The physics of radiation fog: I – a field study

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SUMMARY

The results of a field study of the evolution of radiation fog on three nights are presented. A parallel numerical model (Brown and Roach 1976 – referred to hereafter as II) was also developed to test ideas suggested by the principal features observed during the field study. These were:

(i) Periods of significant fog development appeared to occur when wind speeds dropped below 0.5–1 m s$^{-1}$.
(ii) The liquid water content of the fog was a small fraction of the total condensed out by cooling. The balance of water appears to have been deposited on the ground.
(iii) Radiative cooling (deduced from radiative flux divergence measurements) was in general greater than the actual cooling.
(iv) As the surface became radiatively shielded by developing fog, the radiation inversion migrated to the fog top, accompanied by the establishment of a convective regime with a slight super-adiabatic lapse rate in the lower part of the fog.
(v) Ammonium sulphate was a principal constituent of condensation nuclei.

It is shown that these features are consistent with the suggestion that the development of radiation fog is primarily controlled by a balance between radiative cooling, which encourages fog, and turbulence, which inhibits it. Gravitational settling of fog droplets and soil heat flux also emerge as important factors. The role of cloud microphysics is not passive, but is less clearly defined as yet. The numerical model (II) reproduces most of the observed features, but not the stepwise growth or sharpness of the fog top.

Some of the practical implications of this work for forecasting and for fog modification are briefly discussed.

1. INTRODUCTION

The practical significance of radiation fog has, since World War II, motivated a large number of field projects with the main objective of fog modification or dispersal, particularly in the United States; but relatively little attention has been given to the study of the basic physics of radiation fog formation, maintenance and dissipation. It is generally accepted, however, that radiation fog is controlled by some interaction between radiative cooling and turbulence, but the nature of this interaction – and particularly of the role of turbulence – is not at all clear.

This paper together with part II describes the results of parallel field (I) and numerical (II) studies of the physics of radiation fog. The field study was carried out at Cardington by the Cloud Physics Branch of the Meteorological Office in collaboration (for the field study only) with the Meteorological Office Research Unit, RAF Cardington, Beds. and the Environmental Services Division, Atomic Energy Research Establishment, Harwell.

2. PAST INVESTIGATIONS

(a) Taylor (1917) appears to have made the first serious study of fogs over sea and land surfaces. His land studies were made at Kew, where he noted that clear skies, light winds and high relative humidities were conducive to fog formation, but that fog actually occurred on only about half the occasions when it might have been expected. He observed the cooling and drying-out of the atmosphere near the ground on a clear night, and realized that the initial formation of fog appeared to depend upon a balance between these two

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processes. As he put it "... if the dryness caused by the deposition of dew on the ground diffuses upwards at a greater rate than the coldness is conducted upwards, fog is less likely to form than if the reverse conditions hold". He attributed the "conduction" to turbulent diffusion, and also suggested "... it is possible that the cooling due to radiation from the fog particles after a fog has started may have the effect of making it thicker". He thus implied that turbulence had two opposing effects and discounted (incorrectly) the effect of radiative cooling of the air before fog formation (although he recognized that the ground cooled by radiation). Nevertheless, he appears to have been the first to suggest that fog formation depended upon a balance between the drying and cooling of the lowest few metres of the atmosphere, thus laying the foundation for later studies of radiation fog.

(b) Stewart (1955, 1957) realized the need to measure simultaneously as many as possible of the parameters likely to be significant in fog formation. From his observations (also made at Cardington) he drew the following conclusions:

(i) Direct cooling of the lowest kilometre of the atmosphere by radiation and by turbulent diffusion were comparable.

(ii) The surface deposition of water was comparable with that lost from the air by cooling.

(iii) The lowest layers of the atmosphere often reached and remained at saturation for up to a few hours before the fog actually formed. When fog formed, it usually did so within a few minutes, and subsequently its depth appeared to increase in steps.

Stewart also developed Taylor's suggestion that fog droplets produced their own contribution to radiative cooling, but he was not able to identify the factors which determined when fog would form on a given radiation night.

(c) Kraus (1958) made a series of measurements of wind, temperature and humidity profiles, and of radiation flux at one level on 7 consecutive nights during an anticyclonic period in October 1956. He noted that "Fog began to form when the wind at 1 metre was less than 0.5 m s⁻¹."

Both Kraus and Stewart attempted to estimate heat budgets, but their results were uncertain since some of the terms, particularly radiative flux divergence, were not measured directly.

(d) Many investigations of the atmospheric boundary layer have been made in conditions favourable for fog formation, but with objectives other than fog studies. Monteith (1957) noted that the rate of dew deposition decreased abruptly when the wind speed at 2 m dropped below about 0.5 m s⁻¹. He suggested that this resulted in a virtual cessation of turbulent diffusion, thus removing the primary mechanism for dew deposition.

(e) Rider and Robinson (1951) noted that "the change of temperature in the lowest layers of air is normally the small resultant of much larger tendencies due to changes in radiative and convective fluxes acting in opposite directions". They also noted a quasi-periodic oscillation of about 10 min period in the lowest 0.5 m on one radiation night at about the time of fog formation.

There is a general implication in this work that radiative cooling encourages radiation fog formation and turbulent diffusion inhibits it, but these are essentially qualitative conclusions which do not tell us why fog forms when it forms, nor what its evolution and structure will be, given the initial conditions; nor does it give quantitative information on heat and water budgets.

3. Results

The three case studies to be discussed in this paper were obtained during the winter seasons 1971/2 and 1972/3. The instrumentation used is listed in the appendix. Although
The sequence of events was quite different on each occasion, some common features were apparent. These features, considered in relation to past work and the results of the numerical model (II), lead, in our view, to a consistent picture of the principal meteorological factors controlling the evolution of radiation fog.

