A field study of radiation fog in Meppen, West Germany

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SUMMARY

A field study of the microphysical properties of a radiation fog was conducted in Meppen, West Germany, on 17 February 1978. It is described and interpreted in terms of the prevailing meteorological conditions.

Pronounced periodic fluctuations in liquid water content (intervals ~70s) were observed at times in the radiation fog. It is suggested that these were a result of convective motions in the form of Bénard cells.

The drop size distributions were broad, containing drops of radii up to 25μm. Calculations indicate that these larger drops cannot be produced by radiative cooling from the fog top. It is argued that these large drops may have been produced either by large supersaturation fluctuations near the fog top, resulting from downwards entrainment of warmer moister air, or by convective motions causing a fraction of the larger drops to make several excursions to the radiative cooling region near the fog top. The radiation fog was observed to clear when cloud was advected over the site. It is suggested that this was due mainly to eddy diffusion and gravitational sedimentation of drops to ground, after radiative cooling from the fog top had been severely curtailed by the cloud layer.

1. INTRODUCTION

Some of the most comprehensive analyses of fogs have been carried out by Roach et al. (1976) in a series of experiments at Cardington, Bedfordshire. Measurements of both micrometeorological and microphysical properties were made and described in the paper. Measurements of the water and heat budgets of the fog were made as well as droplet spectra, and the main effects isolated were the significance of gravitational settling and radiative cooling. A numerical study by Brown and Roach (1976) showed that radiative cooling is a maximum at the fog top, which produces there a maximum in the vertical profile of liquid water content. Roach (1976) examined the effect of radiative cooling on droplet growth and demonstrated the importance of gravitational settling on controlling the water budget. He concluded that the maximum radius to which droplets would grow in a fog was about 10μm, which is consistent with the observations made at Cardington, but not with the measurements of Pinnick et al. (1978) who found radii of up to 15μm in Grafenvörh fogs.

Pinnick et al., using a Knollenberg FSSP droplet spectrometer mounted on a balloon, found a maximum in liquid water content at the fog top, up to an order of magnitude higher than the value close to the ground. They also observed an appreciable broadening of the drop spectrum with height, a finding consistent with that of Goodman (1977). However, Pilie et al. (1975a, b) in a series of experiments in New York State, found that the spectra became narrower with altitude, although in this case local topography is likely to have exercised significant effects upon the micrometeorology, especially the wind structures.

The measurements by Roach, Pinnick and Goodman were all made on comparatively level terrain.

Both Roach and Pilie found an unstable layer established beneath the fog top. This is primarily due to the confinement of the radiative cooling to a thin layer at the top of the fog (as a consequence of its high optical density) together with upward transport of soil heat flux. Thus it appears likely that convective motions may occur within radiation fogs and the research presented in this paper attempts to assess the significance of this effect.

We describe herein studies of a radiation fog occurring at Meppen in West Germany on 17 February 1978. As an aid to relating the micrometeorology to the microphysics a
simplified numerical model has been developed and the results of this are also presented.

Measurements of the droplet sizes (for radii $r > 3 \mu m$) were made using a Keily Probe mounted in a wind tunnel 2 m above the ground (Corbin et al. 1978, Blyth et al. 1979). These yielded droplet size distributions $n(r)$ and (by integration) values of liquid water content $L$ and visibility $V$. Visibility was also measured on site using a transmissometer with a baseline of 50 m situated about 30 m away from the Keily Probe. The agreement between the values of $V$ obtained by these two methods was good except for very high values (when the droplet counts were unreliable) or very low values, less than 50 m, when the transmissometer was suspect. Liquid water contents and drop size distributions obtained from the Keily Probe were compared with those obtained from the Knollenberg FSSP device belonging to the Atmospheric Sciences Laboratory, WSMR, USA. Good agreement between the results of the two instruments was consistently found.

Supporting meteorological measurements of temperature, dew point, wind speed and direction were made 10 m above the surface and the height of the top of the fog was estimated using a balloon-borne FSSP device. Satellite photographs produced by the University of Dundee provided information on the advection of cloud to the site.

The analogue pulses from the Keily probe were recorded on magnetic tape at Meppen and processed on a PDP 8e computer in Manchester. The pulses were histogrammed into appropriate time intervals and values of the water characteristics were computed. Programmes were developed to calculate power spectra and autocorrelation functions. The power spectra were evaluated on a CDC 7600 computer using a fast Fourier transform technique.

The observation site (52°52'N; 7°24'E) was the flat ill-drained flood plain of the River Ems. A boundary of thinly planted poplar trees several hundreds of metres away from the instrumentation site is unlikely to have had a significant effect on the data. At the times of the experiments, the ground was covered by 5 cm of level snow.

