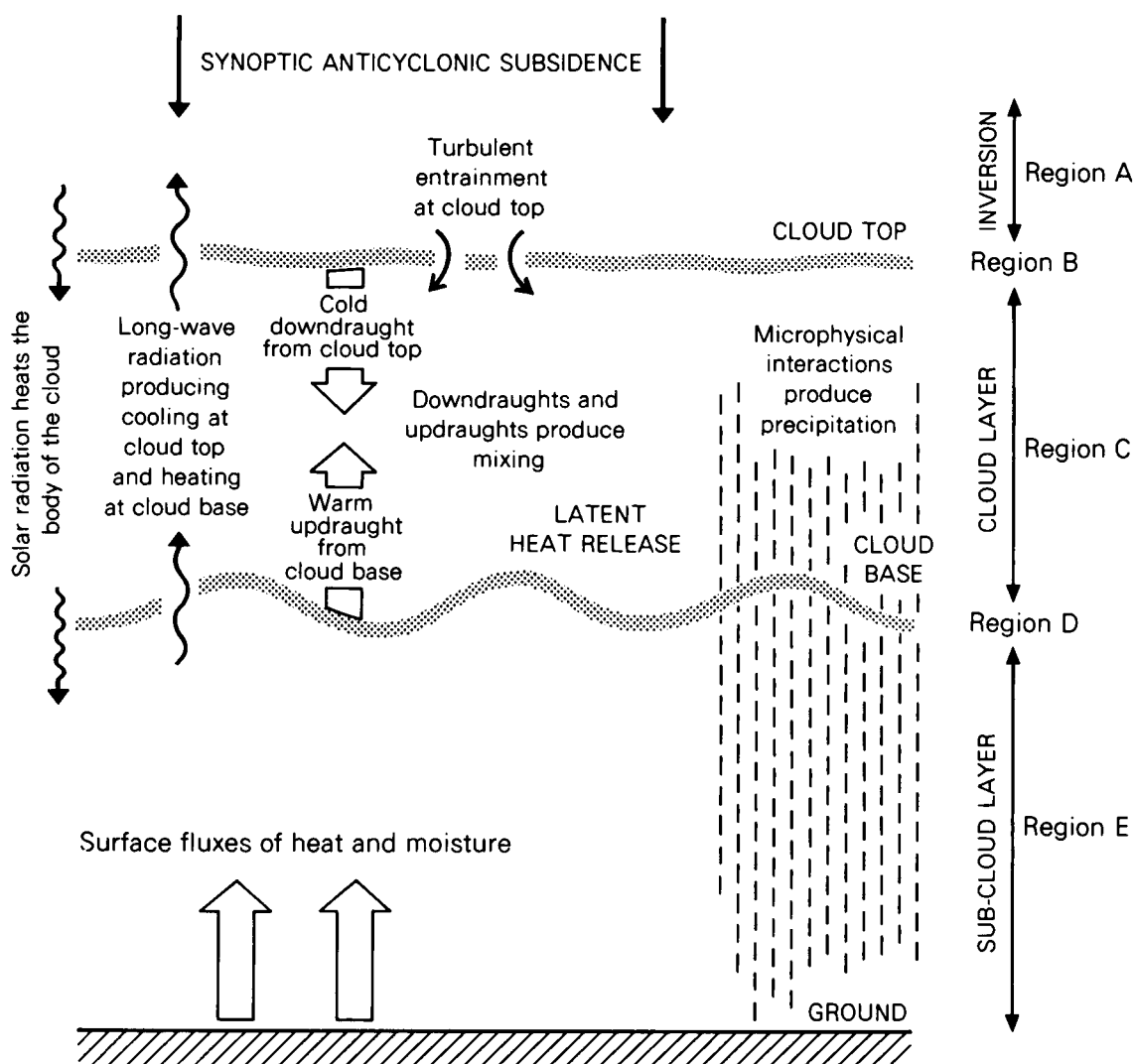
SUB-CLOUD LAYER

Region E

Figure 4.   Summary of physical processes important to the development of stratocumulus.

shown in Fig. 5. Compared to daytime, nocturnal stratocumulus has enhanced cloud-top cooling and reduced heating (not zero as there is long-wave radiation from the ground) throughout the body of the cloud. What will happen to the cloud layer? Two competing processes may be considered (Fig. 5). Process 1:

(i) At night there is a net cooling in the cloud layer.

(ii) Since the water vapour content remains essentially constant, cloud formation is enhanced (this has similarities to fog formation).

(iii) The net effect is that the cloud becomes denser and cloud base lowers.

Process 2:

(i) More cooling at the top and reduced heating at the base change the stability of the cloud layer leading to enhanced turbulence, principally through the presence of stronger downdraughts.
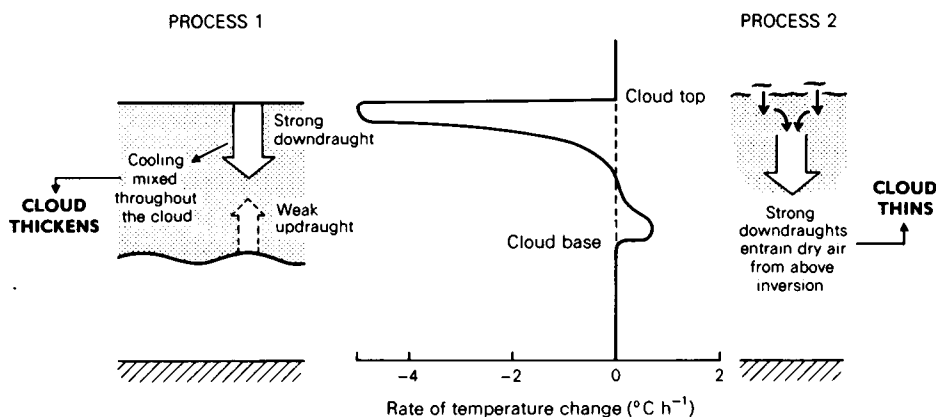
Figure 5. Outline sketch showing effect of the two competing processes on a sheet of nocturnal stratocumulus: Process 1 — radiative cooling at cloud top produces downdraughts which mix cold air throughout cloud layer and cause stratocumulus to thicken, and Process 2 — strong downdraughts entrain dry air which when mixed with cloudy air may disperse the stratocumulus.

(ii) Stronger downdraughts increase the entrainment of dry air from above the inversion.

(iii) If the air above the inversion is sufficiently dry the stratocumulus disperses through mixing.

Therefore at night there are two competing effects, one tending to thicken the stratocumulus and the other tending to disperse it. The outcome depends on the detailed structure of the cloud.

Little effort has been devoted to the investigation of Process 1 since, from a forecasting point of view, the precise details of a cloud layer are unimportant once persistence is assured. Process 2 is much more relevant since if the stratocumulus clears, surface conditions will markedly change. In fact Process 2 is the basis of James's rule (see Appendix 1). This technique was based on a statistical examination of station reports. James (1959) found two parameters to be important: D_m which measures the dryness of the air above the cloud and D_c which depends on the liquid water content and cloud thickness. If $D_m > D_c$ then the air above the cloud is dry enough to evaporate the cloudy layer completely.

James's rule is applicable over land only, mainly because the additional complications of sea surface temperature and the consequent flux of heat and moisture are too difficult to incorporate into a simple rule. It should also be remembered that James's rule is not very reliable because of the difficulty of making measurements accurate enough to distinguish between the two competing physical processes.

(b) *Daytime effects*

Consider now a sheet of nocturnal stratocumulus. As the sun rises, both the main body of the cloud and the ground warm up. At midday the radiation balance is as shown in Fig. 6. Again two processes can be envisaged.
Process 1:

(i) Both the main body of the cloud and the ground begin to warm, eventually achieving a balance.

(ii) The structure of the turbulence changes; updraughts are enhanced due to thermals, caused by the warm ground, penetrating the cloud layer from below, and downdraughts become weaker.

(iii) If the updraughts are sufficiently strong they may penetrate the inversion and induce compensating downdraughts which force dry, above-inversion air into the cloud layer.

This possibility involves a subtle balance. If the updraughts do not reach cloud top then no clearance is possible, indeed the cloud may thicken. Even if the updraughts penetrate the inversion, the air above the cloud top may not be either dry enough or warm enough to induce clearance. It is of crucial

importance that the updraughts should be strong enough and the air sufficiently warm and dry to clear the cloud — or perhaps break it into small fair-weather cumulus. This balance of strength of updraught and state of the air above the inversion is reflected in Kraus's rule (see Appendix 2). Note, however, that Kraus's rule (Kraus 1943) only uses the change in temperature across the inversion. This is partly because he was more confident in measurements of temperature and partly because, in subsiding air, the hydrolapse and temperature inversion are often closely linked. Caution is necessary if the air above the cloud is unusually moist or dry.

