A numerical study of radiation fog with an explicit formulation of the microphysics

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SUMMARY

A model of radiation fog is described containing an explicit formulation of the microphysics of the condensation process. The coupling between the radiative and microphysical processes within the model means that apart from the specification of the turbulence and CCN spectrum it is deterministic.

Results are presented which indicated that:

(i) The drop-size distribution is sensitive to the CCN concentration but not to the presence of large CCN.
(ii) Radiative loss from the drops can have a significant effect upon their growth.
(iii) The drop-size distribution is very sensitive to reductions in the condensation coefficient to a value below 0.033.

Differences between observed and model drop-size distributions are attributed to an underestimate in the model of the level of mixing within a mature fog.

1. INTRODUCTION

Brown and Roach (1976) – hereafter referred to as I – have described a model of radiation fog which gave results broadly in agreement with the data obtained from a field study. It was concluded that the gross features of the fog and the physical processes (apart from turbulence) that are relevant to its formation and dissipation were adequately modelled. However, the model did not contain an explicit description of the microphysics of the condensation process, necessitating parametrization of the radiative effects and the gravitational settling of the fog droplets in terms of liquid water content. In fact these properties are functions of the drop-size distribution which in turn depends upon such factors as the initial spectrum of cloud condensation nuclei. For a given liquid water content, the visibility is also a function of the drop-size distribution.

At the time of publication of I field studies had yielded few microphysical data. Since then a Particle Measuring Systems Inc. ASSP-100 drop-sizing device has been used to produce spectra in real time. After a period of development it has been found to yield accurate drop sizes although the measured concentrations are less certain (Ryder 1976). Detailed information on the behaviour of the drop-size distribution in fog has been obtained as a function of height and time. It seemed desirable, therefore, to extend the model to include an explicit description of the microphysics. This paper describes the extended model and the initial results obtained from its use.

By concentrating on the microphysics we have to some extent turned aside from the problem of defining turbulence in a mature fog, left unresolved in the original model. However, because turbulent mixing may be a major factor in the development of the drop-size distribution the present model may be seen as a step in estimating the level of mixing in a mature fog.

2. THEORY

(a) The governing equations of the model

The basic model equations are essentially the one-dimensional continuity equations for
heat, water vapour and liquid water as used in I with additional equations for the time rate of change of supersaturation, drop radius and concentration.

$$\frac{\partial T}{\partial t} = -\frac{1}{\rho_s c_p} \frac{\partial F_N}{\partial z} + \frac{\partial}{\partial z} \left( \frac{K}{c_p} \frac{\partial \theta}{\partial z} \right) + \frac{LC}{c_p} \quad (1)$$

$$\frac{\partial \sigma}{\partial t} = \frac{\partial q}{\partial t} - \frac{LM}{R_g T^2} \frac{\partial T}{\partial t} \quad (2)$$

$$\frac{\partial r_{ij}}{\partial t} = \frac{\sigma}{r_{ij}} \left( a_1 + \frac{a_3 m_j}{r_{ij}^3} - a_3 Q_i R \right) (A_1 + f_p A_2)^{-1} \quad (3)$$

$$\frac{\partial N_{ij}}{\partial t} = \gamma r_{ij} \frac{\partial N_{ij}}{\partial z} + \frac{\partial}{\partial z} \left( K \frac{\partial N_{ij}}{\partial z} \right) - \frac{N_{ij}}{\Delta r_i} \frac{\partial r_{ij}}{\partial t}$$

$$+ \frac{N_{i-1,j}}{\Delta r_{i-1}} \frac{\partial r_{i-1,j}}{\partial t} \quad \text{when} \quad \frac{\partial r_{i-1,j}}{\partial t} > 0$$

$$+ \frac{N_{i+1,j}}{\Delta r_{i+1}} \frac{\partial r_{i+1,j}}{\partial t} \quad \text{when} \quad \frac{\partial r_{i+1,j}}{\partial t} < 0$$

or

$$\frac{\partial w}{\partial t} = \frac{4 \pi \rho_a}{3 \rho_a} \frac{\partial}{\partial t} \sum_i \sum_j N_{ij} r_{ij}^3$$

$$\frac{\partial G}{\partial z} = \frac{4 \pi \rho_w}{3 \rho_a} \sum_i \sum_j \frac{\partial N_{ij}}{\partial z} r_{ij}^3$$

$$C = \frac{\partial w}{\partial t} - \frac{\partial G}{\partial z} - \frac{\partial}{\partial z} \left( K \frac{\partial w}{\partial z} \right)$$

$$q = (1 + \sigma) q_s \quad (8)$$

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial q}{\partial z} \right) - C \quad (9)$$

$$\frac{\partial n_j}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial n_j}{\partial z} \right) - \Delta n_j \quad (10)$$

with $T$ dry bulb temperature of air

$\theta$ potential temperature of air

$\rho_a$ density of air

$\rho_i$ density of water

$c_p$ specific heat of air at constant pressure

$F_N$ net radiative flux

$z$ height coordinate with origin at the earth's surface

$K$ exchange coefficient for heat, water vapour and liquid water (assumed equal).

$L$ latent heat of vaporization

$C$ rate of condensation per unit mass of air

$\sigma$ supersaturation

$q$ humidity mixing ratio

$q_s$ saturation humidity mixing ratio

$M$ molecular weight of water vapour

$R_g$ universal gas constant

$r_{ij}$ droplet radius at the centre of the $i$th bin with nucleus mass $m_j$

$Q_i$ droplet absorption efficiency factor averaged over wavelength

$R$ net radiation per unit area of drop for unit $Q_i$

$N_{ij}$ concentration of drops with nucleus mass $m_j$ in the $i$th bin
\( \gamma = \nu_T/r^2 \) where \( \nu_T \) is the terminal velocity defined by Stokes Law

\( \Delta r_j \) width of a radius bin

\( w \) liquid water mixing ratio

\( G \) flux of liquid water due to droplet settling under gravity

\( n_j \) concentration of nuclei with mass \( m_j \) (i.e. equilibrium radius \(< 0.3 \mu m\) at ambient relative humidity) \( \Delta n_j = \) concentration of nuclei growing into droplet bins per time step.