In reporting the results of three case studies, a compromise has to be struck between losing the reader in a mass of observational data on the one hand, and on the other of leaving the reader unconvinced by outlining the main conclusions with insufficient accompanying evidence. We have tried to steer between these two extremes by presenting the case studies as far as possible 'in parallel' rather than 'in series'.

The case studies will be referred to as:

A* – Early hours of 7 December 1971
B – Night of 31 October/1 November 1972

(a) General features

Case study A. During the period of interest, Cardington lay near the axis of an almost stationary ridge extending east from a large anticyclone over Ireland. At 00 GMT on 7 December 1971, the country southeast of a line from the Humber to Cornwall lay under a largely unbroken sheet of Sc. Fog had become widespread and persistent to the northwest of this line. The edge of the cloud sheet appeared to move in association with the SE progression of a weak cold front, clearing Cardington at about 0330 GMT. The sequence of events following this clearance is summarized below:

<table>
<thead>
<tr>
<th>Phase</th>
<th>Period (GMT)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>0400–0430</td>
<td>Layer of ground mist forms. Surface inversion begins to develop.</td>
</tr>
<tr>
<td>Ib</td>
<td>0430–0645</td>
<td>Visibility at 1 m fluctuates between 100 and 200 m, decreasing to 50–100 m. Top of fog ill-defined. Its depth fluctuates between 10–40 m. Surface inversion is 10 m deep by end of phase.</td>
</tr>
<tr>
<td>IIa</td>
<td>0700–0845</td>
<td>Inversion lifts off ground and settles near 20 m in vicinity of fog top, which now becomes sharply defined. Sunrise at 0755 GMT</td>
</tr>
<tr>
<td>IIb</td>
<td>0900–1000</td>
<td>Inversion and fog top lift a further 5–10 m.</td>
</tr>
<tr>
<td>III</td>
<td>1000–1030</td>
<td>Dispersal phase. Gradual thinning followed by rapid dispersal. Freshening surface winds.</td>
</tr>
</tbody>
</table>

The division into phases arises naturally from the tendency on this occasion (also observed by Stewart 1955) for short periods (a few minutes) of rapid fog development to alternate with longer, quasi-steady periods. Time cross-sections of 20-minute means of wind and temperature, cooling rate and height of fog top are all shown in Fig. 1.

* This case study was the subject of a preliminary report by Roach, Adams, Garland and Goldsmith (1973).
Figure 1. (a) Temperature/time cross-section based upon 20-min filtered means of temperatures at 2, 4, 8, 16 m and observations of temperature up to 60 m made at irregular intervals with a balloon-borne thermistor. Full lines are isotherms at 1 degC intervals. Dashed lines are approximate isopleths of local heating and cooling rates labelled in degC h\(^{-1}\) – the stippled area denotes cooling > 2 degC h\(^{-1}\). W, C, are zones of maximum heating, cooling. (b) Time cross-section of wind speed, based upon 20-min filtered means of wind speed at 2, 4, 8, 16 m. Solid lines are isotachs at 0-5 m s\(^{-1}\) intervals. Dotted lines show the approximate field of gradient Richardson number – stippled area denotes Ri < 0-25. (c) Time change of opacity at 1 and 5 m (solid lines) and of fog top height (dotted lines).

The main phases of fog development appear to have been associated with periods of marked cooling, and with relative lulls in the wind (i.e. a decrease from a mean level of about 1 m s\(^{-1}\) to 0-5 m s\(^{-1}\) or less. There is also a distinct tendency for fluctuations (on a time scale of 10–20 min) in wind below about 10 m and in visibility at 1 m to be in phase when the fog is shallow (Fig. 2) although the amplitude relationship is very variable. The opacity trace in Fig. 2 is a direct copy of the inverted transmissometer trace labelled with its equivalent (non-linear) opacity scale. Quasi-periodic oscillations of 10–20 minutes were also observed in other parameters and are described in detail in a separate note (Roach 1976). The lifting of the inversion early in phase IIa coincided with a rise in surface temperature and the establishment of a super-adiabatic lapse rate in the lowest 5 m (Ri < 0·25).

Case study B (31 October/1 November 1972). Cardington lay in a col between a deep depression to the NW of Scotland and a shallow depression over Biscay. Warm cloudy air associated with the Biscay depression receded southwards leaving clear skies. The sequence of events is shown below:
Figure 2. Expanded time cross-section of wind (case study A) compared with transmissometer trace (with superimposed opacity scale). Arrows are intended to emphasize a qualitative association between minima (maxima) of opacity and maxima (minima) of wind speed.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Period (GMT)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2200–0015</td>
<td>Break-up of Ac sheet early in period. Shallow fog develops and deepens to 30 m by end of period.</td>
</tr>
<tr>
<td>IIa</td>
<td>0015–0140</td>
<td>Marked wind increase above 10–15 m at beginning of period. Fog decreases in depth and disperses by 0050h, although there was a brief return at 0120h.</td>
</tr>
<tr>
<td>IIb</td>
<td>0140–0215</td>
<td>Wind increase penetrates to surface and destroys surface inversion. Series of quasi-periodic oscillations in wind and temperature at all measuring levels throughout this period. A separate study of these oscillations has been made by Caughey and Readings (1974).</td>
</tr>
<tr>
<td>III</td>
<td>0215–0430</td>
<td>Decrease in wind at all levels followed by rapid return of fog and fall of temperature. Fog depth fluctuates between 20–40 m during period.</td>
</tr>
<tr>
<td>IV</td>
<td>0430–1230</td>
<td>Fog deepens to 100–200 m by 0530h. Surface inversion lifts to top of fog. There was then little change until the fog dispersed fairly rapidly between 1215 and 1230h.</td>
</tr>
</tbody>
</table>

Phase IIb marks the passage of some event – possibly a weak cold front of which there was some evidence in synoptic data. The wind veered from a predominantly southerly direction to northwest during phase IIb, then to east with the return of the fog, and finally – with considerable fluctuations – to south after about 0400h.