As with James's rule, Kraus's rule is in practice less than perfect because of the delicate physical balances involved and the difficulty of making sufficiently accurate and representative measurements. Process 2:

From Fig. 6 it is evident that sometimes the heating due to insolation and the cooling due to long-wave radiation will be of comparable magnitude within the cloud. As discussed earlier the cloud is destabilized causing turbulent motions which produce internal mixing and entrain potentially warmer air through the cloud top. The induced updraughts and downdraughts are now of equal strength and mixing is confined to the cloud layer. To put it another way, if the updraught and downdraught are of different magnitude, mixing takes place throughout the combined depth of the cloud and sub-cloud layers; if they are of equal magnitude, mixing is confined solely to the cloud layer. Thus the motions within the cloud are decoupled from those in the sub-cloud layer.

If this occurs then sub-cloud air no longer enters the cloud and the moisture supply is cut off. We have already seen that owing to entrainment at cloud top and possibly through precipitation there is a steady loss of moisture from the cloud and so if the supply is cut off, cloud base will rise and the cloud will thin and possibly disperse.

Observations show that under these conditions a weak inversion develops beneath the cloud base. If such a feature is observed during the day it suggests that there is evidence that the main cloud layer is beginning to thin and may, depending on its initial thickness, eventually clear. These ideas are discussed in much more detail in Nicholls (1984).

It is important to stress that throughout this section the discussion has concentrated on stratocumulus with radiatively driven convection. In many cases other forms of mixing (e.g. wind shear) may also be
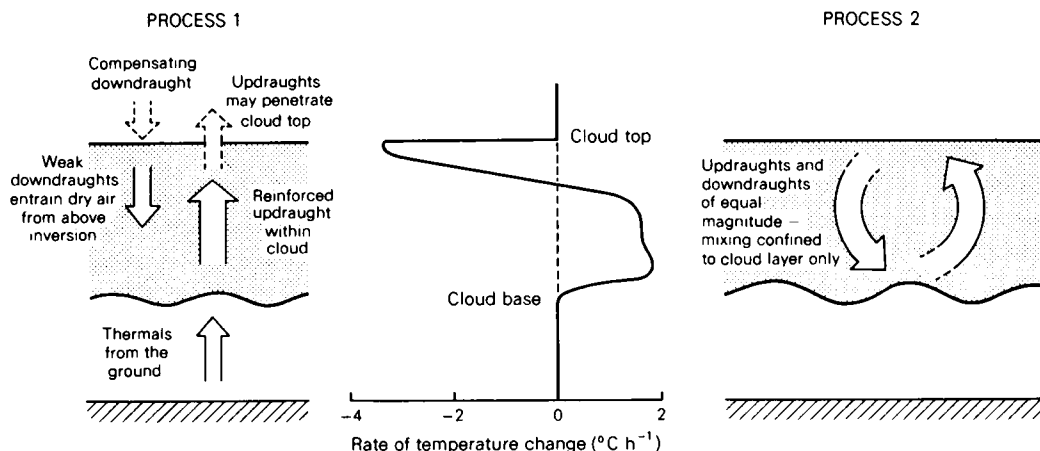

Figure 6.   Outline sketch showing effect of the two competing processes on a sheet of daytime stratocumulus: Process 1 updraughts are enhanced due to warming and may penetrate the cloud top causing compensating downdraughts to entrain dry air, and Process 2   updraughts and downdraughts are of equal magnitude confining mixing to the cloud layer only.

important especially if the cloud is at low level or there are very strong winds. Then the cloud may have quite a different structure and behaviour.

5. Conclusion

This paper has attempted to summarize the main features of our current knowledge concerning the formation and dissipation of stratocumulus in simple terms. It acknowledges that stratocumulus remains a major forecasting problem, primarily because the evolution of the cloud is a response to subtle changes in the balance between a number of different, but interacting, physical processes. Forecasting rules are either completely empirical or are based on extremely simplified forms of this balance. Some progress has been made in recent years towards identifying and quantifying the important processes (see for instance the references in Nicholls, 1984). One of the aims of current research is to design numerical models which more accurately reflect these processes. Information from these models plus, it is hoped, more detailed data on an operational basis will result in better forecasts.

It is only by having a clear understanding of the processes involved that forecasters can make the fullest use of the rather meagre information available at present.

References

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Kraus, E.	1943	Some contributions to the physics of non-frontal layer clouds. *Synoptic Divisions Tech Mem* No. 67, London. (Unpublished, copy available in the National Meteorological Library, Bracknell.)
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Appendix 1 — *Nocturnal dispersal of stratocumulus over land*

James's Rule

The cloud will break if $D_m > D_c$ where D_m is the maximum depression ($^\circ$C) of the dew-point below the dry-bulb temperature in the 50 mb layer above the cloud, and D_c is the value given in Table AI.

Table AI. *Values of D_c ($^\circ$C)*

z (mb)	h (g kg^{-1})					
	0.25	0.5	0.75	1.0	1.25	1.5
10	—		1.00	3.0	6.00	8.5
20	0.00	2.5	5.00	8.0	10.00	13.0
30	4.00	7.0	9.00	12.0	14.50	17.0
40	9.00	11.0	14.00	16.0	19.00	21.0
50	13.00	15.0	18.00	20.5	23.00	26.0
60	17.00	20.0	22.00	25.0	27.00	30.0
70	21.00	24.0	26.50	29.0	32.00	34.0

Where h is the difference (g kg^{-1}) between the humidity mixing ratios at the top and bottom of the 50 mb layer below the cloud, and z is the cloud thickness (mb).
Note: a linear hydrolapse in the layer is assumed.

The technique applies under the following conditions:

(i) The stratocumulus sheet is bounded at its top by a large hydrolapse, that is, a rapid decrease of humidity with height through the region of temperature increase.

(ii) There is no surface front within 400 miles of the locality of the cloud sheet.

(iii) The cloud base is above the condensation level of any convection from the sea (the rule applies only to stratocumulus over land).

(iv) The cloud sheet is extensive, covering several hundred square miles, and gives almost complete cloud cover, more than 6/8 for at least 2 consecutive hours. (The cloud was regarded as having dissipated if it broke to 2/8 or less for at least 2 consecutive hours.)

Failures of the technique in day-to-day forecasting can often be attributed to:

(i) inaccurate assessment of the cloud thickness (in the absence of reports from aircraft), and

(ii) uncertainties as to the magnitude and steepness of the temperature inversion and hydrolapse because of the lag of radiosonde elements.

Appendix 2 — *Dissipation of stratocumulus by convection*
Kraus's Rule

A cloud layer will not disperse by convective mixing with the air above if the pressure at the cloud top is less than P_c, as given below. (If the pressure at the top is greater than P_c the cloud may or may not disperse.)

$$P_c = P + a\,(P_o - 1000)$$

where P_o is the surface pressure (mb) and values of P and a are given in Table AII.

Table AII. *Values of P and a (mb)*

Temperature at cloud top (°C)		Magnitude of inversion containing the cloud layer (°C)								
		10		8		6		4		2
		P	a	P	a	P	a	P	a	P	a
	20	833	0.80	861	0.83	891	0.87	924	0.90	960	0.95
Water	10	803	0.75	834	0.79	869	0.82	906	0.87	951	0.93
cloud	0	755	0.67	789	0.71	830	0.76	877	0.82	932	0.90
	−10	680	0.56	719	0.60	765	0.66	823	0.73	898	0.84
	0	779	0.71	812	0.75	850	0.79	891	0.85	941	0.91
Ice	−10	702	0.59	739	0.63	786	0.69	839	0.76	908	0.85
cloud	−20	586	0.45	628	0.49	679	0.54	747	0.62	841	0.74
	−30	451	0.30	489	0.34	540	0.38	613	0.45	728	0.58

Controlling physiological age for maximum early potato production by the use of degree-day recordings

By C.P. Roe

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Summary

   This paper describes a graphical method devised to enable the farmer to monitor and control his potato-store temperatures in order to achieve optimum physiological age at the right time. The method is based on records taken in the farmer's store and compared with long-term records of degree-days from a suitable meteorological station.

1. Introduction

Potato growers have long recognized that seed potatoes which had sprouted before planting resulted in earlier crops. Research carried out at the University College of Wales, Aberystwyth and in ADAS over the last decade or so has demonstrated very clearly that the sprout lengths of the seed tubers were directly related to degree-days† above 4 °C. Researchers also found that the number of degree-days affected the yield of the ensuing crop (Hayes 1984). The effect of sprouting seed potatoes by exposure to increased temperatures is an ageing process, appropriately termed 'physiological ageing'.

   Any technique which can bring forward the date of harvesting the early potato crop will have obvious financial rewards. The technique of physiological ageing of early potato seed was developed for this reason.

   The physiological age (PA) of seed potatoes is measured in terms of degree-days above 4 °C over a certain stage of the life cycle of the seed potato. The optimum PA at planting varies according to potato variety and the intended date of planting. Agronomists have shown that achieving the optimum PA at planting time is an essential prerequisite to a successful crop.

1.1 *Definition of physiological age*

   The PA of a seed potato is defined as the number of degree-days above 4 °C (measured in the vicinity of the potatoes) between the date of breaking dormancy and the date of planting. The date of breaking dormancy is said to occur when 50% of the seed tubers in a batch have sprouts of 3 mm or longer. The optimum PA, measured in degree-days greater than 4 °C, depends on the variety and planting date of the potatoes as shown in Table I.