The terms on the right-hand side of Eq. (1) represent the change of temperature due to radiative cooling, divergence of the turbulent heat flux and latent heat release. In Eq. (2) the supersaturation changes in response to removal of water vapour and change of temperature. Besides the usual supersaturation, curvature and solute terms Eq. (3) contains an additional term derived by Roach (1976) to allow for the net radiative loss from the droplet. The droplet concentration (Eq. (4)) changes due to the divergences of the gravitational settling flux and the flux due to turbulent diffusion and also by condensational growth or evaporation as prescribed by Eq. (3). The method of solution of Eq. (3) and (4) is described in section (b).

In this paper a cloud condensation nucleus is so designated if it has an equilibrium radius \( \leq 0.3 \mu m \) at the ambient supersaturation. According to Eq. (10) nuclei are diffused but their gravitational settling is ignored. They play no part in the model thermodynamics or radiative processes but merely act as a source of droplets. The growth of the nuclei is not calculated explicitly, they are adjusted to their equilibrium radius at the ambient supersaturation at each radiation time-step. Those with an equilibrium radius \( \geq 0.3 \mu m \) are reclassified as drops and placed in the appropriate radius bin. Here they grow by condensation, release latent heat, settle under gravity and are subject to turbulent diffusion.

The coefficients in Eq. (3) are:

\[
a_1 = \frac{2SM}{\rho g R_g T}
\]

\[
a_2 = 6.05 \times 10^{-5} m^3 kg^{-1}
\]

\[
a_3 = \frac{1}{k T}\left( \frac{LM}{R_g T} - 1 \right)
\]

\[
R = \frac{1}{2}(F^\uparrow + F^\downarrow) - s T^4
\]

\[
Q_i = 1.18\{1 - \exp(-0.28r)\}
\]

\[
A_1 = \frac{L \rho_i}{k T}\left( \frac{LM}{R_g T} - 1 \right)
\]

\[
A_2 = \frac{\rho g R_g T}{DM \varepsilon_c(T)}
\]

\[
f_\beta = 1 + l_i/r_{ij}
\]

\[
l_\beta = \left( \frac{2 \pi M}{R_g T} \right)^{1\over 3} {D \over \beta}
\]

with

\( S \) surface tension of pure water

\( k \) thermal conductivity of air

\( F^\uparrow, F^\downarrow \) upward and downward longwave fluxes at height \( Z \)

\( s \) Stefan–Boltzmann constant

\( D \) diffusivity of water vapour in air

\( e_c(T) \) saturation vapour pressure at temperature \( T \)

\( \beta \) condensation coefficient
The nuclei are assumed to be ammonium sulphate.

The value of $a_2$ is based on a linear fit by Garland (1969) to the values of vapour pressure over ammonium sulphate solution given in the International Critical Tables. This avoids the uncertainty over van't Hoff's factor encountered when a theoretical expression for the vapour pressure is used. The expression for $R$ has been derived by Roach (1976) who also gives the analytic fit to $Q_e$. The factor $f_r$ has been incorporated into the droplet growth equation following Fukuta and Walter (1970) to allow for temperature and vapour density discontinuities within one molecular mean free path of the droplet surface. The condensation coefficient is taken to be 0.033 unless stated otherwise.

The temperature distribution within the soil is assumed to be given by

$$\frac{\partial T_j}{\partial t} = K_s \left( \frac{\partial^2 T_j}{\partial z^2} \right)$$

where $T_j$ is the soil temperature and $K_s$ is an exchange coefficient taking a value of $3.7 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$, which is an appropriate value for sandy-clay soil with a 15% water content. This value has been calculated using a soil density of $1.78 \times 10^3 \text{ kg m}^{-3}$, a thermal conductivity of $0.92 \text{ W m}^{-1} \text{ K}^{-1}$ and a thermal capacity of $1380 \text{ J kg}^{-1} \text{ K}^{-1}$. Equations (1)–(10) are integrated numerically using forward time differences with a one-second time step except for the radiation integration which uses a one-minute time step. The model grid extends from 1 metre below the soil surface to 200 m above using 26 grid points. The grid spacing is logarithmic but a transformation to a linear grid is used for the integration of the turbulent flux components of Eqs. (1)–(10) and for the evaluation of gradients.

(b) Solution of the droplet growth equation

It is not practical to integrate Eq. (3) directly because each drop has a unique supersaturation history and to follow the growth of each would require a prohibitive amount of computer storage. To overcome this problem Eq. (4) is introduced to predict the concentration of drops within radius bins of fixed width. The use of a similar technique has been successfully demonstrated by Kovetz and Olund (1969). Equation (4) is based on the assumption that over a time step $\tau$ a fraction $\Delta N_{ij} = \frac{N_{i+1,j} \partial r_{ij}}{\Delta r_i} \mid_0^\tau$ of the drops in bin $i$ grow into bin $(i+1)$. The radius range 0.3–20 $\mu$m is covered by 55 bins. Up to 4 $\mu$m the radius varies by 12% across a bin whilst above this a constant 0.5 $\mu$m width is used.

A disadvantage of the bin technique, when used to solve the equation for the growth of drops by condensation, is that it is subject to numerical spreading, because for an activated drop the solution is positive for all larger radii. If at time step 1 a fraction of the activated drops grow from bin $i$ to bin $(i+1)$, then at time step 2 a fraction of these will grow to bin $(i+2)$, even though Eq. (3) predicts that the change in drop radius over two time steps will be much less than $\Delta r_{i+1}$. This appears not to have been a problem to Kovetz and Olund because they modelled a situation in which the growth of the drops by coalescence was important on a timescale of fifteen minutes. This would mask the appearance of larger drops by numerical spreading. Coalescence is not considered within this study since it is only likely to occur in a deep, mature fog.

The spreading has been reduced to an acceptable level by various techniques, the most important being the use in Eq. (4) of the concentration at the boundary between two bins. The rationale for this is that for activated drops the growth over a time step is much less than the bin width, so that only drops adjacent to the bin edge grow into the next bin. Also drops are not allowed to grow into bin $(i+1)$ until the slope of the distribution between bin $(i-1)$ and bin $i$ predicts that drops are present at the boundary between bin $i$ and bin $(i+1)$.