2. THE RADIATION FOG OF 17 FEBRUARY 1978

A surface anticyclone, central pressure 1036 mb, was situated near East Greenland and was associated with a strong thermal ridge at the 500 mb level. A deep 500 mb trough covered much of Europe with an axis lying north-south at around 15°E. Between these two features there was a strong north-westerly flow with weak cold advection down the North Sea and an associated weak surface cold front moving south-east. At the surface a cold ridge was extending south-east from the main anticyclone and covered Meppen; and therefore surface geostrophic winds were very light in the area. This ridge intensified somewhat during the 17th. The surface chart for 1800h* on 17 February is shown in Fig. 1.

The air at Meppen on 17 February at 1800h had been advected south from the Arctic ice by a direct route over the North Sea during the preceding few days. During this process the air was warmed at the surface from $-28^\circ C$ at 1200h on the 15th to around $-3^\circ C$ over the North Sea on the 17th with dew points raised to around $-4^\circ C$ to $-5^\circ C$. The infrared satellite photograph taken at 1911h on 17 February 1978 is presented in Fig. 2. This shows the line of cloud associated with the cold front approaching the north coast of Germany, together with some further convective clouds generated due to instability caused by the surface warming described above. Snow showers were reported from coastal regions throughout the period. Inland, however, near the axis of the ridge, low level subsidence was taking place and at 1800h skies were reported free of cloud at all inland stations around Meppen, as is confirmed by the satellite photograph. Radiative cooling has produced a strong surface inversion and extensive radiation fog (clearly visible on Fig. 2) has formed

* All times quoted in this paper are GMT.
over the low lying parts of north Germany, with surface temperatures between $-8^\circ C$ and $-13^\circ C$.

Figure 1. Surface synoptic chart for 1800h on 17 February 1978.

Figure 2. Infrared satellite photograph of Germany and the southern North Sea taken at 1911h on 17 February 1978. Photograph supplied by the University of Dundee.
Using European ascent stations, north to south vertical cross-sections of wet bulb potential temperature and dew point depression were plotted for the Meppen area. They showed a region of warmer and moister air to be present just ahead of the cold front, particularly between the 850 mb and 550 mb pressure levels. This was probably associated with the frontal cloud sheet. The ascent indicates that there was a temperature inversion about 400 m deep close to the surface. Local vertical profiles of temperature through the depth of the fog were not available. The 0000h ascent on 18 February at Essen (about 30 miles east of Meppen) is shown in Fig. 3. Taking account of wind strength in the area between 850 mb and 550 mb it was estimated that the cloud sheet arrived over Meppen between 2300 and 2400h on 17 February. Light snow was first reported from Meppen at 2316h and thus it was assumed that precipitation started soon after the arrival of the cloud.

Figure 3. Radiosonde ascent at Essen of temperature $T_A$ and dew point $T_D$ at 0000h 18 February 1978.
TABLE 1. METEOROLOGICAL DATA MEASURED AT MEPPEN ON 17 FEBRUARY 1978. $T_d$ IS THE DRY-BULB TEMPERATURE, $T_w$ THE WET BULB TEMPERATURE, $W$ THE WIND DIRECTION AND $U$ THE WIND SPEED

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<th>$T_w$(°C)</th>
<th>$W$(°)</th>
<th>$U$(m s$^{-1}$)</th>
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<td>240</td>
<td>2.1</td>
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sheet, the latter causing the clearance of the fog after 2300h. Table 1 presents meteorological data from 17 February.

(a) General description of the fog

The data are marked by a very strong cyclic behaviour of the liquid water content during the interval 2058 to 2118h with a corresponding variation in the visibility and mean drop radius, which ranges from 10-4 Μμm in regions of maximum liquid water content to 4-7 Μμm in the minimum. After 2118h the regime changes to one of higher frequency, smaller amplitude fluctuations with a mean drop radius almost constant at 6 Μμm and a liquid water content of around 0-2 g m$^{-3}$. A return to large amplitude fluctuations then occurs after 2145h. At 2315h light snow was observed, the fog started to clear and did so totally in the following 50 minutes. During this time all periodicities and large-scale fluctuations disappeared.

The fog will now be discussed in more detail. The water balance and microphysical structure will be covered first. This is followed by separate discussions of the fluctuations and the dispersing phase.