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* ADAS   Agricultural Development and Advisory Service   the advisory branch of the Ministry of Agriculture, Fisheries and Food (MAFF)
    WOAD   Welsh Office Agriculture Department

† Degree-days are the integrated sum of temperatures above a given threshold (in this case 4°C) for a continuous temperature curve. A sine wave is used to estimate the daily temperature curve based on maximum and minimum temperatures. Empirical formulae incorporating maximum and minimum temperature and base temperature give the daily increment to the °C day total. The Meteorological Office preferred term is 'accumulated temperature', see the *Meteorological Glossary* (Meteorological Office 1972). However, industry, particularly heating engineers, prefers to use the traditional term of 'degree-days'.

Table I. *Optimum physiological age of potatoes at planting (degree-days above 4 ° C)*

| | Planting date | |
Variety	Early February	Early March
Arran Comet	500	700
Ukama	500	600
Estima	500	700
Manna	400	500

Note: an allowance of 50 either side of the optimum is acceptable. (Figures supplied by Agronomy Department, Trawsgoed for Dyfed development store.)

1.2 *Current research into the PA technique in Wales*

In studies carried out at Syke Farm in Pembrokeshire over the last 3 years, agronomists and mechanization specialists have investigated the commercial manipulation of PA for maximum early potato production. The results from this work are encouraging — giving improved yields and an earlier crop over the more traditional husbandry methods used by farmers (Birkenshaw 1984) — and are now being used more widely in potato-store management.

However, development work at Syke Farm required a purpose-built environmentally controlled potato store (Hull 1984) to optimize the PA process. At a cost of £7500, the store was far beyond the means of many farmers. Other factors, such as the novelty of microprocessor technology and the risk factor involved with a new technique, combined to discourage farmers from installing it. What they needed was a simple method of controlling PA (albeit not to the accuracy of the environmentally controlled store) using their existing store (normally a glasshouse or similar building).

1.3 *Controlling PA in a traditional store*

The management tactics adopted in any particular year to achieve optimum PA by planting depend on several factors:
   (i)   the date when dormancy breaks,
   (ii) the optimum PA for the variety stored and the planting date aimed for, and
   (iii) the season's weather.
The aim of the farmer is to reach target PA with the minimum of management input, energy use and, hence, cost. This can be done simply by recording the development of PA through the season in store, and advancing or retarding development according to the trend in previous years determined from records of degree-days over a number of years at a suitable meteorological station nearby.

This paper considers the likelihood of achieving a target of 500 degree-days by mid-February — a typical requirement in Wales — for various dates of dormancy break at Syke Farm. Long-term records from Dale Fort climatological station are used throughout with a temperature adjustment to simulate store conditions. A graphical method is devised to show when heating or cooling, to speed up or slow down the progression of PA, is required to reach optimum PA.

2. The probability of reaching optimum PA for selected dates of dormancy

The date when potato seed breaks dormancy depends on both its variety and the weather conditions. If the farmer buys his seed from a supplier he will have no control over this factor. However,

home-grown seed can either be delayed by cool storage or speeded up by heating so that dormancy breaks at a certain time. It is often advantageous to do this.

Past weather records show the effect late or early breaks of dormancy will have on the probability (expressed as years in 20) of achieving target PA. Ideally many years of records within the store are required but in their absence, as is usually the case, records from the nearest suitable meteorological site must be used. These latter records must be compared with in-store temperatures to determine the temperature elevation in the store as a consequence of the building itself and the heat generated by the potatoes.

This was done by ADAS agronomists for Syke Farm where the temperature excess over Dale Fort climatological station, some 7 km to the south-west, was found to be on average 2 °C. Potatoes within the store are kept in trays stacked 20 high, with potatoes piled two or three layers deep. This allows air to circulate freely between the trays and prevents the high temperature rises associated with potatoes piled in heaps on the floor.

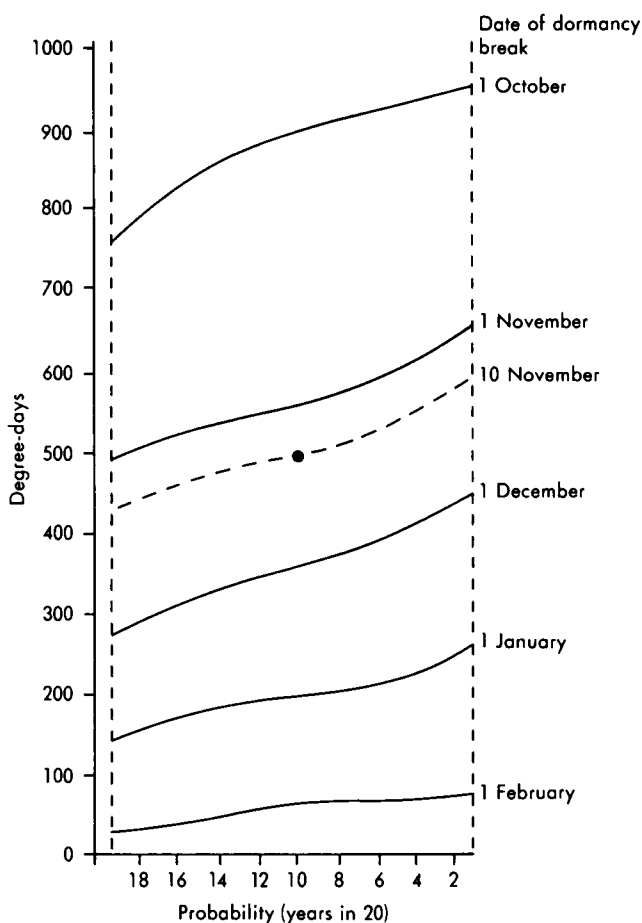Fig. 1 shows the probability curves for various dates of dormancy break on the first day of the month

Figure 1.   Probability curves for various dates of dormancy break for the years 1963–82 at Syke Farm, Dyfed showing the likelihood of achieving the optimum physiological age (500 degree-days) before planting in mid-February. The ideal date of dormancy break is indicated by the dashed line.

for the years 1963–82. (Intermediate dates can be estimated by eye from the existing curves.) If 500 degree-days are required by mid-February this will be achieved in all years if dormancy breaks in October; if dormacy does not break until December there is little hope of accumulating 500 degree-days by this date. A good time to break dormancy is early November (see curve for 10 November); this will give between 440 and 500 degree-days in the coolest 10 years (see • in Fig. 1). Thus the final degree-day total accrued will never be greatly divergent from the target and should be readily achieved with little management input.

3. Store management tactics to achieve optimum PA

In the majority of years, optimum PA will not be achieved without some management input in the form of advancing or retarding the progression of PA. Fig. 2 shows the median amount of heating or cooling needed to reach 500 degree-days by mid-February for selected dates of dormancy break. The dashed line was estimated by eye to show the seasonal accumulation required to achieve the target
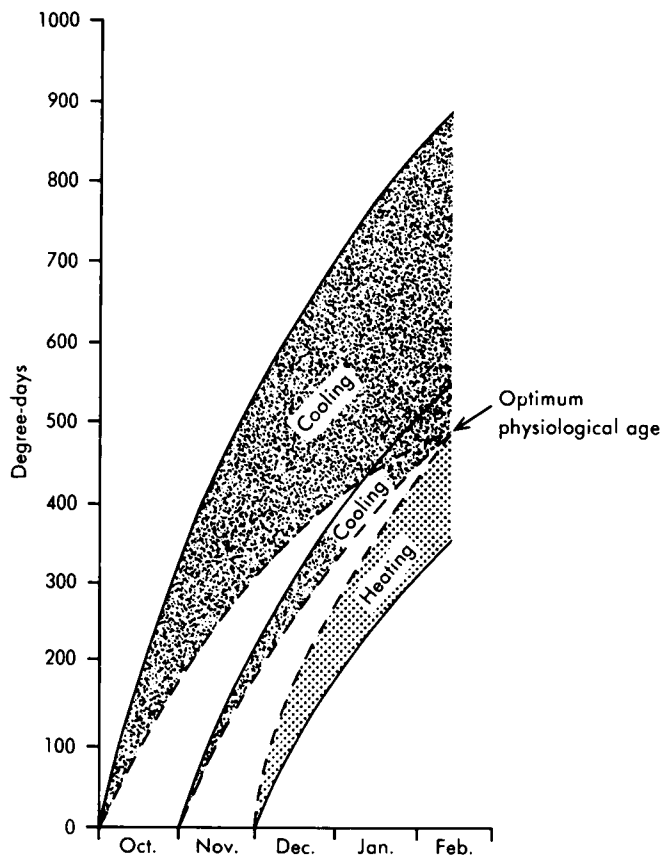

Figure 2.   Requirement for heating or cooling (shaded areas) at Syke Farm, Dyfed to reach optimum physiological age (500 degree-days) by mid-February for three dates of dormancy break. The solid lines show the expected degree-day totals (10 years in 20) over the period 1963–82. The dashed lines show the optimum totals required to achieve the target.

exactly. The slope of the line reflects decreasing temperatures through the season. The solid lines represent the median year degree-day values over the 20-year period 1963–82.

Clearly if dormancy breaks early on during October, or if the winter is very mild, too many degree-days will accrue so a good deal of cooling will probably be required. Stores are cooled by opening all doors and keeping vents open; where fans are installed these can facilitate cooling.