The accuracy of the final version of the bin technique has been examined by applying it
to the solution of the simplified droplet growth equation \( \frac{dr}{dt} = A/r \). Initially drops of only one size were considered. Since turbulent diffusion was excluded from these tests, the exact solution as the droplets grow remains a monodisperse size distribution which is shown by a vertical bar in Fig. 1. After 30 minutes integration the bin technique produced a drop-size distribution with a half width of 1.5 \( \mu m \) as can be seen from Fig. 1. The mean of the distribution is within 3% of the exact solution. The loss of drops at 30 minutes is caused by gravitational settling. In a second test the initial drop-size distribution had a mean radius of 6 \( \mu m \) with a dispersion (ratio of standard deviation to mean radius) of 15%. The analytic solution of the simplified growth equation with an initially disperse drop-size distribution has been given by Kovetz (1969). Droplet settling was excluded from this integration in order to determine how well the bin technique conserved liquid water. After 45 minutes integration the mean radius of the drop-size distribution produced by the bin technique was within 0.7% of the exact solution and the liquid water contents agreed to within 4%. Thus, although the scheme does not explicitly conserve liquid water, in practice it is almost conserved. The bin technique predicted the narrowing with time of the drop-size distribution but produced a dispersion of 5.5% after 45 minutes compared to the exact dispersion of 2.4%. The large relative error in the dispersion arises from the fact that the bin technique cannot predict dispersions below about 5%. This was demonstrated in the first test where a similar dispersion was obtained despite the fact that the true dispersion was zero. When the full model equation set is used the resultant drop-size distributions have dispersions of typically 40%. The tests show that such large dispersions are not numerically induced. To smooth out spurious detail the model spectra are presented using a class width of 2 \( \mu m \).

(c) Solution of the radiative component of Equation (1)

The formulation of the equation for the radiative heating rate and the evaluation of the transmissivity due to water vapour and carbon dioxide is exactly as described in I. The transmissivity due to the droplets is of the form

\[
\tau_d(z,z') = \exp\{-\phi(z,z')\}
\]  

(12)
where
\[ \phi(z, z') = 1.66 \int_z^{z'} \int_0^\infty N(r, z'') r^2 Q_d(r) dr dz'' . \]

\( \tau_d(z, z') \) is the slab transmissivity due to the drops between \( z \) and \( z' \) and \( Q_d(r) \) is the efficiency factor for absorption of droplets of radius \( r \). Using the data of Herman (1962) the mean efficiency factor has been calculated inside and outside the 8–13 \( \mu \)m window following Roach (1976). Up to 11 \( \mu \)m radius the results can be fitted by the expression:
\[ Q_d(r) = Q_o \{1 - \exp(-\alpha r)\} . \]

where
\[ Q_o = 1.15 \quad \alpha = 0.326 \mu m^{-1} \text{ outside 8–13 \( \mu \)m window} \]
\[ Q_o = 0.945 \quad \alpha = 0.229 \mu m^{-1} \text{ inside 8–13 \( \mu \)m window} \]

Above 11 \( \mu \)m radius \( Q_d(r) \) is taken to be constant at 1.11 outside the window and 0.86 inside. The values of \( Q_d(r) \) from Herman are for pure water and may not be appropriate for the unactivated drops but they should only make a small contribution to the transmissivity compared to the activated drops in the mature fog.

The effect of scattering by droplets has been omitted since it has a small effect on the cooling rate. For example Stephens (1978), using a detailed multiple scattering model, obtained a maximum error of 4\% in the cooling rate at cloudtop when scattering was omitted. Roach and Slingo (1979), using a high resolution radiation scheme designed to calculate cooling rates in a cloudy atmosphere, found a reduction of 9\% in the cloud top cooling rate when scattering was not accounted for. However, since this reduction was brought about by a redistribution of the radiative cooling deeper into the cloud, the effect on droplet growth is likely to be less than 9\%.

In the original model the droplets contributed radiatively only once the air was saturated. By assuming \( Q_d(r) = E_r \), where \( E \) is a constant taking the value 0.12 \( \mu m^{-1} \) inside the 8–13 \( \mu \)m window and 0.18 \( \mu m^{-1} \) outside, it was possible to express the droplet transmissivity in terms of liquid water path, the relationship being independent of the drop-size distribution. With microphysics calculated explicitly it is possible to take some account of the radiative effects of the swelling nuclei before saturation is reached and also to use a more accurate expression for \( Q_d(r) \). The droplet spectrum used in Eq. (13) is predicted by the model so that there is direct coupling between the microphysics and radiation.

(d) Boundary conditions

At the upper boundary the temperature and humidity mixing ratio are held constant at their initial values, hence the relative humidity is constant. The concentrations of drops and nuclei are similarly held constant implying that those lost by diffusion and settling to lower levels are replaced by diffusion from above. The downward longwave radiative fluxes need to be specified. Values of 235 \( W \) m\(^{-2} \) outside the 8–13 \( \mu \)m window and 30 \( W \) m\(^{-2} \) inside are used for an initial temperature of 5\(^\circ\)C and their evaluation is described in I. They yield an initial value of the net upward flux at the surface of 72 \( W \) m\(^{-2} \) a typical value for a clear night in the British Isles.

The boundary conditions at the ground–air interface are:

\[ F_N + F_H + F_L + F_S = 0; \quad T = T_S; \quad N_{ij} = 0; \quad \frac{\partial n_{ij}}{\partial z} = 0 \quad \text{at} \ z = 0 \]

where \( F_N \) is the net radiative flux, \( F_H \) is the sensible heat flux, \( F_L \) the latent heat flux and \( F_S \) the soil heat flux. The first two conditions allow the surface temperature to be calculated as a function of time following Zdunkowski and Nielsen (1969). Once the air at the surface has
become saturated the water vapour mixing ratio here is adjusted to the saturation value as the ground continues to cool.

The zero droplet concentration at the surface implies that drops are lost by impaction on the surface foliage or settle through the laminar sublayer adjacent to the ground on a time scale small compared to that for turbulent diffusion near the surface. Use of a similar condition for the nuclei produced a significant depletion of nuclei near the surface before fog had formed. Taking into consideration the fact that the model contains no source term for nuclei other than turbulent diffusion from above it seems more realistic to assume a zero flux of nuclei towards the surface. The abrupt change of boundary condition at 0.3 μm radius is rather artificial and in the future it is planned to examine the use of a boundary condition which is a function of drop radius.

(e) Initial conditions

Unless stated otherwise the initial temperature is a constant 5°C from -1 m to 200 m and the relative humidity is 95% from the surface to 60 m falling to 84% at 200 m. The drier air aloft prevents the fog from growing to the model top boundary. This must be done to avoid problems with the boundary conditions for drops and nuclei. The model III exchange coefficients profile illustrated in I is used for all integrations. This is a linear function of height to 50 m with $K_{max} = 10^{-2}$ m$^2$ s$^{-1}$ at 50 m decreasing to $2.3 \times 10^{-4}$ m$^2$ s$^{-1}$ at 200 m. The exchange coefficients are constant in time.