Time cross-sections of wind and temperature, with visibility and fog top data, are displayed in Fig. 3.

The association between wind lulls, cooling and fog development (e.g. changes in fog top height) is again evident. The return to fog at 0220h, although coinciding with a
sharp decrease in temperature and wind, seems to have been too rapid to be ascribed to local developments, and was more likely to have been advected in association with the 'event' of phase IIb. Phase IV (not shown in Fig. 3) was characterized by fairly homogeneous conditions beneath the fog top (now at about 100 m) with some evidence of an unstable lapse in the lowest few metres. There was a slow warming and increase in wind speed which accelerated about an hour before the fog dispersed.

Case study C. This study was made at the end of a generally foggy period associated with a stationary ridge extending from the Azores to Scandinavia. During the period of this case study, advancing fronts had already started to push the ridge southeastwards, and freshening winds cleared the fog a few hours after the start of observations. The sequence of events was as shown below.

The sequence of events in phase 1a and b parallels to some degree the events of phases 1b and IIa of case study A. Wind, temperature, visibility and fog top height data during these phases are shown in Fig. 4.

The associations previously noted in A and B are again apparent. Phase 1c represents a commonly observed phenomenon (Saunders 1960) discussed in section 3(e) of II.
Phase | Period (GMT)  | Remarks                                                                 |
------|--------------|--------------------------------------------------------------------------|
Ia    | 1700–2000    | A period of fluctuating, shallow fog under clear skies.                 |
Ib    | 2000–2200    | Onset of period marked by an abrupt fall of temperature and return of thick fog, both spreading up from ground to 30–40 m by 2020h. Surface inversion lifts to top of fog. |
Ic    | 2200–0000    | Incursion of Sc sheet at beginning of period. Gradual thinning of the fog from the top downwards. |
IIa   | 0000–0430    | Increase of wind at all levels to about 2 m s\(^{-1}\) and final clearance of fog at beginning of period. |
IIb   | 0430–0800    | Cloud sheet begins to break up and finally clears by 0530h. Wind increases to 3–4 m s\(^{-1}\) at this time, but subsequently decreases to less than 1 m s\(^{-1}\) for a short period soon after sunrise. This was accompanied by a decrease in visibility to 1–2 km, but no return of fog. |

Figure 4. As Fig. 3.
Phase I Ib is of interest in demonstrating the effect of a light breeze in maintaining good visibility conditions on a radiation night. The wind lull soon after sunrise may well, if it had lasted another 10 minutes or so, have resulted in fog formation.

(b) Heat budget

The observations yield estimates of some terms in the heat budgets of atmospheric layers, and of the surface heat balance. The relevant equation (with energy terms expressed as the equivalent rate of temperature change) is

\[ H_T = H_R + H_E + H_L + H_A \]  

(1)

where \( H_T \) = observed local rate of temperature increase due to:

\( H_R \) = radiative flux divergence
\( H_E \) = eddy flux divergence of sensible heat
\( H_L \) = latent heat release by condensation
\( H_A \) = advection of sensible heat.

In practice, it was only possible to obtain reliable measurements over periods of not less than 20 min of \( H_T \) and \( H_R \), the balance being attributed to non-radiative heating, \( H_N(= H_E + H_L + H_A) \). The relative significance of \( H_E, H_L, H_A \) in particular circumstances can sometimes be inferred indirectly from other observations.

The heights of the radiometers define the layers of atmosphere for which \( H_T \) and \( H_E \) are estimated. These quantities are shown in Fig. 5(a) and are based on 30 min running means.

The overall tendency for radiative cooling to exceed observed cooling (\( H_N \) positive) is apparent. Features of particular interest are:

*Case study A.* From about 0800-0945h, the 2–9 m layer maintained a virtually constant temperature. Yet at 0800h (near the end of phase Ila) \( H_R \) was \(-4 \text{degC} \cdot \text{h}^{-1}\), implying that \( H_N \) was \(+4 \text{degC} \cdot \text{h}^{-1}\), but by the beginning of phase IIb, \( H_N \) and \( H_R \) had returned to zero. \( H_T \sim 0 \) implies \( H_L \) and \( H_A \) will be small, so that \( H_N \sim H_E \). \( H_E \) is attributed to the collection (convergence) of soil heat flux (convected upwards from the surface) beneath the fog top inversion. When this lifted between 0830 and 0845h (Fig. 1), it may also have lifted the zone of eddy flux convergence with it out of the 2–9 m layer. \( H_E \sim 4 \text{degC} \cdot \text{h}^{-1} \) corresponds to a flux convergence of about 10 W m\(^{-2}\) in this layer, which is about half the soil heat flux.

In the 9–37 m layer, the increase in radiative cooling in phase II reflects the presence of the fog top within the layer and this persists until the fog is dispersed, well after sunrise. In contrast, \( H_R \) becomes positive in the lower layer after sunrise due (presumably) to absorption of thermal radiation emitted by the ground warmed by solar insolation.

*Case study B.* \( H_N \) is generally positive during phases I–III, except for a short period just after the return of fog at 0220h, when \( H_N \) becomes negative. This was more apparent on a shorter time scale, where it is estimated that \( H_N \) approached \(-10 \text{degC} \cdot \text{h}^{-1}\) for a few minutes. In this case, the dominant contribution appears to be due to advection.

We note also that there was a small heating of \(0\text{-}5\text{-1} \text{degC} \cdot \text{h}^{-1}\) during phase IV. This could be produced by the absorption of soil heat flux of 20 W m\(^{-2}\) in the lowest 100 m, but does not explain why the fog in this layer was not dispersed – the amount of heat required being only a fraction of 20 W m\(^{-2}\).