If dormancy break is delayed until December, or if the winter is cold, the store must be kept as warm as possible. Some heating is provided by the potatoes themselves when the doors are closed, fans are turned off and some, but not all, vents are closed. However, in very cold weather additional heaters will be required to prevent frosting of the tubers and to boost the degree-day total.

4. Timing when to heat or cool

Long-term weather records show the likelihood that heating or cooling will be required — the store management strategy. Weather conditions in a particular year might dictate that the exact opposite action is required, so tactical management should consider each season on its own merit.

Decisions on when to heat or cool can only be made by comparing degree-day totals measured within the store (methods of doing this are described later) with the 'target lines' (i.e. dashed lines) shown in Fig. 2. One might then decide to heat the store whenever the actual total was more than a critical amount behind the target at a particular time. Similarly cooling might be applied when the actual total exceeded the target by this critical amount. A suitable value for the critical difference might be 50 degree-days. Agronomists have pointed out that the target PA is not a critical number and that provided the degree-day total at planting does not differ by more than 50 degree-days either side of the target, the performance of the potatoes will not suffer unduly once planted. 'Overcooking' the seeds will lower their performance as will planting under-developed seed.

Fig. 3 shows three actual seasons at Syke Farm compared with the target. In each season the potatoes broke dormancy on 1 November. In 1975/76 620 degree-days would have been reached by mid-February. The actual exceeded the target by 50 degree-days around the third week in December indicating that cooling was required. The low temperatures in December would allow this excess to be corrected but if action was delayed until 1 February, when the excess was 110 degree-days, it would have been impossible to prevent 'overcooking'. In 1966/67 a similar situation occurred but corrective action was not necessary until the middle of January. In 1976/77 the maximum difference between target and actual was only 30 degree-days so no corrections were required.

Fig. 4 is similar to Fig. 3 except that dormancy broke one month later. 1981/82 was an exceptionally cold winter and the degree-day total fell more than 50 degree-days behind the target almost straight away. In a season like this, the doors should be opened as little as possible and extra heaters would be needed overnight. The 1967/68 winter was less severe and corrective action was not required until mid-December. It is likely that in this year closing the doors would have provided sufficient warming to get back on target. 1974/75 was exceptionally mild and no corrective action was needed.

The above examples suggest that most stores in south-west Dyfed will require some form of heating or cooling over the winter. Provided the farmer keeps a close eye on the degree-day totals within his store he should be able to stay on course.

5. Methods of recording degree-days within a potato store

The only accurate way to monitor PA in-store is to record degree-days within the potato bulk. These recordings will indicate both the current age of the tubers and also enable the temperature excess over
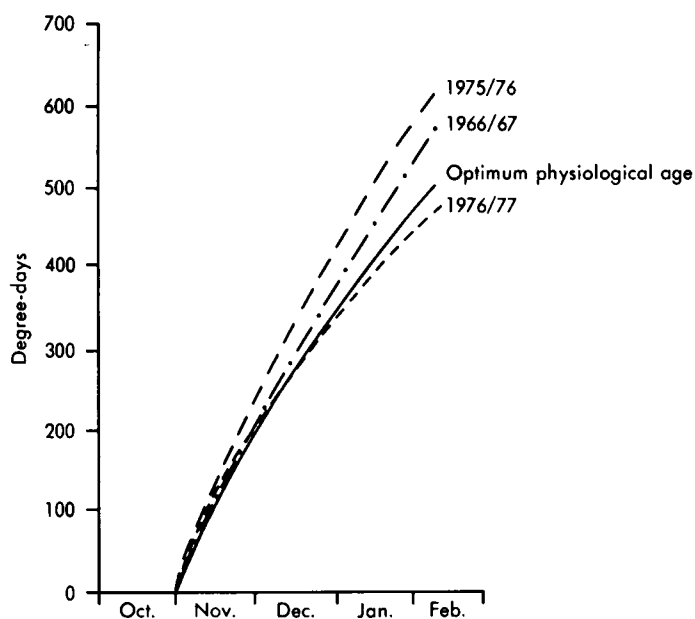
Figure 3.   Comparison of recorded degree-days for three individual seasons at Syke Farm, Dyfed with the optimum value of 500 degree-days, where the dormancy break in each case was 1 November.
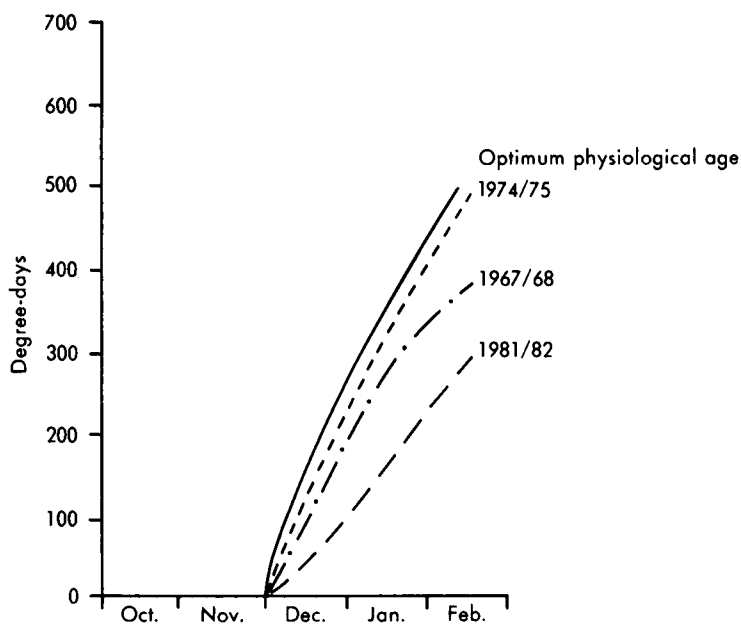

Figure 4.   As Fig. 3 but for a dormancy break of 1 December.

ambient conditions at a nearby meteorological station to be established. One of two methods is available to the grower:

(a) High-quality maximum and minimum thermometers can be placed in the air spaces between the potatoes and read daily at 0900 GMT. The daily increment to the degree-day total is then read off from tables and noted each day. A form prepared to enable growers to log these recordings is shown in the Appendix. (A good deal of effort has been devoted at shows by the Agrometeorological Department in persuading growers that the Six's thermometer as marketed by many agricultural suppliers is not sufficiently accurate for this type of work.)

(b) A battery or mains-operated temperature integrator, as described by Roe (1981), can be installed consisting of a thermistor which is exposed within the potatoes, and a counter which clocks up the degree-days from the date the counter was last reset. Once set up, the integrator (Fig. 5) will run unaided

Figure 5.   Electronic digital temperature integrator.

for many months and can be read whenever the farmer chooses, therefore saving valuable time.

An integrator is more accurate than the thermometers because it continuously integrates the temperatures and does not rely upon empirical formulae. Also the instrument is reliable and not easily broken. However, the cost of the integrator is four times that of two thermometers and the method is not, as yet, in general use.

6. Conclusions

This paper outlines a simple method whereby growers can monitor and control PA in their potato using meteorological data. Provided careful attention is given to routine checking of PA levels, and additional heaters are available, there is no reason why optimum PA cannot be achieved successfully. The following list itemizes the steps a grower would have to follow using this technique:

(i) Determine the date of dormancy break and decide on a planting date. Obtain optimum PA for variety of potato from ADAS agronomists.

(ii) Record degree-days above 4 °C within the potatoes from the date dormancy is broken.

(iii) Request target line from the Regional Agrometeorological Department of ADAS and plot the graph (see Figs 3 and 4).

(iv) At weekly intervals plot the in-store degree-day total from the date of dormancy break on the

graph. If this value differs by more than 50 degree-days from the target, heat or cool as required. (Delaying corrective action makes getting back on course more difficult.)

(v) Having reached optimum PA (within 50 degree-days), plant as soon as soil and weather conditions are suitable.

Acknowledgements

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Hayes, J.D.	1984	Basic research on controlling physiological age, ibid.
Hull, P.J.	1984	Temperature control, ibid.
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Roe, C.P.	1981	Degree-day measurements using an automatic temperature integrator. (Unpublished, copy available in the National Meteorological Library, Bracknell.)

Appendix — *Form for recording physiological ageing of store potatoes over a two-month period*

Recordings of the physiological ageing of store potatoes

taken at . . . . during 19 . . . .

Date of dormancy break: . . . .

Month: . . . .   Month: . . . .

Day	Max (thrown back)	Min	Today's degree-day total	Degree-day from dormancy	Day	Max (thrown back)	Min	Today's degree-day total	Degree-day from dormancy
1					1				
2					2				
3					3				
4					4				
5					5				
6					6				
7					7				
8					8				
9					9				
10					10				
11					11				
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31					31				

Rainfall investigations at Cardington and Winchcombe 1954–67

By R.P.W. Lewis

(Meteorological Office, Bracknell)

Summary

An account is given of the setting up and operation of two investigations carried out by the Meteorological Office into the fine-scale structure in space and time of heavy downfalls of rain using networks of synchronized open-scale rain recorders, one in flat and one in hilly country.