3. Results

The integrations discussed in this paper are an attempt to assess the influence of microphysical factors on the fog drop-size distribution, visibility and liquid water content. Besides being of fundamental importance to the understanding of visibility in radiation fog this assessment is a prerequisite for an examination of the role of turbulence in determining the drop size distribution. If the fog drop-size distributions are found to be sensitive to changes in microphysical factors which cannot be measured, it will be difficult to assign an unambiguous role to the influence of turbulent mixing. If, however, the drop size distributions are relatively insensitive to microphysical influences then it should be possible by comparison of model and observed spectra to assign some limits to the degree of turbulent mixing within a mature fog.

The following points should be noted concerning the presentation of the model results. From the model-predicted drop-size distributions we may assign an unambiguous value to the scattering coefficient ($\sigma_s$)

$$\sigma_s = \pi \sum_i \sum_j N_{ij} r_{ij}^2 Q_{sl}$$

where $Q_{sl}$ is the scattering efficiency factor appropriate to the $i$th radius bin. Values of $Q_{sl}$ for a wavelength of 0.55 μm have been taken from the tabulations of angular scattering functions for spherical water droplets by H. B. Howell (1969). For ease of interpretation the scattering coefficient has been converted to the meteorological visibility by the relationship

$$V = 3.0/\sigma_s$$

and henceforth this will be called the visibility.

The model spectra are presented with droplets in the range 0–2 μm omitted. Their concentration typically varies from 1000 to 10,000 cm$^{-3}$ depending on the spectrum of nuclei and such high concentrations would not allow the choice of a suitable scale for the larger drops. They are also omitted from discussions of the predicted drop concentrations.
and in calculating mean radii. The rationale for this is that most observational techniques are not sensitive to these smaller drops. They are of course included in the calculation of the extinction coefficient.

(i) Influence of the mass distribution of the cloud condensation nuclei

In this section the influence of the width and shape of the mass spectrum of nuclei is examined. A systematic investigation of the effect of varying the concentration of nuclei whilst retaining a constant spectral shape is reported in section (ii).

A complete list of the spectra of nuclei used in this paper is given in Table 1. Spectra A-E have the shape of the idealized Junge spectrum due to Garland (1969) and vary only in width and concentration. The nuclei are taken to be ammonium sulphate.

The role of the larger nuclei has been examined in a series of three integrations using spectra (A) to (C) which represent progressive removal of the larger nuclei. Close inspection of the results reveals a slight tendency for increasing liquid water content and decreasing visibility with the removal of the larger nuclei. These differences are not significant as can be seen from the course of the visibility in Fig. 2 and the spectra at four hours in Fig. 3.

| TABLE 1a. NUCLEUS SPECTRA USED DURING THE INTEGRATIONS DISCUSSED IN THIS PAPER |
|------------------------------------------|-------|-------|-------|-------|-------|
| Spectrum (g)                             | A     | B     | C     | D     | E     |
| Mass                                    | 741   | 741   | 741   | 1853  | 3705  |
| 2·7 × 10⁻¹⁵                              |       |       |       |       |       |
| 5·9 × 10⁻¹⁵                              |       |       |       |       |       |
| 1·2 × 10⁻¹⁴                              | 463   | 463   | 463   | 1158  | 2315  |
| 2·64 × 10⁻¹⁴                             | 210   | 210   | 210   | 525   | 1050  |
| 5·81 × 10⁻¹⁴                             | 96    | 96    |       | 239   | 480   |
| 1·3 × 10⁻¹³                             | 43    | 43    |       | 109   | 215   |
| 2·8 × 10⁻¹³                             | 20    | 20    |       | 49    | 100   |
| 6·2 × 10⁻¹³                             | 9     | 9     |       | 23    | 45    |
| 1·4 × 10⁻¹²                             | 4     |       |       |       |       |
| 3·0 × 10⁻¹²                             | 2     |       |       |       |       |
| Total concentration (cm⁻²)              | 2329  | 2323  | 2153  | 5809  | 1·16 × 10⁴ |
| Total mass (µg m⁻³)                     | 50    | 40    | 20    | 100   | 200   |

| TABLE 1b. NUCLEUS SPECTRUM CONTAINING A HIGH CONCENTRATION OF LARGE NUCLEI |
|----------------------------------------|-------|
| Spectrum (g)                          | F     |
| Mass                                   |       |
| 2·10⁻¹¹                                 | 17    |
| 6·4 × 10⁻¹²                             | 22    |
| 2·0 × 10⁻¹²                             | 30    |
| 6·4 × 10⁻¹³                             | 38    |
| 2·0 × 10⁻¹³                             | 54    |
| 6·4 × 10⁻¹⁴                             | 70    |
| 2·0 × 10⁻¹⁴                             | 95    |
| 6·4 × 10⁻¹⁵                             | 121   |
| Total concentration (cm⁻³)             | 447   |
| Total mass (µg m⁻³)                    | 583   |

Therefore the three integrations will be treated together in a discussion of the salient features of the fog produced by the model.

As described in detail in I the radiative cooling of the air to the colder ground produces saturation of the air below 2 m between 1 and 1 1/4 hours from the start of the integration. This is shown in Fig. 4. The visibility has fallen to about 1 km after one hour due to the swelling of the nuclei. The supersaturation of the air between 1 and 1 1/4 hours causes several nucleus classes to be activated and the initial rapid growth of the droplets (due to their small radius) produces a sharp fall of visibility to 200 m at a height of 2 m by 1 1/4 hours. This compares well with the observations of Stewart (1955) at Cardington and also of Roach et al. (1976) that once the visibility falls to about 1500 m then there is a rather abrupt descent into a thick fog. As time proceeds the visibility declines more slowly due to the reduction of the growth rate of the drops with increasing radius and reduced supersaturation and radiative loss. Eventually the loss of drops to the surface by gravitational settling and turbulent diffusion becomes significant and causes a slight rise in the visibility after 3 1/2 hours. The same features are observed at higher levels but with a time delay. The peak supersaturation decreases with height up to 10 m and above this is in the range 0.03 to 0.04 %. The minimum visibility is independent of height below 30 m. Above this it increases slowly with height because the termination of the integration at 4 hours prevents the true minimum from being reached. At this time the fog is 80 m deep.