(b) Heat balance of the fog

It was estimated from balloon ascents made during the experiment that the fog depth was 100-120 m. The mean liquid water content was 0.2-0.3 g m$^{-3}$ at the surface and probably increased substantially with altitude. Therefore the assumption was made that the ground was effectively shielded radiatively at terrestrial wavelengths by the fog. In the absence of detailed vertical temperature profiles it was assumed that the fog was in approximate radiative equilibrium with the ground. However, an upward soil heat flux of no more than 10 W m$^{-2}$ was estimated taking account of the snow cover, and the frozen state of the ground following the prolonged cold spell in this area. The exact value of this figure is unimportant as it contributes only around 4% of the energy budget of the fog. Confirmation of this estimate is given in the discussion.

Assuming the fog to be roughly isothermal (later it will be suggested that convective motions are occurring within it but it is very unlikely that the temperature difference between the fog top and the ground exceeded 1 °C) and equal to the surface temperature of -7 °C then the upward radiative flux from the fog top will be about 285 W m$^{-2}$. The downward flux, due mostly to water vapour, was calculated in a similar manner to Brown and Roach (1976) and estimated to be about 220 W m$^{-2}$. This gives an overall cooling rate of 55 W m$^{-2}$. 
(c) Water content and comparison with observed cooling rates

The formation of the fog began at about 1600h (before the start of microphysical measurements). The temperature at this time was $-5.4^\circ C$ and fell to a minimum value of $-7.9^\circ C$ at 1900h. The air was saturated throughout this period and the condensation rate was calculated to be $0.14 \text{ g kg}^{-1} \text{ h}^{-1}$. The observed cooling rate was greatest early in this period, and decreased later. This observed cooling rate is rather low to be consistent with the estimated net power loss, even when account is taken of the increasing depth of the fog during the period, up to the maximum of about 130 m observed later, and the progressive shielding of the ground by the fog toward the end of the period. It is found that the observed power loss would have to have been uniformly distributed over a depth of about 140 m on average throughout this period for total consistency to exist. This discrepancy, together with short-term fluctuations observed in the temperature record, suggest that significant downward entrainment of warm air was taking place. The total water condensed due to the observed cooling would be $0.42 \text{ g kg}^{-1}$. The observed mean liquid water content of the fog was around $0.2-0.3 \text{ g m}^{-3}$ later in the period. This suggests substantial loss due to gravitational sedimentation and eddy diffusion to ground.

For the remainder of the period the surface temperature stayed roughly constant at about $-7^\circ C$. (This includes the time during which the microphysical measurements were made.) A decrease in the surface cooling rate is consistent with the increasing vertical depth of the fog and the progressive screening of the ground by the thicker, deeper fog, with the main radiative heat sink transferred to the fog top. As pointed out by Brown and Roach (1976) this will result in a steepening of the lapse rate within the fog and, as discussed in the following section, appears in this case to result in the development of regular convective motion within the fog. However, once this steeper lapse rate had become established one would still expect a surface cooling rate of around $0.5^\circ C \text{ h}^{-1}$ for a fog of 100–130 m in depth.

The increase in turbulence and convective motions associated with the decrease in Richardson number below the radiative sink are likely to result in an increase in the entrainment of air of higher wet bulb potential temperature downwards through the inversion layer from above the fog top, thereby producing an enhanced downward flux of both sensible heat and moisture into the fog. It would seem that in the period up to the dispersing phase of the fog this downward heat flux plus the upward soil heat flux is approximately cancelled by the radiative cooling from the fog and that the droplet loss to the ground (now enhanced by increased eddy diffusion due to the decreased stability) is broadly balanced by the flux of moisture for this particular fog. There are, however, some detailed variations in the water content during the period of microphysical measurements. These will be discussed in detail in the following section.

(d) Periodicities in the fog

In the period 2058 to 2315h three distinct modes of behaviour were evident. From 2058 to 2118h a strong periodicity of 51 s exists with a mean of $0.29 \text{ g m}^{-3}$. A water content record from this period is shown in Fig. 4A. From 2119 to 2130h the fluctuations are of smaller amplitude and period about 31 s with a mean liquid water content of $0.2 \text{ g m}^{-3}$ (Fig. 4B) but other frequency components are also evident. In the period 2130–2140h (Fig. 4C) the fluctuations are greater in amplitude and of longer period with the liquid water content rising to a mean of $0.28 \text{ g m}^{-3}$ until from 2145 to 2200h very large amplitude regular fluctuations of period 96 s have developed. Power spectra for the first two periods are presented in Fig. 5. Because of discrete sampling of the data, an autocorrelation method
was used to evaluate the Fourier coefficients: 95% confidence limits are indicated in the figure.

The most likely explanation for these fluctuations is a form of regular cellular convection developed in an unstable layer below the inversion level in the fog being advected over the site at approximately 1.5 m s\(^{-1}\) by the surface wind (such unstable layers have been observed by Roach et al., 1976). The landscape around the observation site is flat and largely featureless and so it is unlikely that topographical features played an important role.