Introduction

During the period 1954–67 the Meteorological Office set up and ran two investigations into the fine-scale structure in space and time of heavy falls of rain, principally in connection with the problems of urban storm-water drainage; one investigation was near Cardington in Bedfordshire, and the other near Winchcombe in the Cotswolds. Holland (1967) has given a general survey of the work at Cardington, but the work at Winchcombe has received little publicity, although the results have long since been incorporated into the Office's store of data and have been used in such important publications as the *Flood studies report* (Natural Environment Research Council 1975). The present article attempts to put both investigations into perspective as part of the work planned and co-ordinated by the Joint Committee on Rainfall and Run-off (JCRR), and to give an account of how both were set up; it is in no way intended to be a scientific assessment of the results.

Formation of the JCRR

The Meteorological Office has for many years had a close working relationship with engineers and officials concerned with designing and installing systems of storm-water sewers to alleviate the nuisance caused by local flooding following heavy thundery downpours. (All who worked at the Meteorological Office at Harrow between 1945 and 1961 will recall that the main road near the entrance to the drive would become impassable from time to time.) Between 1948 and 1954 the British Climatology Branch (M. O. 3) was represented on the Rainfall, Run-off and Floods Committee of the Institute of Civil Engineers (ICE), the Hydrological Research Group of the Institution of Water Engineers (IWE) and had regular contact with the Inland Water Survey and the Road Research Laboratory (RRL). In 1954 the JCRR of the Ministry of Housing and Local Government and the Road Research Board was formed on which the Office was initially represented by Dr J. Glasspoole. The Committee met for the first time on 11 September 1954 and, after surveying the contemporary state of knowledge, put forward a program of research and investigation. The RRL were tasked with investigating how heavy falls of rain produced run-off from urban catchments of varying sizes and shapes, and with elucidating the principles of designing networks of sewers to improve drainage and alleviate nuisance. The Office was tasked with (a) revising and improving the classical Bilham formula for predicting the return periods of heavy falls of rain in short periods at a point and (b) relating observations of such falls to the spatial and temporal structure of the whole downpour over the surrounding area. The general economic criterion at that time for the effective design of a storm-water sewerage scheme was that flooding should not occur more frequently than once every ten years on average, i.e. a return period of ten years; more recently, a five-year return period has been adopted.

The Cardington experiment

Before the first meeting of the JCRR, the rainfall section of the M.O.3 had already planned and begun to set up a suitable dense network of recording rain-gauges. It was necessary for the chosen area to be fairly flat (because hills or mountains with steep slopes and narrow valleys would produce complicated orographic effects untypical of most of the urban areas to which the results would be applied); it was desirable for electricity to be made easily available to all the gauges; and it was also extremely desirable for trained Meteorological Office staff to be already within easy reach to run the investigation. All these conditions were found to be satisfied over an area of some 20 hectares on and adjoining the meteorological office at RAF Cardington, near Bedford. Some of this area was already on Government property, but most of the gauges had to be sited on private land, including farms, and there were at times difficulties in reconciling the layout of a scientifically suitable network with the necessary avoidance of inconvenience to farmers and other occupiers.

While sites were being chosen and leases and way-leaves negotiated, the Instrument Development Branch (M.O.16) at Harrow devised an 'open-scale' chart mechanism which could be attached to the normal Meteorological Office tilting-siphon (T/S) rain recorder in place of the daily drum. This open-scale device would feed a strip-chart from one drum to another at a speed which was about 14 times that of the movement of the ordinary daily chart, thereby enabling a detailed analysis of heavy rainfall to be made much more easily; the mechanism was worked either by clockwork or electricity (battery or mains), and a chart would last for four days.

By the end of the summer of 1956 sixteen open-scale rain recorders had been installed at Cardington, all powered by mains electricity and producing records that were in theory synchronized. The strip-chart mechanism did, however, give a certain amount of trouble, and the charts were liable to jam or slip. A fundamental snag in this simple adaptation of the standard rain recorder was that the chart had to be pulled horizontally from one vertically mounted spool to another; gravity thus tended to act at right angles to the desired direction of motion and small defects in the sprocket holes or the driving mechanism, or some other minor irregularity, had exaggerated consequences. There were additional adverse effects due to bird droppings, dust and leaves, and the net result was that seldom if ever were all the recorders in the network serviceable simultaneously, although for most of the time the majority would be. Another hazard was that during thunderstorms — which produced exactly the sort of rainfall that the network had been devised for — the electricity supply was likely to fail.

All recorders were visited every day, and a quarter of all the charts were changed. Although a Land Rover would have been ideal for getting round the network, for some years the transport officer was able to supply only one-ton or (worse) three-ton lorries which were naturally more difficult to manoeuvre through gates and tended to churn up the tracks very badly, much to the annoyance of the local farmers. One recorder was in the middle of a pig farm and the enclosure was defended against meteorologists by a guard of ferocious pigs. During the summer of 1959 three extra recorders were installed near the meteorological office to form a particularly dense cluster, and during the following winter three more were installed on sites stretching away in a north-easterly direction near the villages of Cople, Mogerhanger and Sandy. (These last three were powered by batteries, not mains electricity.) The locations of all the recorders used at Cardington, except the last two mentioned, are shown in Fig. 1.

Use of statistical methods

Towards the end of 1958 a small meeting was convened at Dunstable by Mr J.S. Sawyer (later to become Director of Research) to discuss methods of handling and analysing the Cardington data; the meeting was attended by the author. Mr Sawyer remarked that the variability of areal falls of rain might
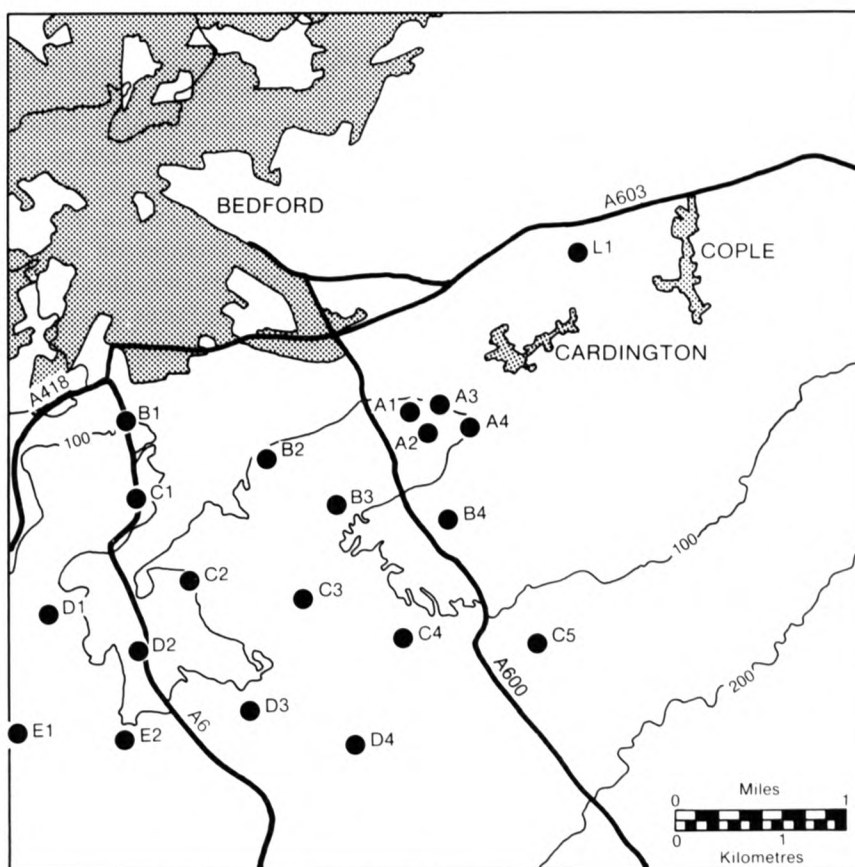
Figure 1.   Open-scale rain recorder sites at Cardington. The identifiers (A1, B3, etc.) are those used during the investigation. Sites L2 and L3 lie outside the figure, about 3.4 km east and 6.3 km east-north-east of L1 respectively.

profitably be investigated by an extension into two dimensions of the methods he had employed on the variability of mean upper winds along a one-dimensional track (Sawyer 1950), and that the somewhat intractable frequency distributions that had been found for the Cardington two-minute rainfalls could be treated by 'Monte Carlo' methods using computer simulation with a pseudo-random-number generator. The author's request for official expenses to study these new methods at Monte Carlo was rejected out of hand; however, he was able to provide the necessary extension of Sawyer's formula to a circular area on the assumption — later to be verified for the special case of the Cardington network - - that the correlations between two-minute rainfalls at two points were independent of direction. (Later, D.J. Holland provided analogous formulae for the more awkward case of a square.) The discovery that measurements along a line could to a large extent replace measurements over an area led to the extension of the network along a line to the north-east as described previously.