*Case study C.* Large fluctuations of visibility and temperature during phase Ia made
Figure 5. (a) Observed heat inrates of specified layers: —— total heating rate \( (H_T) \); —— radiative heating rate \( (H_R) \); . . . non-radiative heating rate \( (H_N) \) for the case studies indicated on each diagram. (b) Higher resolution detail of \( H_R \) for period 19-23h during C for layers 2-9 m —— ; 9-17 m — — ; 17-37 m . . .
it impossible to separate advection from development. \( H_R \) and \( H_T \) both attained values of order \(-5\) degC h\(^{-1}\) for short periods. Of some interest is the behaviour of \( H_R \) in the three layers \(2-9\) m, \(9-17\) m, \(17-37\) m during phase 1b. The upward passage of the fog top through each successive layer is indicated by a trough in \( H_R \) in that layer (Fig. 5(b)). It seems likely that this event was largely advective.

(ii) **Surface.** The heat balance equation is:

\[
F_R + F_E + F_L + F_S = 0
\]

(2)

where \( F_R \) = net radiative transfer
\( F_E \) = eddy transfer of latent heat
\( F_L \) = eddy transfer of sensible heat
\( F_S \) = conduction of heat through soil surface.

\( F_R \) is estimated by a radiometer at \(2\) m (even in fog, flux divergence in the lowest \(2\) m is not likely to exceed \(3\) W m\(^{-2}\)). \( F_L \) is measured by a lysimeter. Unfortunately, in foggy conditions this instrument cannot distinguish between the deposition of fog (latent heat released in the atmosphere) and dew (latent heat released at the surface). The lysimeter observations are discussed in the section on water budget. Attempts to measure \( F_E \) in fog were unsuccessful.

\( F_S \) was estimated by linear extrapolation of the measured soil flux at \(4\) and \(8\) cm, and was found in all cases studied to be \(20-30\) W m\(^{-2}\). The relative magnitude of \( F_R \) and \( F_E \) appeared to form the main constraints in the surface heat balance regime: \(|F_R| > |F_S|\) corresponded to surface inversion conditions when there was thin or no fog; \(|F_R| < |F_S|\) occurred during deep fog conditions with the establishment of an unstable lapse rate beneath the fog top as the surface became a source of heat.

(c) **Water budget**

The budget for a layer of atmosphere integrated from the ground to a height \(z\) for a specified period of time is given by:

\[
\Delta V = (V_E)_z - (V_E)_0 + V_A - C \quad \text{(vapour)}
\]

\[
\Delta W = (W_E)_z - (W_E)_0 + (W_D)_z - (W_D)_0 + W_A + C \quad \text{(liquid)}
\]

(3)

(4)

where \(\Delta V\) = change in vapour content of layer in time \(t\)
\((V_E)_z,0\) = eddy flux of vapour at heights \(z\) and \(0\)
\(V_A\) = advection of vapour
\(C\) = condensation in atmosphere
\(\Delta W\) = change in liquid water content of layer in time \(t\)
\((W_E)_z,0\) = eddy flux of liquid water at heights \(z\) and \(0\)
\((W_D)_z,0\) = gravitational flux of liquid water at heights \(z\) and \(0\)
\(W_A\) = advection of fog liquid water content.

Now \((V_E)_0\) = dew deposition and \((W_E)_0 + (W_D)_0 = fog deposition. Therefore \(L = (V_E)_0 + (W_E)_0 + (W_D)_0\) = lysimeter measurement.

There are two basic regimes:

(i) **Radiation night; no fog:** \(\Delta V = (V_E)_z - L + V_A\). In practice, if advection can be neglected, and the integration carried up to a height where \((V_E)_z \ll (V_E)_0\), then

\[
L = -\Delta V
\]

(5)

(ii) **Radiation night; fog.** Neglecting advection, and integrating from the beginning of fog and to a height which is always above the fog top, we have \(\Delta V = -C - (V_E)_0\) and \(\Delta W = C - (W_E)_0 - (W_D)_0\) where \(\Delta W\) = liquid water content of fog. Therefore

\[
L = -\Delta V - \Delta W
\]

(6)
The terms in Eqs. (5) and (6) are measurable. $\Delta V$ can be obtained either by direct humidity observations, or in the case of an atmosphere that is saturated throughout (as was usually the case), by application of the Clausius–Clapeyron relationship to the observed change in temperature. $\Delta W$ was measured at intervals with a cascade impactor and impinger.

**Case study A.**

**TABLE 1. WATER BALANCE**

<table>
<thead>
<tr>
<th>Period (GMT)</th>
<th>$L$ (gm$^{-2}$)</th>
<th>$\Delta V$ (gm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0400–0630 (I)</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>0630–0730 (IIa)</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>0730–0830 (IIa)</td>
<td>25</td>
<td>small</td>
</tr>
<tr>
<td>0830–1000 (IIb)</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>75</td>
</tr>
</tbody>
</table>

**TABLE 2. LIQUID WATER CONTENT**

<table>
<thead>
<tr>
<th>Time (GMT)</th>
<th>l.w.c. (gm$^{-3}$)</th>
<th>C</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>0400</td>
<td>0.05</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>0610</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0714</td>
<td>0.12</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>1005</td>
<td>0.10</td>
<td>0.08</td>
<td></td>
</tr>
</tbody>
</table>

C = cascade impactor  I = impinger

Now $\Delta W \sim$ liquid water content times depth of fog $\sim 1$–$5$ gm$^{-2}$. The agreement between the overall totals of $L$ and $\Delta V$ is good, but over shorter periods of 1–2h the agreement is poor. The liquid water content of the fog accounts for only a few per cent of the total.

It is difficult to know how much significance can be ascribed to discrepancies between $L$ and $\Delta V$ over short periods. The period 0730–0830h is of particular interest as being virtually quasi-steady with little change in temperature or fog depth. The only way of satisfying the water budget in this case is to replenish the loss of fog water by gravitational settling or by turbulent transfer of water vapour downwards through the fog-top inversion where presumably condensation occurs. The marked wind shear through the fog top may have made this possible.