The droplet spectra at four hours are very similar as can be seen from Fig. 3. This reflects the fact that after activation the solute term in the growth equation quickly becomes
negligible compared to the supersaturation and radiative loss term. The latter term dominates near the surface after 2\text{1/2} hours because by this time the drop radii are in the 5-10 \mu m range where their absorption efficiency factor for longwave radiation is approaching unity. The mode radius is rather larger than we have observed in fog but it is approached sometimes, e.g. Fig. 7a, 7c. The initial model drop concentrations are in the range 130-150 cm\(^{-3}\) but fall to 60-70 cm\(^{-3}\) after four hours, due to gravitational settling. The latter figure is generally lower than we have observed although Fig. 7c measured at the surface in a 150 m deep fog, shows a concentration similar to the model at four hours. The mean drop-size and dispersion show little variation with height except just beneath the fog top where the drops have been recently activated. The drop concentration decreases with height above 30 m because drops are being lost by gravitational settling faster than they can be replaced by the diffusion of fresh nuclei into the fog from above.

A further integration has been motivated by the observations of Pilie et al. (1975) of considerable fluctuations in the concentration of haze nuclei. These were defined to be those nuclei with an equilibrium radius greater than 1 \mu m with an ambient humidity in the range 95-100\%. A low concentration of order 20 cm\(^{-3}\) of haze nuclei was associated with fog
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Figure 4. Supersaturation at a height of 2 m as a function of time. ——— Spectrum B, —— Spectrum F, . . . . . . Spectrum E, —— Spectrum B with no radiative loss term in the droplet growth equation.

formation but on a day with 200 cm$^{-3}$ of haze nuclei no fog formed. Spectrum F contains 200 cm$^{-3}$ of nuclei with an equilibrium radius greater than 1 μm at a relative humidity of 98% and is based on the relationship $N = C \sigma^k$ where $N$ is the concentration of nuclei activated at supersaturation $\sigma$, $C = 1500 \text{cm}^{-3}$ and $k = 0.5$.

Figure 2 shows that even at the start of the integration the nuclei have swollen sufficiently to reduce the visibility to 1500 m. Thereafter there is a much slower rise in supersaturation compared to the previous integrations, Fig. 4, especially after one hour. This is due to the activation of the larger nuclei when the relative humidity is less than 100%. As shown by Roach (1976) and in section (iii) such droplets are able to grow under these conditions because of their net radiative loss. As the drops formed on larger nuclei, whose growth controls the supersaturation, settle out, then the supersaturation slowly rises allowing fresh nuclei to be activated within the fog. This leads to the slow fall of visibility shown in Fig. 2 with a final value of less than 100 m. This result does not support the implication in Pilie’s observations that a high concentration of large nuclei can prevent fog formation. However, there is evidence that the formation of thick fog is delayed. The spectrum at a height of 2 m after 4 hours’ integration is similar to the others in Fig. 3 at radii greater than 8 μm. The large peak in the 2–4 μm class is composed of unactivated nuclei with an equilibrium radius greater than 2 μm at the prevailing supersaturation. In the previous integrations
these would have been activated by the higher peak supersaturation.

The insensitivity of the drop spectrum to the nucleus spectral shape illustrated in Fig. 3 is encouraging from the practical point of view. Most CCN counters are inaccurate below about 0.2% supersaturation and so do not provide information about the spectral shape within the region from which fog drops are activated. Thus we are left to infer the size distribution of the larger nuclei and if the spectrum of activated drops had been sensitive to this there would be little hope of correlating the observed spectra with other parameters such as turbulent mixing.

(ii) Influence of the nucleus concentration

A priori one would expect the drop-size distribution to display some sensitivity to variations in the nucleus concentration. This dependence has been inferred from observations of the drop-size distributions in continental and maritime cumulus, e.g. Squires (1956), and has also been invoked as an explanation of the high concentration of small drops prevalent in fog in the polluted London air of the 'fifties, Stewart (1957). Theoretical investigations have been confined mainly to a demonstration of the colloidal stability of a maritime compared to a continental drop-size distribution. In some models, e.g. Mason and Jonas (1974), the drops are grown from nuclei, but again attention is directed to variations in the concentration of drops larger than 20 μm radius which are required to initialize coalescence. These are much more numerous with a maritime nucleus spectrum.
Figure 6. Drop-size distributions at a height of 2 m after four hours integration. Each distribution is for a different nucleus concentration as annotated.

Most previous investigations considered the growth of drops in an ascending parcel of air in which adiabatic cooling produced the supersaturation necessary for droplet growth. Increasing the nucleus concentration affected the growth of the droplets by increasing the competition for the available water. In this numerical study radiative cooling is the driving force for droplet growth. Thus it is possible that variations in nucleus concentration may affect the droplet growth by altering the radiation field.

A series of integrations has been performed using a nucleus spectrum of constant shape but varying total concentration. The spectra used were (B), (D) and (E) the latter two having concentrations two-and-a-half and five times (B) respectively. As the nucleus concentration is increased the peak supersaturation is lowered, for example from 0.05% to 0.03% at 2 m, Fig. 4, and the visibility is reduced, Fig. 5. For a fixed liquid water content it is easily shown that the visibility is proportional to $N^{-3}$ where $N$ is the droplet concentration. Here it is found that the minimum visibility is proportional to $N_c^{-4}$ where $N_c$ is the concen-
Figure 7. Examples of drop-size distributions obtained during the Cardington Fog Project. Each distribution is a mean over the period shown of data obtained at 10 s intervals.

...tration of nuclei. This does not imply that the reduction in visibility is brought about wholly by the redistribution of available water as a high concentration of small drops. Although this is partly the reason, there is also an increase in liquid water content. For example with spectrum E the maximum liquid water content is increased by 20% and the average over the course of the integration by 50%.

As anticipated, increasing the nucleus concentration produces a drop-size distribution with a higher drop concentration and smaller mean radius. The spectra at 2 m after four hours integration in Fig. 6 illustrate this. At this time the fog is 100 m deep. Some of the
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range of spectra observed at Cardington are shown for comparison in Fig. 7. The top spectra in Fig. 7 were obtained at a height of 1 m in one of the densest fogs encountered during the project. Unfortunately it is of unknown vertical extent. The liquid water content and visibility derived from the spectra are also shown on Fig. 7. The spectra of 18.11.76 are an example of distributions containing a relatively high concentration of small drops. They were obtained at a height of 15 m within a fog 150 to 200 m deep. The fog showed a tendency to lift into stratus and so may have been subject to a greater degree of turbulent mixing than the other two fogs from which the spectra were derived. The example of 13.7.78 was obtained at a height of 1 m in a fog 150 m deep and is one of the flattest distributions we have yet observed.