Liaison with local authorities

Once M.O.16 had devised an open-scale strip-chart mechanism for attachment to the standard T/S recorder, arrangements were made for the production of several hundred by a commercial firm, and by

1958 letters were being sent out by M. O. 3* to local authorities in England and Wales inviting them to co-operate in making much more accurate records of rates of rainfall than had hitherto been available. The response from local authorities was enthusiastic — indeed, embarrassingly so, because various troubles that arose in the course of manufacture of the mechanisms led to unforeseen delays in supply. These troubles were overcome, however, and by the early 1960s a considerable number of authorities as well as official Meteorological Office stations were taking part in supplying open-scale records for analysis. The data from these analyses were, before long, incorporated in the long series of records of 'heavy falls in short periods' that began in the nineteenth century and continues, in modified form, to the present day. Some results (which can never, of course, be regarded as final) can be found in the papers by Holland (1964), and Jackson and Larke (1974) and have gone some way to dealing with the first task laid upon the Office by the JCRR in 1954. This aspect of the work, however, seems likely to continue for a very long time to come, with more and more information becoming available on regional and local differences in the incidence of heavy falls; unlike the specific investigations at Cardington and Winchcombe it has no definite end, and will not here be considered further.

Extension of investigation to a hilly area

Now that the Cardington investigation was well under way and beginning to produce results, it was thought desirable to mount another investigation on a similar scale in an area that was hilly (but not mountainous), and reasonably possible for urban development, to see if there were systematic differences between it and Cardington in the way that violent falls of rain varied in space and time. If the differences were small, or could be clearly related in an obvious fashion to the topography, then advice relevant to the design of storm-water sewers could be tendered fairly confidently for a wide range of urban sites in southern Britain. A sub-committee recommended one or two suitable areas, and by early 1959 one had been selected about ten miles south-west of Dorchester in Dorset covering a height range from about 350 to 700 feet and consisting largely of rough uncultivated ground. A suitable network of rain recorder sites was planned using large-scale maps, and by the middle of the summer plans were sufficiently advanced for a field excursion to take matters further. On a hot sunny day in July 1959, therefore, L.H. Watkins of the RRL (Secretary to the JCRR) and the author set out from London by car to meet an Air Ministry Lands Officer and local farmers and landowners to explain the scheme and negotiate leases and way-leaves; they were looking forward to an enjoyable, busy, and useful couple of days in pleasant country. However, by tea-time that afternoon they had all been sent packing with a few brusque phrases from the first farmer they met. He would be delighted for them to put down their gauges, he said. How long did they want them there? A fortnight? Three weeks? *Three years?* He had, it seemed, been busy pushing upward the level of cultivation and one of the two dense arrays would have been in the middle of a cornfield. He stamped off angrily and the Dorset investigation was strangled at birth; Mr Watkins and the author returned, crestfallen, to London the following day. The title of the relevant file was promptly changed from 'Rainfall investigation in Dorset' to 'Rainfall investigation in hilly country'.

The Winchcombe experiment

The lesson of the Dorset fiasco — namely, that the people on the spot should have been consulted in advance — was immediately absorbed. The JCRR sub-committee was reconvened, and before long put forward two more areas which might be suitable for an investigation in hilly country, both in the

* By then called 'Climatological Services'.

Cotswolds. The rain-gauge inspector at the time (I.H. Chuter) was despatched in early May 1960 to survey these areas and talk informally to all the local people who might be involved — landlords, tenant farmers, and so on — so that they understood the purpose of the investigation and could raise any likely difficulties and objections. Mr Chuter's visit was successful, and he returned to Harrow with a firm proposal for an investigation in the area south of Winchcombe. Three weeks later he went round the area again with the author, and the Winchcombe investigation was under way.* The sub-committee visited the site in August, and during the following autumn and winter firm planning began. Whereas at Cardington the meteorological office was already staffed to carry out special observational and research work, and the demands of the rainfall investigation could be met by the addition of a couple of Scientific Assistants, for the Winchcombe experiment it was necessary to establish a separate small unit of a Senior Scientific Assistant and two Scientific Assistants which would be attached for convenience to the meteorological office at RAF Little Rissington; additionally, an Assistant Experimental Officer was to be stationed at Little Rissington for a few months to supervise the initial arrangements, liaising with M.O.3, the Meteorological Officer at Little Rissington, local works services and contractors, and so on. Because the provision of mains electricity to all the sites at Winchcombe would have been prohibitively difficult and expensive, it was decided to operate the strip-chart mechanisms there by electric batteries and use clocks fitted with a crystal control system for accurate timing. The network as originally planned should have contained 34 recorder sites including two dense clusters of 5 sites each. In the event, for various reasons including shortage of equipment, some objections raised by the farmers (though the relationship between the meteorologists and the farming community was on the whole excellent) and the sheer operational difficulty of coping with so many sites, the number was reduced to 24. Later on, in 1964, three more sites were added to the north-west at the request of the radar meteorologists working at Malvern; in addition to open-scale rain recorders these sites were equipped with radar reflectors to help provide estimates of attenuation. All sites that were actually used during the investigation are shown in Fig. 2.

Difficulties in supplying the clocks and crystal control units unfortunately led to considerable delays in making the network operational. Although the sites had been prepared and fenced and the recorders installed by the summer of 1961, it was the summer of 1962 before the network was working even at half strength, and 1963 before all the sites came into operation. The appalling weather of the 1962/63 winter posed severe problems for the rainfall unit, and in January 1963 an urgent rescue operation had to be mounted to bring indoors as many accumulators as possible lest the acid should freeze and damage the plates beyond repair. For many weeks a considerable number of sites were totally inaccessible, but when the thaw came it was found that the recorders had survived unscathed. The network was finally closed down in October 1967 after data had been collected for over 130 storms. The Reports of Work of the unit show that, as at Cardington, the provision of transport was an unexpected worry; at Winchcombe, the main difficulty was over the provision of drivers to cover various holiday periods.

Analysis of data

While the Winchcombe investigation was in progress, the earlier one at Cardington was deemed to have run its course and the network there was closed down in June 1963, data from some 150 storms having been collected; after September 1961 data collection had been confined to the summer half-year. Both at Cardington and Winchcombe, a good deal of the analysis of the strip-chart records was carried out by the Assistants on the spot. Further analysis was carried out at Headquarters (first at Harrow and

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* It is gratifying to be able to record that the Winchcombe site was, in the event, much better than the one in Dorset would have been.
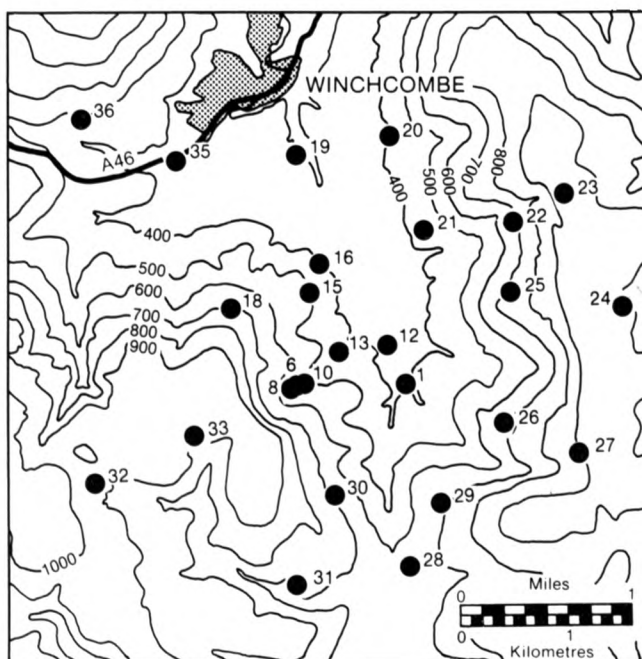
Figure 2.   Open-scale rain recorder sites used at Winchcombe. Some additional sites were prepared but did not come into operation.

then at Bracknell) and two pieces of apparatus of distinctly Heath Robinson design were constructed known as 'OSCAR' Marks I and II, OSCAR standing for 'Open-Scale Chart Analyser (Reversing)'. OSCAR possessed drums with sprockets, cog-wheels and an electric motor. At Cardington, however, the apparatus consisted of two smooth stones for holding a strip chart flat on a table-top, together with a perspex scale. By the late 1960s, all two-minute rainfalls, for every occasion of interest, from every serviceable recorder at Cardington and Winchcombe, had been transferred to magnetic tape. Considerable care was taken to allow for losses in catch during the siphoning process, an important matter for intense falls of rain. Much attention was also given to the relative efficiency of catch of the various gauges by comparing long-term totals, and to the elimination, as far as was humanly possible, of the inevitable errors of synchronization introduced into the records by the way in which the strip charts tended to jump sprockets, or slip, or pull alternately too taut and too loose. To quote the words of D.J. Holland from an unpublished report: 'the field workers and analysts were soon connoisseurs of these mechanisms' foibles and became adept at interpreting what were sometimes very puzzling inconsistencies; but a good many such inconsistencies have had to remain unresolvable to the requisite degree of timing-accuracy and have therefore had to be very circumspectly interpreted when put on to maps'. (It is safe to say that these inconsistencies are only important for comparison between the records of *different* recorders, and not between different portions of the record of one shower at the *same* recorder.) It is almost certainly true — even if saying so is somewhat pointless — that if the instrumental technology of 25 years later had been available the results of the investigations would have been much more reliable.

Visit by representatives of the Joint Committee on Rainfall and Run-off (JCRR) to Winchcombe in October 1961. From left to right: D.J. Holland (Meteorological Office), D.J. MacLean (Road Research Laboratory), L. Evans (Meteorological Office) in local charge of the investigation, and L.H. Watkins (Road Research Laboratory) secretary to the JCRR.