**Case study B.**

**TABLE 3. WATER BALANCE**

<table>
<thead>
<tr>
<th>Period (GMT)</th>
<th>$L$ (gm$^{-2}$)</th>
<th>$\Delta V$ (gm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200–2300</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>2300–0000</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>0000–0100</td>
<td>0</td>
<td>small</td>
</tr>
<tr>
<td>0100–0200</td>
<td>8</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>15</td>
</tr>
</tbody>
</table>

The lysimeter broke down at the end of this period.
TABLE 4. LIQUID WATER CONTENT

<table>
<thead>
<tr>
<th>Time (GMT)</th>
<th>C₂</th>
<th>C₂₈</th>
<th>I₁</th>
<th>I₉</th>
</tr>
</thead>
<tbody>
<tr>
<td>2258</td>
<td>0.06</td>
<td></td>
<td>0.14</td>
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</tr>
<tr>
<td>2335</td>
<td>0.07</td>
<td></td>
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<td>0.05</td>
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<tr>
<td>2345</td>
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</tr>
<tr>
<td>0310</td>
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</tr>
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<td>0333</td>
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<td>0734</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0747</td>
<td></td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0900</td>
<td></td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0918</td>
<td></td>
<td>0.15</td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>1032</td>
<td></td>
<td></td>
<td>0.17</td>
<td>0.18</td>
</tr>
</tbody>
</table>

C₃₂₈ = cascade impactor at heights of 3 and 28 m
I₁,₉ = impinger at heights of 1 and 9 m

There is no systematic variation of liquid water content with height or with time in the above tables apart from an indication that the wettest period is at about 0700h. However, the general level is similar to case study A and again only accounts for a small fraction of the total water deposition.

Case study C.

TABLE 5. WATER BALANCE

<table>
<thead>
<tr>
<th>Period (GMT)</th>
<th>L (g m⁻²)</th>
<th>ΔV (g m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1700-1800</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>1800-1900</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>1900-2000</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>2000-2100</td>
<td>22</td>
<td>55</td>
</tr>
<tr>
<td>2100-2200</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>2200-2300</td>
<td>7</td>
<td>small</td>
</tr>
<tr>
<td>2300-0000</td>
<td>7</td>
<td>-10</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>65</td>
</tr>
</tbody>
</table>

Similar remarks apply to this case as to cases A and B. The very large value of ΔV during 2000-2100h may be mainly advective in character.

(d) Turbulent diffusion

It had been intended that a study of the field of turbulent diffusion should have formed an essential part of the field project. Unfortunately, turbulent diffusion proved virtually impossible either to observe (from eddy flux measurements) or to infer (from profile measurements) in fog. The output from the hot wire probes is unreliable in low wind-speeds and is affected by fog moisture, while the established flux-profile relationships used so extensively in boundary layer studies break down in the highly stable conditions associated with radiation fog. Profiles become erratic as, to quote Webb (1970) "... with the severely weakened turbulence, other processes such as gravity waves and katabatic or other meso-scale drifts supervene".
One general feature was apparent. Once the fog top lifted off the ground, two regimes of turbulent diffusion were created:

(i) Below the radiation inversion, a convective regime becomes established in which soil heat flux is transferred upwards via the super-adiabatic lapse rate which establishes itself above the radiatively shielded ground.

(ii) In and above these inversions, it seems likely that height above ground may cease to be a relevant scaling length; the fog top and its associated inversion may now contain effective reference surfaces for radiative and turbulent heat transport.

Case study A. It is apparent from Fig. 1 that the wind profiles were generally irregular in shape. Some attempts were made to estimate exchange coefficients from the few profiles which were approximately log-linear in shape which yielded values of order $5 \times 10^{-3} \text{m}^2\text{s}^{-1}$ near the ground increasing to $0.1 \text{m}^2\text{s}^{-1}$ near the fog top (corresponding to values of $u_*$ of 1–3 cm s$^{-1}$). However, Richardson numbers (Fig. 1) were in general large (except in the lowest 5 m in phase II) and turbulence likely to be weak and intermittent.

The convective regime under the fog top is of interest. If the large value of $H_N$ inferred for the 2–9 m layer during phase II (Fig. 5(a)) is attributed to eddy heat flux convergence, then application of the Fickian diffusion equation suggests a value of order $10^{-3} \text{m}^2\text{s}^{-1}$ for the exchange coefficient. The later decrease in $H_N$ may have been associated with the upward movement of the radiation inversion possibly carrying the main zone of eddy flux convergence with it and out of the 2–9 m layer.

These considerations gave a rough idea of one regime of exchange coefficients to be used in the numerical model.

Case study B. This was the first study in which turbulence probes were used. Above the fog, values of vertical velocity variance ($\sigma_w$) were generally $0.05–0.1 \text{m} \text{s}^{-1}$ (except during the wave disturbance during phase IIb when $\sigma_w$ reached $0.3 \text{m} \text{s}^{-1}$). Momentum fluxes were erratic, with values varying between $-0.05$ and $+0.1 \text{m}^2\text{s}^{-2}$ at higher levels, but decreasing to $\pm 10^{-2} \text{m}^2\text{s}^{-2}$ at lower levels. This implies exchange coefficients somewhat higher than in A, but still of order $0.1–1 \text{m}^2\text{s}^{-1}$. Eddy heat fluxes were also erratic – of order $5 \text{J m}^{-2}\text{s}^{-1}$, increasing spasmodically to $\pm 30 \text{J m}^{-2}\text{s}^{-1}$.

While it is considered that observed flux differences cannot be used to estimate $H_E$ (Eq. (1)) with any confidence, there does appear to be some tendency for $H_E$ to change from positive to negative with increasing height – suggesting an overall convergence of eddy heat flux above the fog.