A further effect of the increased nucleus concentration, not encountered in cumulus, is imposed through the radiative cooling process. The initial radiative effect of the aerosol is a strong function of relative humidity because for the unactivated drops $Q_i \propto r$ approximately; thus $\phi \propto \int_0^\infty r^3 \, dr$. At the initial relative humidity of 95% the additional cooling due to the unactivated droplets is about 0.01 °C h⁻¹ (Spectrum B) and 0.02 °C h⁻¹ (Spectrum E) compared to a gaseous radiative cooling of 0.2 °C h⁻¹. When the relative humidity approaches 100% the droplet radiative cooling increases to 0.1 °C h⁻¹ (Spectrum B) and 0.5 °C h⁻¹ (Spectrum E). The latter is comparable with the ambient gaseous cooling of 0.7 °C h⁻¹. Despite this the enhanced cooling with the highest nucleus concentration makes little difference to the time of supersaturation of the air below 2 m. It should be noted that since the model results are output every 15 minutes, time differences less than this are not resolved.

Once the fog has grown above 10 m radiative cooling rates of 3–4 °C h⁻¹ (Spectrum B) and 6–7 °C h⁻¹ (Spectrum E) are obtained. While the fog is optically thin, so that the entire column of atmosphere within the fog is being cooled radiatively by the droplets, the enhanced cooling due to the highest aerosol concentration results in a doubling of the liquid water content. By definition, when the fog becomes optically thick the entire column of atmosphere within the fog experiences the same radiative loss irrespective of whether this produces a large radiative cooling near the fog top (Spectrum E) or a smaller radiative cooling distributed more evenly through the fog (Spectrum B). This is reflected in the behaviour of the liquid water content. As the fog deepens the liquid water content in the fog with the lowest aerosol content approaches that in the fog with the highest and levels off at about 20% less. This difference is probably caused by the lower settling velocity, associated with the smaller mean drop size, in the fog with the highest aerosol content.

(iii) Comparison with a fog model containing parametrized microphysics

It is instructive to compare the results from the microphysical model with those from the original fog model which used parametrized microphysics. The models are identical otherwise, apart from the use of a more accurate numerical method to solve the diffusion equation in the microphysical model. The logarithmically spaced grid is transformed to a linear grid for the solution of the diffusion equation. This was not possible in the original model since the grid spacing was not an analytical function of height, although some correction for the non-linear grid was applied by introducing second order terms into the finite difference scheme. Both models used the same initial conditions, which were described earlier.

Table 2 shows a comparison of some of the more important properties of the fogs produced by the models. The time of fog development has been taken as the time at which the air becomes saturated at any grid point above the surface. With this definition fog forms
TABLE 2. A COMPARISON OF THE RESULTS FROM THE MICROPHYSICAL FOG MODEL WITH THOSE FROM THE ORIGINAL FOG MODEL

<table>
<thead>
<tr>
<th></th>
<th>Original model parametrized microphysics</th>
<th>Microphysical model nucleus spectrum B</th>
<th>Microphysical model nucleus spectrum E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of fog formation minutes</td>
<td>75</td>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td>Fog top height after 4 hours' integration (m)</td>
<td>20</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Maximum liquid water content up to 4 hours (g kg(^{-1}))</td>
<td>0.20</td>
<td>0.40</td>
<td>0.49</td>
</tr>
<tr>
<td>Maximum radiative cooling up to 4 hours (°C h(^{-1}))</td>
<td>-3.6</td>
<td>-4.5</td>
<td>-7.2</td>
</tr>
<tr>
<td>Liquid water path required to reduce surface net flux to 35 W m(^{-2}) (g m(^{-2}))</td>
<td>6.4</td>
<td>5.6</td>
<td>2.4</td>
</tr>
</tbody>
</table>

at about the same time in both models. This demonstrates that the radiative cooling due to the aerosol, omitted from the earlier model, does not reduce the time taken for the air to become saturated. The surface temperature in the microphysical model falls an extra 0.25 °C during the first hour compared to the original model. This is brought about by the improvement in the numerical solution of the diffusion equation and must contribute to the earlier formation of fog in the microphysical model with nucleus spectrum B. Using nucleus spectrum E saturation of the air is delayed by 15 minutes. This indicates that the enhanced radiative cooling due to the high nucleus concentration has been more than offset by removal of water vapour from the air by the swelling nuclei. However, in this case the visibility near the surface has fallen to 200 m at one hour even though the air is not quite saturated.

Fog development is more rapid in the microphysical model both in terms of liquid water content and fog depth. One reason for this is that the use of a linearized \( Q_d(r) \) in the original model caused the radiative cooling in the immature fog to be underestimated. The constant of proportionality between \( Q_d(r) \) and radius was chosen to prevent excessively large \( Q_d(r) \) values for drops of radius > 10 µm but this caused it to be underestimated for drops of radius < 5 µm. It is difficult to determine the accuracy of the original model radiation scheme from the model outputs since the radiative cooling is a function of the liquid water and temperature profiles which are never identical in the two models. However, when fogs of a similar liquid water content are compared the radiative cooling rates in the original model appear to be underestimated by about 30%, compared to the microphysical model with nucleus spectrum B, for liquid water contents less than 0.15 g kg\(^{-1}\). At higher liquid water contents there is no obvious difference. With nucleus spectrum E the radiative cooling rates in the microphysical model are about double those in the original model at all liquid water contents. This is because \( Q_d(r) \) is not truly a linear function of radius so that the radiative cooling is not entirely independent of the drop-size distribution. A more precise comparison of the radiation schemes has been performed by computing the liquid water path in the fog when the surface net radiation is reduced to 35 W m\(^{-2}\). As can be seen from Table 2 this is 13% less in the microphysical model with nucleus spectrum B and 63% less with nucleus spectrum E.

A second reason for the lower liquid water content in the original model is that the droplet settling was overestimated. It was assumed that \( \bar{v} = 6.25 \bar{w} \) where \( \bar{v} \) is the mean settling velocity in cm s\(^{-1}\) and \( \bar{w} \) is the liquid water mixing ratio in g kg\(^{-1}\). This was based on a few observed drop-size distributions. The scatter in the relationship between \( \bar{v} \) and \( \bar{w} \) was such that a linear fit seemed adequate. This relationship is a reasonable approximation to the data from the microphysical model with nucleus spectrum B up to 0.2 g kg\(^{-1}\). Above this it
overestimates \( \bar{v} \) by up to 40\%. With nucleus spectrum E the mean fall speeds are much lower because of the smaller mean drop size. In this case the microphysical model results can be represented approximately by the relationship \( \bar{v} = 2.5 \bar{w} \). It is not surprising that the parametrization of the settling used in the original model agrees best with the microphysical model results with a low nucleus concentration since it was based on data obtained at a rural site.