Site No. 10, Winchcombe area (grid reference SP027256), looking towards the east, May 1962. This view gives a good idea of the general characteristics of the area.

Results of the investigations

As stated above, it is not the intention of the author to give a full scientific assessment of the results of the Cardington and Winchcombe investigations. Rather unfortunately, the Meteorological Office was not able to provide such an assessment immediately after the program of data extraction had been completed, probably because of the necessity to divert staff and other resources into other, more pressing, work such as the Dee Weather Radar Project. Also, the attention of hydrologists at that time was turning towards considerably bigger catchments than those of which the Cardington and Winchcombe networks were representative. The data have, however, been discussed in some detail by Marshall (1980) in relation to the movement and shape of storms, and he showed that there were indeed systematic differences, related to topographical features, between Cardington and Winchcombe.

For more immediately practical purposes, the data have been used in design studies for storm-water sewers (Department of the Environment 1976) and for the pattern of urban run-off (Kidd and Lowing 1979).

Some current applications

Later and more elaborate programs of investigation into rainfall distribution, such as Project Scillonia, the Dee Weather Radar Project (Central Water Planning Unit 1977) and FRONTIERS (Browning 1979) might be thought to have few, if any, points of contact with the work at Cardington and Winchcombe. These more recent studies have been concerned either with deepening our scientific understanding of the processes of rain formation or with developing the use of radar to provide detailed very-short-range forecasts of rainfall ('nowcasting') to help in controlling river flow and in alleviating flooding; at Cardington and Winchcombe, on the other hand, the purpose was to provide long-term statistical information for the design of fixed networks of sewers. Recently, however, it has become apparent that the radar estimates of rainfall, which are averaged over 5×5 km squares, can be much too smooth and that some remarkable variations on scales of 1 km or less can occur; the Cardington and Winchcombe data provide a wealth of valuable information on these fine-scale effects, in particular the relationships between point and areal rainfalls.

Difficulties in the field

It should not be thought by the reader that people mentioned by name in the present article were the only ones to make a significant contribution to the success of the Cardington and Winchcombe investigations, still less that they were the only ones involved at all. In such an extended piece of work, lasting well over ten years, important contributions were made by many Meteorological Office staff of all grades from Assistant (Scientific) to Assistant Director, the dirtiest and toughest tasks being undertaken by the Assistants and Senior Assistants who performed the daily round of inspecting and adjusting the rain recorders and changing the strip charts, whatever the weather. For example, the entry in the daily log at Cardington for 13 February 1960 finished with the remark, written in red ink, 'ITS SNOWING LIKE HELL!!' (Examination of the more official synoptic record shows that it was.)

At Winchcombe, life was harder still. The terrain was rougher, with gradients of up to 1 in 3 in places. The standard round involved opening and closing some 140 gates, and each site had about six or seven locks (for the entrance gate, the rain recorder, the 'black box' timing device, the battery case, and so on), each lock being operated by a different key. Several times meteorologists had to take cover to avoid being fired on by hunters shooting duck, once they became involved with a fox-hunt, and once they had trouble with an obstreperous bull. The weather was frequently appalling, and in the Report of Work for

February 1966 it is recorded that 'parts of the Winchcombe area are waterlogged, and under-foot conditions are sometimes atrocious. Occasionally the staff more often resemble participants in the Eton wall game than Civil Servants'. The typical enthusiasm and dedication shown by the meteorologists in making sure the job was done, and done well, whatever the circumstances, seems not to have been shared to anything like the same extent by the drivers of the RAF vehicles who doubtless considered the whole operation to be completely mad.

Acknowledgements

Sources

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Awards

L.G. Groves Memorial Prizes and Awards

The presentations of the L.G. Groves Memorial Prizes and Awards for 1984 were made on 16 October 1985 at the Main Building, Ministry of Defence, Whitehall. Air Vice-Marshal A.G. Skingsley, CB (ACAS) presided, and Commander Michael Peer Groves RN (retd) made the presentations. Commander Groves is a nephew of the late Major Keith Groves who, with his wife, founded the L.G. Groves Memorial Fund in memory of their son. Among the several members of the Groves family who were present were Mr Nicholas Abbott, Miss Margaret Groves and Mr Robin Wight who have all acted as presenters of the prizes on various occasions in the past.

Air Vice-Marshal Skingsley opened the proceedings by welcoming all the guests and prize-winners. He reminded the audience that the L.G. Groves Memorial Fund was established in memory of Sergeant Louis Grimble Groves who lost his life in 1945 while serving as an Air Meteorological Observer with No. 517 Squadron of Coastal Command and remarked that since their inception in 1946 the awards had stimulated many ideas of great theoretical and practical value. He explained that the changes in the titles of three of the Prizes and Awards forecast by his predecessor in the role of president of the ceremony (Air Marshal Sir Peter Harding) had now been put into effect. He gave a brief account of the current awards and offered his own congratulations to the winners.

Air Vice-Marshal Skingsley then introduced Commander Groves and called upon him to say a few words before making the presentations. In response, Commander Groves expressed his pleasure in being present and related an amusing story about flight safety based on his own experience of early naval aviation.

The citations were then read by Air Commodore P. King, OBE (Inspector of Flight Safety, RAF), and Commander Groves presented the winners with their prizes and certificates, adding his own personal congratulations.

The 1984 Air Safety Prize was awarded to Sergeant T. Meechan, then of the Survival Equipment Section, RAF Cottesmore (now serving at RAF Coningsby) in recognition of his initiative and inventiveness in designing a gauge to measure the cutter movement in life-saving jacket operating heads. The gauge, which is applicable to all survival equipment inflation systems, facilitates accurate checking of cutter movement and should ensure the correct inflation of life-jackets and life-rafts. The gauge is cheap, easy to produce and has Service-wide applications. It is being introduced as part of a Servicing Instruction.

The 1984 Meteorology Prize was awarded to Dr J.F.B. Mitchell of the Meteorological Office. Dr Mitchell is the leader of a highly successful group within the Dynamical Climatology Branch which uses complex numerical models of the climate system to understand, and ultimately predict, climate variations. Recent events in Africa have demonstrated that, in an increasingly sensitive world, climatic variations can have consequences that go far beyond their area of origin to affect the whole global community. To an increasing extent they may have to be taken into account in strategic planning, both civil and military. Under his enthusiastic leadership the group has considerably enhanced our appreciation of the physical basis of climate and climatic variability.

Dr Mitchell's personal research has been concerned mainly with estimating the effects of increased atmospheric carbon dioxide concentrations, the primary cause of which is the burning of the Earth's supply of fossil fuels. It is a problem which has been causing growing international concern. Dr Mitchell's work has been wide-ranging and notable for its detailed assessment of the physical causes

Dr J.F.B. Mitchell, winner of the Meteorology Prize, receives his prize from Commander Michael Peer Groves.

Mr G.J. Day, winner of the Meteorological Observer's Award, is congratulated by Commander Michael Peer Groves.

L.G. Groves Memorial Prize and Award winners with Commander Michael Peer Groves, Air Vice-Marshall A.G. Skingsley and Air Commodore P. King, left to right: Air Commodore King, Flight Lieutenant R.P. Minards, Dr J.F.B. Mitchell, Air Vice-Marshall Skingsley, Commander Groves, Mr G.J. Day and Sergeant T. Meechan.

of the changes. In particular, he has analysed and elucidated the tendency in a number of estimates for parts of the subtropics and middle latitudes, already comparatively dry, to become even drier.

His expertise is widely recognized at home and abroad and he has contributed not only to the work of the Meteorological Office but also to research programs under the European Economic Community and the US Department of Energy.

The 1984 Meteorological Observer's Award was presented to Mr G.J. Day, now retired but formerly Assistant Director (International and Planning) in the Meteorological Office.

The collection of wind, temperature and aircraft position data from the main air routes and around the airfields of the world will make a significant contribution to flight safety and economics in guiding weather forecasting and warning methods. In some data-sparse areas and on flight paths inbound and outbound from airfields the identification of strong shear zones, regions of turbulence and significant icing potential could be vital. The so-called Aircraft to Satellite Data Relay (ASDAR) facility provides just such a data collection method.

As Assistant Director, Mr Day had no particular responsibility to encourage the development of observing methods. In practice, and almost single-handed, he has devised a method of funding an ASDAR development program through an international consortium, cajoled other nations to take part, encouraged British industry to bid (successfully) for the development contract, nursed development through all the normal, and some unique, shoals and persuaded international airlines and satellite authorities to collaborate, to the point where flight certification units are being fitted to wide-bodied jets in the fleets of British Airways, British Caledonia, Trans World Airlines and United Airlines. The RAF is giving the equipment serious consideration with a view to equipping some of their aircraft. Plans have been laid to install and maintain 40 to 50 such units in airlines around the world in the next few years. He

has been the driving force behind all this activity, much of it conducted in his spare time, whilst earning the gratitude, friendship and respect of those around him.