Case study C. On this occasion, turbulence probes were only operative at the 8 and 46 m levels – the upper probe being above the fog top except during phase Ic. Values of $\sigma_w$ were again of order $0.05–0.1 \text{m} \text{s}^{-1}$, and of $\sigma_* 0.2–0.5 \text{m} \text{s}^{-1}$. Momentum flux in shear flow is generally found to be about $0.4 \sigma_* \sigma_w$ (Townsend 1956). This quantity is plotted against observed $u'w'$ in Fig. 6. It is seen that $0.4 \sigma_* \sigma_w$ is up to an order of magnitude higher than $u'w'$ for low values of the latter at both probe levels. This result is not inconsistent with the presence of gravity wave disturbance, particularly when the probe is in the vicinity of the fog top. This is particularly evident in the temperature trace which was observed to fluctuate over a range of up to 4 degC in this situation.

Gravity waves ‘always’ appear to be present in stable atmospheres. They transfer momentum, but not heat (in the absence of turbulence) although quite large values of $w^2\varphi$ may be observed. This so-called ‘inactive’ component of observed eddy fluxes has always been a problem in boundary layer studies, particularly in stable conditions.

(e) Fog structure

Some size distributions observed during A are displayed in Fig. 7. The development
of a secondary peak in droplet radii between 5–10 µm is a feature already noted in earlier measurements by Garland (1971). Both the liquid water concentration and visibility can be explained in terms of the observed droplet population, although the large increase in liquid water content associated with the development of the secondary peak has little effect on visibility. The number of cloud condensation nuclei (30–100 cm⁻³) observed at 0.8% supersaturation was of the same order as the total number of droplets in the large droplet peak.

There does not appear to be any consistent correlation between visibility and other parameters. During the early stages of fog development there is a qualitative correlation between wind speed and visibility (Fig. 2) which vanishes when the fog top lifts well above the level of visibility observations.

The vertical gradient of visibility is very variable. During the early stages of a fog there is usually a rapid decrease of opacity with height (Figs. 1(c), 3(c) and 4(c)), but this may reverse later, producing a maximum at some level between the ground and fog top—the latter often becoming very sharp.

The results of chemical sampling of atmospheric aerosol during A are shown in Fig. 8. The sampling was carried out 800 m from the main investigation site and was mostly out of fog. The ion concentrations showed a more or less steady decrease during the period of the fog, particularly the nitrate ion. This was followed by an abrupt increase in all concentrations following the dispersal of the fog. There was also a temporary increase at
07 to 08h just after the transition to phase II. The large chloride concentration so far inland suggests an industrial source. The anion–cation balance shows roughly 30% excess anions throughout (except for 06–07h) indicating the presence of moderate amounts of some cation other than ammonium. The sulphur dioxide concentration dropped prior to fog formation, fluctuated about an ill-defined minimum during the fog period, and increased again after fog dispersal. These changes probably reflect changes in vertical mixing which appears to be a minimum during the fog period, although it may also reflect the scavenging action of fog droplet deposition to some degree.

4. Discussion

(a) The role of advection

Despite the difficulty in separating objectively the contributions of advection and development to changes observed in fog structure at one site, some general inferences can be drawn since it is a common observation that radiation fog forms more or less simultaneously over an area of perhaps a few hundred km², implying that the vertical structure of the atmosphere is the main factor controlling fog development. On the other hand, it is also a common observation that there are always considerable spatial fluctuations of fog structure for which variations in the nature and slope of the local terrain are at least partly responsible. These generate mesoscale drifts which may control fluctuations in observed parameters at a fixed point on time scales up to a few minutes. Thus it seems that the shorter the period over which a change occurs, the more likely will the change be due to advection rather than to development.
In interpreting the observations reported here, a marked change (e.g. in visibility or temperature) is attributed to advection if it takes less than 5–10 minutes; and to development if it takes more than this, although clearly there is no well-defined criterion.

The sites used for studies of fog and dew formation reported here and elsewhere were all open, grassed areas, the boundaries of which (buildings, trees, fences, hedges) were in general 200–500 m from the site of observation – at Cardington, the sheds (60 m high, 250 m long) were 500 m N of the site – but it is not possible to quantify the effects this departure from a ‘perfect’ site will have on the observations.

(b) Interpretation of observations

It is convenient (and consistent with paper II) to discuss the observations in terms of the one-dimensional equations for heat, water vapour and liquid water written in simplified form

\[
H_T = H_R + \partial H/\partial z + (L/c_p)C
\]

(7)

\[
\partial q/\partial t = \partial Q/\partial z - C
\]

(8)

\[
\partial w/\partial t = \partial W/\partial z + \partial G/\partial z + C
\]

(9)

\[C = \text{condensation rate} = -q_s(LM/RT^2)H_T\]

(10)

from Clausius–Clapeyron relationship, where \(H_T\) and \(H_R\) are as defined in Eq. (1), and

\[
\begin{align*}
q &= \text{water vapour} \\
q_s &= \text{saturation} \\
w &= \text{liquid water} \\
H &= \text{eddy heat} \\
Q &= \text{eddy water vapour} \\
W &= \text{eddy liquid water} \\
G &= \text{gravitational liquid water}
\end{align*}
\]

The principal features of the observations apparently related to the development (rather than advection) of fog which require explanation are:

(i) Lulls in wind were accompanied by maxima in cooling, and major lulls coincided with periods of significant fog development. Conversely, increasing wind (to > 2 m s\(^{-1}\)) appeared to be associated in this field study with fog dispersal. A ‘lull’ in this context means a decrease from a mean wind speed of 1–2 m s\(^{-1}\) to 0.5 m s\(^{-1}\) or less. Standard airfield anemometers have a stopping speed of about 2 m s\(^{-1}\) and such an instrument at Cardington recorded a flat calm throughout most of our field runs. This feature is consistent with the inference from observations of dew deposition (Monteith 1957) that a drop in wind below a certain level may result in a virtual cessation of turbulence. The mechanism for dew deposition thus ceases, so that a saturated atmosphere which continues to cool radiatively is ultimately forced to condense excess water \textit{in situ} in the form of fog.