The fog grows upwards more rapidly in the microphysical model because of the increased radiative cooling within the fog near the top. This results in a colder fog top and enhanced radiative cooling of the air above the fog. The variation of fog-top height at four hours with nucleus concentration shown in Table 2 may be an overestimate. With nucleus spectrum E a superadiabatic lapse rate has developed in the upper half of the fog by four hours. If the exchange coefficients were functions of stability this would result in enhanced mixing and a consequent increase in fog-top temperature as a wet adiabatic lapse rate was established throughout the fog.

(iv) The importance of the net radiative loss from the droplets in prescribing their rate of growth

Roach (1976) has discussed the effect of radiative exchange on the growth of fog drops and suggested that it is the principal agent in such growth. This contention was supported by the results of a model fog with a prescribed supersaturation and opacity.

The microphysical model provides an excellent opportunity to perform a more realistic examination of the importance of this effect. Two integrations have been performed with the radiative term removed from Eq. (3), using a high and low nucleus concentration (spectrum E and B respectively). The radiative cooling of the air by the drops is still included through Eqs. (1), (12) and (13), since it is necessary for the realistic development of the fog, as shown in I. This is inconsistent with the removal of the radiative term from Eq. (3) because without this term droplet growth theory predicts that the drops will be warmer than their environment. However, the intention of this section is to examine the magnitude of the errors arising from the omission of the radiative term from equation (3) since it has only recently been introduced into the literature and is not widely used.

It is found that with a low nucleus concentration the radiative term has a significant effect. With the radiative term removed the mean drop radius is decreased by about 30\% and there is a similar increase in liquid water content. The influence on the drop spectrum after four hours integration is shown in Fig. 8 where the mode radius decreases from 11 \( \mu m \) to 9 \( \mu m \). More noticeable from this figure is the increased drop concentration, from 70 to 150 cm\(^{-3}\) with radiative loss compared to 250-350 cm\(^{-3}\) with no radiative loss. The extra drops are first generated by the activation of additional nuclei, because with no radiative loss the maximum supersaturation increases from 0:05 to 0:07\% (Fig. 4). Radiative exchange lowers the maximum supersaturation by lowering the critical supersaturation of the larger nuclei. This is shown in Table 3 where the critical supersaturation is listed as a function of nucleus mass with no radiative exchange and with \( R \) equal to -25 W m\(^{-2}\). The larger nuclei are activated before the air is saturated and as they grow vapour depletion inhibits the increase of the supersaturation. As can be seen from Table 3 radiative exchange hardly affects the critical supersaturation of the smaller nuclei (< 10^{-14} g) and hence they are not activated resulting in a lower concentration of activated nuclei with the radiative term present. As the integration proceeds the supersaturation falls to a similar value in both cases (Fig. 4) so that the drops grow more slowly when they do not experience a radiative loss. The lower mean radius results in reduced gravitational settling which main-
Figure 8. Drop-size distributions at a height of 2 m after four hours integration. —— with the radiative term in Eq. (3), —— without the radiative term in Eq. (3).

Table 3: Values of the critical supersaturation \( \sigma_a \) in percent for ammonium sulphate nuclei with no radiative loss and with a radiative loss (per unit absorption efficiency) of 25 W m\(^{-2}\).

<table>
<thead>
<tr>
<th>Nucleus mass (g)</th>
<th>( \sigma_a (R = 0) )</th>
<th>( \sigma_a (R = -25 \text{ W m}^{-2}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{-11} )</td>
<td>( 2.0 \times 10^{-3} )</td>
<td>(-0.11)</td>
</tr>
<tr>
<td>( 10^{-12} )</td>
<td>( 6.3 \times 10^{-3} )</td>
<td>(-4 \times 10^{-2})</td>
</tr>
<tr>
<td>( 10^{-13} )</td>
<td>( 2.0 \times 10^{-2} )</td>
<td>(7 \times 10^{-3})</td>
</tr>
<tr>
<td>( 10^{-14} )</td>
<td>( 6.3 \times 10^{-2} )</td>
<td>(6.1 \times 10^{-2})</td>
</tr>
<tr>
<td>( 10^{-15} )</td>
<td>( 0.2 )</td>
<td>(0.2)</td>
</tr>
</tbody>
</table>

The radiative term has little influence with a high nucleus concentration, its removal causing the maximum mean radius to be reduced by 5%, the maximum liquid water content...
to be reduced by 8% and the minimum visibility to be decreased by 20% from 23 to 18 m. There is also a much less significant effect on the drop spectra as can be seen from Fig. 8. The difference in effectiveness of the radiative term is due to the influence of the nucleus concentration on the optical depth of the fog. With spectrum E the net radiative loss $R$ is reduced to 7 W m$^{-2}$ at 18 m beneath the fog top and to 2 W m$^{-2}$ at 35 m. Equivalent figures for spectrum B are 35 W m$^{-2}$ and 27 W m$^{-2}$ respectively. The smaller drops grown from a high nucleus concentration have values of $Q_t$ significantly less than unity and this must also diminish the effectiveness of the radiative loss term. With a low nucleus concentration we have a positive feedback situation where as the drops grow their emissivity increases, droplet settling reduces the concentration and the droplets experience a radiative loss deeper into the fog promoting more growth etc. Even when the emissivity approaches a constant value the droplet settling still operates to reduce the optical depth of the fog.

In summary it appears that radiative exchange between a drop and its environment will not be a significant process in heavily polluted air. It will have a significant impact on the development of the spectra in clean radiation fogs, and maritime layer clouds and advection fogs and should be included in microphysical treatments of these topics.

(v) Variation of the condensation coefficient

When allowance is made for discontinuities in the vapour and temperature fields close to a drop, as for example in the formulation of Fukuta and Walter (1970) used here, the value assigned to the condensation coefficient ($\beta$) can greatly influence the growth rate of the smaller drops. There is still some controversy over the value of $\beta$ for pure water. Fitzgerald (1972) has reviewed several of the available determinations and finds values ranging from 0.02 to 0.3 with most values less than 0.05. It is not proposed to give here a comprehensive review of later determinations but only to note that Chodes, Warner and Gagnon (1974) have deduced a value of 0.033 from measurements in a thermal diffusion chamber, whilst Vietti and Fastook (1975) using an expansion cloud chamber conclude that $\beta = 1$.