The 1984 Ground Safety Award was awarded to Flight Lieutenant R.P. Minards, then Station Flight Safety Officer (SFSO) at RAF Bruggen (now undergoing refresher training at the Central Flying School) for his initiative and effort in producing the flight safety video film *Safeguard*. The film, shown to all new arrivals at RAF Bruggen, emphasizes the potential flight safety hazards on a busy front-line station. The film is used by the Inspectorate of Flight Safety on their flight safety course and a number of SFSOs are considering the idea.

Obituary

Mr I.J.W. Pothecary, Assistant Director (Defence Services), died suddenly on 27 November 1985. He was aged 57 and had served for 34 of those years in the Meteorological Office.

Ivan Pothecary was born and brought up in Wiltshire and attended the grammar school in Chippenham through the years of the Second World War. In 1945 he joined the Royal Engineers, took the Engineers' short course at the University of Birmingham and was commissioned as Second Lieutenant. Three years later he returned to the University to complete a degree in Mathematics, Physics and Geography, qualified as a glider pilot and became a Pilot Officer (General Duties) in the Royal Air Force Volunteer Reserve.

Ivan Pothecary joined the Office in October 1951 and, after taking the Scientific Officers' Course at the Meteorological Office Training School in Stanmore, he was posted to the Meteorological Research Flight at the Royal Aircraft Establishment, Farnborough. He was there for only one year, the idea then being that, in their first few formative years in the Office, the young scientists should sample a wide variety of the work being undertaken. He enjoyed the flying, of course, but he also laid the foundations for scientific papers, which later appeared in print under his name, on clear air turbulence, the use of aircraft to measure wind shear by observation of vertical smoke trails, gravity waves, and pressure surges. After Farnborough, he spent nine months at the Main Meteorological Office at Gloucester, where he showed himself to be a proficient forecaster, before moving on to M. O. 21 at Dunstable, then the Short Period Forecasting Research Branch, to work under R.C.Sutcliffe and J.S.Sawyer in the Napier Shaw Laboratory. Here, he impressed his superiors not only with his thoroughness and industry in tackling scientific problems but also with his personality and strength of character, and he found himself appointed in September 1955 as scientific aide-de-camp in the office of the Director of the Meteorological Office, Dr (later Sir Graham) Sutton at Victory House in Kingsway, London.

He was promoted to Senior Scientific Officer and returned to Dunstable early in 1957 but he soon applied, and was accepted, for a post on secondment as Principal Scientific Officer in the British Caribbean Meteorological Service in Piarco, Trinidad, which he took up in November 1957. There he was Assistant Director in charge of the Eastern Division of what shortly became the West Indies Meteorological Service. Qualities already displayed elsewhere quickly came to the fore, in particular a gift for office organization and an ability to handle staff firmly whilst still remaining popular with them. Not unnaturally, he came to grips in Piarco with the problems of hurricane forecasting and, as ever, his enthusiasm and interest in this new area were such that he soon made his mark. He received a commendation for his work from the Federal Minister of Communications that referred to the several occasions on which he had stayed on duty for 24 hours or more when a hurricane threat developed. In

hurricane forecasting there was a need for close co-operation with the US Weather Bureau in San Juan, Puerto Rico and when he left for the United Kingdom in November 1960, the Meteorologist-in-Charge, Ralph Higgs, wrote that co-operation between the two offices had reached heights never before achieved.

It may have been another comment made in the West Indies — that he had shown a refreshing interest in instruments and an ability to keep them in working order — that led immediately on his return from the tropics to a midwinter posting to Eskdalemuir Observatory in the Southern Uplands of Scotland. There he was Superintendent for the best part of three years doing an excellent job in a post that he would not have chosen for himself. At Eskdalemuir he was concerned not only with meteorology but, in liaison with the Royal Observatory, Herstmonceux and the Blackford Hill Observatory, Edinburgh, was responsible for magnetic and seismic observations. In his term of office there was constructed a new seismic vault and a surface laboratory and Eskdalemuir became the leading UK Seismic Observatory. He also experimented with the *in situ* calibration of daylight recorders and with proton magnetometers.

Ivan Pothecary's career took another eventful turn when he was sent from Eskdalemuir towards the end of 1963 to become a Senior Forecaster at London/Heathrow Airport. He was given a special responsibility there for developing the use of satellite data in aviation forecast. Within a year he had mastered the forecasting job and had paid a visit to the US Weather Bureau Satellite Meteorology Laboratory to build on the new interest. He also found time to write a book, *The atmosphere in action*, which was published by Macmillan in November 1965 as No. 4 in the Quantum series of text-books. (This was translated into Danish.) He also contributed articles on satellite meteorology to the *Meteorological Magazine*. There was a natural progression in 1965 to the Senior Forecaster roster in the Central Forecasting Office at Bracknell and this was followed by a last spell in the Research Directorate of the Office, as deputy to the Chief Meteorological Officer at the Meteorological Research Flight, during 1967–69. There he was involved in a number of projects including the testing and use of an airborne infra-red radiation thermometer and a design study for a projected quartz crystal hygrometer but his main interest centred on the organization of the work of the Flight as a whole and the development of workable solutions to the many problems encountered.

In 1969 he joined the Defence Services Branch (Met O 6) in which he served with distinction for the remainder of his career. His first posting in this area was as deputy to the Chief Meteorological Officer at Headquarters, RAF Strike Command and in 1971 he was selected to join the National Defence College course in Defence Studies at Latimer. This he enjoyed immensely, his instructors noting that his intellectual curiosity led him to ask awkward questions when others hesitated. The course strongly coloured his attitude to his work thereafter. He returned to Strike Command but in September 1973, and with temporary promotion to Senior Principal Scientific Officer, he took up the appointment of Chief Meteorological Officer at the Headquarters, Near East Air Force in Cyprus with responsibility for the organization and administration of meteorological offices serving the RAF over an area extending from Gan (Addu Atoll) in the Indian Ocean to Gibraltar. In Cyprus he was faced at first with the problems of the military emergency of the time and later with the need to streamline his resources very substantially in meeting the needs of the smaller Command which came into being. He drew praise from the Commander British Forces, Near East for his able direction and objective thinking and for his wide military interests.

Returning to the Meteorological Office Headquarters at Bracknell in 1975 he was soon appointed Assistant Director (Defence Services) and headed Met O 6 for the next decade. He was very well suited for this role and became deeply committed to the military requirement. This was quickly recognized by the many within the British and foreign military services with whom he came in contact. He was a member throughout of the NATO Military Committee Meteorological Group, the present chairman, Captain John R. Lincoln, US Navy writing 'The meteorological community of all of NATO is richer by

far for Ivan's contributions. He served an outstanding term of three years as our Chairman. His abilities for working with and providing the guiding light of leadership in this international forum were unique ...'. At the same time he worked to maintain the closest possible understanding with the Air Staff at home and strove to develop a similar relationship with Army Staffs. Liaison with the Directorate of Naval Oceanography and Meteorology was never better, a circumstance that paid handsome dividends in respect of the quality of the meteorological support that was given to all the armed services in the South Atlantic during the Falklands campaign and after.

He was elected to the Council of the Royal Meteorological Society in 1969 and became a member of the Finance and General Purposes Committee. He had been a member of the Committee of the Scottish Branch of the Society while at Eskdalemuir. His interest in military matters lead to his regular attendance at meetings of the Royal United Services Institute for Defence Studies. He was always on the look-out for details of historic military occasions in which the weather had played a significant part and had planned to write a book on the subject after his retirement. We have surely been deprived of an original and entertaining work. His last public talk was given on the *Effects of Weather on the Persian Wars 492–480 BC,* to the History Group of the Royal Meteorological Society.

Ivan Pothecary's social life was very much bound up with his profession. His closest friends were from within the Office, and the house guests of himself and his wife Anne were often acquaintances, old and new, from amongst the many overseas meteorologists with whom he came into contact throughout his career. He was interested in archaeology and spent many happy hours in trenches at digs throughout the country and in Cyprus, fishing out bits of pot and bone with brush and trowel. He also discovered in himself a gift for water divining and an outdoor party-piece was the location of wells, drains or water-mains beneath his host's lawn.

Ivan Pothecary had a very personal style of management. He showed great loyalty to the Office and inspired the same in his staff. As he was apt to say, he did not run his Branch by committee. His leadership was felt throughout. Not surprisingly, his untimely passing has left a great gap and a strong sense of personal loss to his very many professional friends and colleagues at home and abroad.

Correction

Meteorological Magazine, January 1985, p.27, caption to Figure 3. ('How the meteorological reconnaissance flights began' by E.B. Kraus.)

Several knowledgeable readers have written to us pointing out that the tail-fin shown in the figure cannot possibly belong to a Blenheim but is that of a Hudson. We can but apologize.

Meteorological Magazine

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

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Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately.

Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

Tables should be numbered using roman numerals and provided with headings. We consider vertical and horizontal rules to be unnecessary in a well-designed table; spaces should be used instead.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

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Diagrams must be supplied either drawn to professional standards or drawn clearly, preferably in ink. They should be about 1½ to 3 times the final printed size and should not contain any unnecessary or irrelevant details. Any symbols and lettering must be large enough to remain legible after reduction. Explanatory text should not appear on the diagram itself but in the caption. Captions should be typed on a separate sheet of paper and should, as far as possible, explain the meanings of the diagrams without the reader having to refer to the text.

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