The mechanism by which mixing of damp air masses of different temperatures will produce fog does not appear to be significant, possibly because the temperature differences mixed by eddies generated by light winds on a radiation night is too small to produce appreciable supersaturation. This is roughly proportional to the square of the initial temperature difference which has to be several degrees to produce a liquid water content characteristic of that found in fogs.

(ii) The observed radiative cooling \((H_R)\) was in general greater than observed total cooling \((H_T)\) under clear night skies. This observation has been made both in fog and in the absence of fog (Rider and Robinson 1957).
Interpreting (i) and (ii) in terms of Eq. (7), it would appear that radiative cooling is offset by convergence of eddy heat flux during 'gusts' (due to increased mixing eroding the radiation inversion from above) and by release of latent heat during 'lulls' (due to fog formation). This may account for (ii) but not necessarily for (i). However, observations (particularly case A) and theory (ii) show that the appearance of fog greatly increases $H_R$. During a 'lull' period $\partial H/\partial z$ is probably small, so that, using Eq. (10), Eq. (7) becomes

$$H_R = H_T(1 + (q_L M/c_p R T^2)) \sim 2H_T$$

for $T \sim 275K$; i.e. radiative cooling is about twice the observed cooling.

Thus departures of this ratio from this value in a saturated, cooling atmosphere might in principle be used to indicate the significance in any particular situation of the eddy flux convergence term – e.g. the behaviour of the heat budget terms in the 2–9 m layer during phase IIa of A suggests a transition from a strong divergence to a strong convergence of eddy heat flux.

(iii) The water condensed by cooling appears to have been mainly deposited on the ground. The water content of the fog was a small fraction of the total water condensed out over a few hours. This feature highlights a significant mechanism hitherto neglected in fog studies – the gravitational settling of fog droplets. In II, it is shown that the omission of this effect results in liquid water concentrations of order 1–2 g m$^{-3}$. This value is characteristic of growing cumulus clouds, but is an order of magnitude greater than is characteristic of fogs. Introduction into the fog model (II) of an empirical term for gravitational settling based on these results reduced liquid water contents to 0·1–0·3 g m$^{-3}$. Nevertheless, there is some indication that the lysimeter sometimes records a rate of settling 2–3 times that computed from the observed drop size distribution. Now even in very light winds, fog droplets near the ground will have a nearly horizontal trajectory, and will thus be scavenged from the air by grass blades. The longer and coarser the grass the more effective this scavenging might be, but this could only result in a drying out of the fog in the lowest few centimetres since the supply of moisture is controlled from above. Local variations in the grass surface could however produce large local variations in scavenging rate. The grass on the lysimeter pan was not obviously different from its surroundings, but there were marked variations in grass texture on scales of a metre or so over the site in general.

Gravitational settling may also be relevant to Stewart's (1955) observation that saturated conditions persisted for up to 3 hours before fog actually formed. However, Eq. (9) shows that condensation must be occurring in a saturated cooling atmosphere, so that for $\partial w/\partial t$ to be zero, the other terms must be negative. Since radiation fog tends to develop from the surface upwards, it is likely that $\partial G/\partial z$ is negative, but it is not obvious which sign $\partial W/\partial z$ will take. It is also possible that on the occasions referred to by Stewart, there may have been a very shallow ground mist of horizontal visibility not less than several hundred metres which may well be scarcely discernible at night.

(iv) The development of a surface radiation inversion continued for some time after the appearance of a shallow fog, but at some stage, this inversion lifted off the ground with the fog top, while a new, fairly homogeneous and steady-state regime was established beneath the fog top, with a definite super-adiabatic lapse rate in the lowest few metres.

The surface is radiatively shielded by a developing fog. At some stage, the net loss of heat from the surface due to radiation will fall below the supply of heat from the soil. The net flux of heat at the surface then becomes directed upwards, its temperature rises and the radiation inversion lifts off the ground. This was particularly well marked in A; the inversion lifted when the net radiative flux at 2 m had decreased to about 30 W m$^{-2}$ – not significantly different from the soil heat flux.
The fog top then becomes the effective 'surface' from a radiative and possibly also from a boundary layer turbulence view-point. The super-adiabatic lapse rate which then becomes established in the lowest few metres is probably associated with the upward (convective) transfer of soil heat flux. A heat input of 20 W m$^{-2}$ is enough to evaporate a 50 m depth of fog of liquid water content 0·2 g m$^{-3}$ in about 20 minutes. In practical terms, the prevailing soil temperature must therefore have a significant influence on the visibilities that are likely to occur near the ground in a persistent fog situation. This has already been observed by Saunders (1960).

(v) Quasi-periodic oscillations in various parameters. These are discussed separately in Roach (1976).

(c) The role of cloud microphysics

The interpretation of the meteorological constraints so far presented have only taken account of the bulk parameters of the fog structure in respect of liquid water content and gravitational settling. It is clear even from these that microphysics plays more than a passive role in the development of radiation fog in the following respects.

(i) Interdependence of radiative cooling and liquid water content. General considerations (see II) suggest that radiative cooling is insensitive to size distribution; but

(ii) interdependence of gravitational settling and size distribution occurs because gravitational settling greatly modifies liquid water content, therefore size distribution has an important indirect feedback effect on radiation.

(iii) The cloud condensation nucleus concentration (CCNC). This feeds back to (i) and (ii) above and is probably the main factor controlling the relationship between liquid water content and visibility.

If the CCNC increased by an order of magnitude, then for a given liquid water content, $N r^3 \sim$ constant, so that mean droplet radius and visibility would be reduced by a factor of about 2. However, fallout would be reduced by a factor of 4 since fall speed $\propto r^2$ so that liquid water content would increase, thus exaggerating the decrease in visibility. These considerations may be related to the formation of the well-known 'pea-souper' common before World War II, which are now rare. One result of the Clean Air Act has been to reduce the CCNC in the lower atmosphere.