The results presented so far have been based on a value 0.033 for $\beta$. By taking $\beta$ as unity with nucleus spectrum B it was found that the maximum supersaturation was reduced from 0.057% to 0.037% due to the faster drop growth rate and that the concentration of nuclei activated was halved to 70 cm$^{-3}$. The minimum visibility was increased by 35% from 52 m to 70 m and the maximum liquid water content was reduced by 22%. The mean drop radius was increased by about 15% on average and this small increase is illustrated in Fig. 9 at four hours. The 15% difference in mean radii seems surprisingly small compared to the reduction in growth rate brought about by a decrease in $\beta$ from 1 to 0.033, e.g. 200% for a 2 $\mu$m radius drop, 50% for a 5 $\mu$m radius drop and 15% for a 15 $\mu$m radius drop. It may be accounted for by the increased supersaturation obtained with the lower value and by the fact that for most of their lives the drops have radii of 10 $\mu$m or larger.

From the results described above it can be seen that uncertainties in the experimentally determined value of $\beta$ do not lead to large variations in the fog microphysical structure, the most sensitive parameter being the drop concentration. In particular by reducing $\beta$ from 1 to 0.033 it has not been possible to account for the high concentration of small drops often observed, e.g. Fig. 7 (b).

It has been observed in the laboratory that by coating nuclei with long-chain fatty acids or alcohols their growth rate can be considerably reduced, e.g. Storozhilova (1971). Podzimek and Saad (1975) have modelled this process by assuming that each nucleus was coated by a constant mass of surfactant so that the thickness of the coating decreased as the drops grew. Above a critical thickness, $\beta$ decreased by three orders of magnitude to $3.5 \times 10^{-5}$. Because it is not yet established that the carefully controlled laboratory conditions required to coat a drop can occur naturally it did not seem worth while in an initial study to
use the analysis of Podzimek and Saad. Instead $\beta$ was decreased by an order of magnitude for all drops. This is a modest reduction compared to that used by Podzimek and Saad.

The results with a reduced $\beta$ and nucleus spectrum B were quite dramatic as can be seen from the drop-size distributions at four hours, Fig. 9. The maximum mean drop radius during the course of the integration was reduced by 50% from 11.5 $\mu$m ($\beta = 3.3 \times 10^{-2}$) to 5.9 $\mu$m ($\beta = 3.3 \times 10^{-3}$). The smaller drops are not just a direct result of slower growth due to the reduction in $\beta$. The slower growth of the drops initially causes the maximum supersaturation to be increased from 0.05% ($\beta = 3.3 \times 10^{-2}$) to 0.16% ($\beta = 3.3 \times 10^{-3}$) resulting in a much higher concentration of activated drops. Competition for the available water then reduces the mean drop size. The concentration of drops with radius larger than 2 $\mu$m ranges
from 800 to 1000 cm\(^{-3}\) which is about three times as high as we have yet measured at Cardington. This strongly suggests that we have not encountered a situation in which \(\beta\) was as low as \(3.3 \times 10^{-3}\). The reduced \(\beta\) effects a reduction in the minimum visibility from 52 m to 19 m (65\%) and an increase in the maximum liquid water content of 45\%.

With increasing nucleus concentration there is a reduction in the sensitivity of the results to changes in \(\beta\). For example with nucleus spectrum E the minimum visibility is reduced by 50\% to 12 m, the lowest value we have yet attained, the maximum liquid water content increased by 33\% and the maximum mean radius reduced by 25\% to 5.6 \(\mu\)m.

These results could have implications for the use of surfactants to inhibit fog formation. This process involves coating the nuclei so that their rate of uptake of water is reduced and activation is delayed. It has been argued that an efficient surfactant coating, by reducing the condensation coefficient to the minimum value achieved in the laboratory of \(3 \times 10^{-5}\), could prevent the nuclei from reaching activation on the time scale of a night. However, since the coating must be complete and the surfactant must be oriented with its non-polar portion towards the air it seems probable that a much smaller reduction in condensation coefficient could be induced in practice. Furthermore it is likely that a surfactant which retarded the activation of the nuclei would also inhibit the growth of any droplets which became activated, leading to the probability of the development of a denser fog. It is not possible to test this idea rigorously with the present model because the effect of a surfactant on nuclei can only be included when these have reached a radius of 0.3 \(\mu\)m. Prior to this they are assumed to be in equilibrium with the prevailing relative humidity.

To check whether a large reduction in condensation coefficient could inhibit fog formation within the model by reducing the growth rate of the nuclei between 0.3 \(\mu\)m radius and activation, one integration was performed with the condensation coefficient reduced to \(3.3 \times 10^{-5}\). This delayed the formation of a visibility of less than 100 m by only fifteen minutes. The reduction in growth rate due to the low condensation coefficient appears to have been largely offset by the increase in supersaturation, which approached 6\%.

4. Conclusions and discussion

The microphysical model has shown the drop-size distribution in radiation fog to be insensitive to the shape of the nucleus spectrum but to depend on the nucleus concentration and the value of the condensation coefficient. Increasing the nucleus concentration or decreasing the condensation coefficient below 0.033 results in a reduction in the mean radius and an increase in the concentration of drops with radii larger than 2 \(\mu\)m. When matching observed and model distributions it seems difficult to obtain agreement of both the total concentration and mean radius. The latter can be matched by reducing the condensation coefficient or increasing the nucleus concentration but then the drop concentrations are higher than those we have observed at Cardington to be associated with low mean drop size.

One possible explanation is that the turbulent mixing in a mature fog is larger than implied by the value of exchange coefficient used here. Certainly it was concluded in I that these low values are required for fog formation on a realistic time scale and this has been confirmed by Lala, Mandel and Juisto (1975). However, unpublished results from the original model suggested that although a shallow fog was dissipated by increased mixing the upward growth of a deeper fog was greater. The increased turbulence within a deep fog would be generated by the reduction in stability associated with the cooling fog top and warming surface, the latter being due to the soil heat flux. Increased mixing will reduce the mean drop size by reducing the residence time of the drops in the fog and also probably by reducing the supersaturation. It is therefore planned to make the exchange coefficients a function of stability (or fog depth) in an attempt to assess the range of values appropriate to a developed fog.
ACKNOWLEDGMENT

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