(d) Practical implications

(i) Forecasting. These results suggest that, given clear skies and a saturated atmosphere, the development of radiation fog is imminent if the mean wind drops below about 1 m s$^{-1}$. Unfortunately, advection of fog formed elsewhere will not necessarily conform to this condition. For instance, about an hour after the dispersal by solar insolation of fog A, a deep bank of fog moved in accompanied by a wind increase to 3 m s$^{-1}$. This may have been the edge of the large area of persistent fog covering the Midlands moving south as a meso cold front lifting the sun-warmed air ahead of it.

Once deep, persistent fog is established, there is some evidence (e.g. Saunders 1960) that the soil temperature in relation to the air temperature influences the visibility near the ground.

(ii) Modification. If the mean wind speed on a radiation night could be kept artificially above the threshold of 1 m s$^{-1}$ - e.g. by jet engines blowing down a runway - the time of fog formation might conceivably be delayed for a time, but the advection of fog formed outside the ventilated area would probably limit the usefulness of this device.

An aircraft requires a volume of order $10^5$ m$^3$ to land in and radiative heat loss from
this volume is of order 100 MW, so that any method which disperses fairly shallow fog has radiative cooling as well as advection to contend with.

In the case of a deep, persistent fog in which the lowest 50–100 m are radiatively shielded from the sky, surface heating of 1–10 MW over an area of order $10^5 \text{m}^2$ might be sufficient to improve visibility below 100 m altitude, providing winds were below about 1 m s$^{-1}$.

These considerations, however, add little to a recent survey of methods of fog dispersal or modifications by Silverman and Weinstein (1973).

5. Conclusions

The interpretation of the field study observations, supported as they are by the results of the numerical fog model, lead, in our view, to a significant clarification of the principal constraints in the development of radiation fog. Radiative cooling encourages fog formation, while turbulence inhibits it. Gravitational settling of fog droplets and soil heat flux emerge as important factors. The role of microphysics is less clear but the indications are that it is not passive, especially in determining the actual visibility conditions in fog.

Acknowledgments

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References


**APPENDIX**

The data on this project were obtained using established instrumentation as far as possible. This is listed below with comments as necessary. The equipment was used on all case studies unless indicated, e.g. (A) after a parameter indicates it was made during case study A only.

(a) *Cloud Physics Branch, Meteorological Office*

(i) Continuous records of temperature and dewpoint at 2 m and surface temperature.

(ii) Fog top detector and thermistor (for temperature profile) attached to the cable of a tethered balloon. The detector consisted of a hot wire element which evaporated fog droplets in an air-stream drawn over it by a pump. The resulting change of resistance in the detector element is converted to frequency change and transmitted to a ground receiver using standard electronic techniques.

(iii) Net radiative fluxes at heights of 2, 9, 17(B, C) and 37 m using Funk radiometers. The main practical difficulty in operating these radiometers in fog is in keeping the protective polythene domes free of moisture. The ventilation and heating rings provided for this purpose by the manufacturer work for dew but not for fog. A more powerful (and successful) ventilation system blowing 1–2 litre/minute of dried air was used, but unavoidably blocked part of the radiometer field of view. Corrections were made for this, but precise radiometry of the type employed by Funk (1962) was impossible. However, the fairly wide vertical spacing of the radiometers coupled with the very large changes in net flux with height from base to top of fog (of order 50 W m\(^{-2}\)) enabled useful estimates of radiative heating rate to about ±1 deg Ch\(^{-1}\) to be made in an environment in which cooling rates up to 5 deg Ch\(^{-1}\) were observed.

(b) *Meteorological Office Research Unit, Cardington*

(i) Wind speed (2 minutes run of wind) measurements at 2, 4, 8, 16 m with wind direction at 16 m using Porton anemometers. Addition of levels 0.5 and 1 m for B and C.

(ii) Temperature measurements at 4, 8, 16 m at 2 minute intervals. Addition of levels 0.2, 0.5, 1 m for B and C.

(iii) Soil flux measurements.

(iv) Surface moisture deposition using a lysimeter.

(v) Balthum ascents at 6-hourly intervals giving temperature, dewpoint and wind speed profiles to 1 km.

(vi) Four turbulence probes (Readings and Butler 1972) attached to the cable of a tethered balloon at heights of 8, 46, 93, 183 m. These probes unfortunately did not operate satisfactorily in fog, but provided some measurement of the turbulence regime above fog top.
(i) Visibility was measured at 1 m with a transmissometer. This consisted of a collimated receiver and projector separated by about 30 m. Visibility at 5 m (A), 9 m (B and C), 27 m (B) was measured with an integrating nephelometer. This consisted of a photomultiplier which detected the amount of light scattered in a small volume of atmosphere illuminated by a flash lamp (Garland and Rae 1970).

(ii) Drop-size distributions down to about 1 \( \mu m \) radius were obtained by impacting droplets on thin plastic foils coated with gelatin (Garland 1971).

(iii) Liquid water content was measured with an impinger – a simple glass collection device operated in conjunction with a small wind tunnel.

(iv) Cloud condensation nucleus concentration (A) was measured by a thermal diffusion cloud chamber developed at Harwell, and maintained at a supersaturation of up to 1% in an airflow of 10 cm\(^3\) s\(^{-1}\). Droplets formed on cloud nuclei in the chamber scatter light from a narrow collimated beam to a photomultiplier, and the resulting pulses are counted electronically.

(v) Chemical sampling of atmospheric aerosol was obtained by drawing air at about 0.3 m\(^3\) min\(^{-1}\) (but 0.01 m\(^3\) min\(^{-1}\) for SO\(_2\) sampling) through an area of filter paper tape, which is moved forward once per hour. Details of the samplers and analytical techniques are described in Eggleton and Atkins (1972).