It appeared possible that the fluctuations may result from gravity waves in the highly stable inversion layer. These induce downdraughts in the fog layer below, so bringing down to ground the very high liquid water content region envisaged near the fog top, where the radiative cooling is a maximum. The angular frequency, \(N\), of the gravity wave in an inversion layer is given by

\[
N = \left( \frac{g}{\theta dz} \right)^{\frac{1}{2}}
\]  

(1)
where $\theta$ is potential temperature, $z$ is altitude and $g$ is the acceleration due to gravity.

The period of gravity waves in the low-level inversion was calculated for several radiosonde ascents taken at 0000h on 18 February in the area surrounding Meppen. In each case the resultant period was around 250 s, much too long to account for the oscillations observed. In some power spectra a small subsidiary peak is observed at this period.

Another possible explanation for the observed periodicities in the water properties involves regular convection in the shallow, slightly unstable boundary layers.

Rayleigh (1916) performed experiments on the nature of convective motion occurring when a stable layer of fluid overlies an unstable layer. The criterion for such motions was found to be defined by the Rayleigh number

$$R_a = \frac{g^2 \alpha d^4}{vK} > 1700$$

where $\alpha = (1 - \rho/\rho_0)/T$. In these expressions $\rho$ is the density of air, $\rho_0$ the density of air at
0 °C, \( T \) the air temperature, \( \Gamma \) the temperature lapse rate in the unstable layer, \( v \) the kinematic eddy viscosity of air, \( K \) the eddy diffusivity, and \( d \) the depth of the unstable layer.

For values of \( R_a \) only slightly in excess of this critical value a regular hexagonal pattern of cellular convection is to be expected (Hardy and Otterson 1968). Steady two dimensional roll convection is likely for higher \( R_a \) (up to about \( 2 \times 10^4 \)), while at still higher values progressively more irregular time dependent convection is expected.

It seems likely that convective motions of some kind are responsible for the fluctuations in the fog since

(a) the estimated thermal structure of the fog suggests strongly that \( R_a \) is greater than 1700 for the fog layer;
(b) the motions occurred only while rapid cooling at the fog top was maintained. When the radiative cooling from the fog top was effectively halted by advection of cloud cover after 2300h, the motion immediately ceased;
(c) the regions of high liquid water content observed in the fluctuations are consistent with the idea of downdraughts bringing to earth regions of substantial water content located near the fog top.

A detailed knowledge of the vertical temperature profile through this fog is not available to facilitate an accurate determination of \( R_a \). However, the following arguments suggest that the periodicities were due to convection of the Bénard cell type, rather than roll convection. It is generally observed that convective rolls are orientated nearly parallel to the mean flow with a typical wavelength-to-height ratio of 3:1. The mean flow in the fog was around \( 1.5 \text{ m s}^{-1} \) and it is therefore very unlikely that in roll convection one locality would observe an advective flow pattern of period less than the 100s observed. On the other hand Hardy and Otterson (1968) have reported that the hexagonal Bénard cells (which they observed in a slightly convective boundary layer) are simply advected along by the mean flow. In addition, Hardy has reported that although the motion in these cells is strongly dependent upon the distribution of eddy viscosity with height, one might generally expect broad upward flow in the middle and narrow, stronger downward flow around the edges of the cell. This prediction is consistent with the liquid-water-content/time plots presented in Fig. 4, if we assume, as seems likely, that the regions of high liquid water content are correlated with downdraughts. Finally, we suggest that the small vertical depth of the convection layer is consistent with the stable development for values of \( R_a \) (which depends on \( d^3 \)) close to the critical value. The maximum possible value of \( d \) is the depth of the fog, about 100–130 m. It will, in practice, be less than this by an amount dependent on the absorption depth of the fog for infrared radiation.

(e) Effect of motions on the water budget of the fog

Calculations were performed to estimate the rate of loss of water to ground by gravitational sedimentation and eddy diffusion. In these calculations we employed exchange coefficient profiles for stable conditions deduced by Smith (1975), with \( K_{\text{max}} \sim 0.25 \text{ m}^2 \text{s}^{-1} \) at 100 m, and also an adiabatic profile, with \( K = 5 \text{ m}^2 \text{s}^{-1} \) at 100 m. In view of the deep well-developed fog, in which the main radiative cooling inversion was well above the ground, we considered that substantially higher values of the exchange coefficient than those used by Roach and Brown were appropriate for a shallow fog in the early stages of development.

The major finding was that in the periods of large fluctuations the rate of droplet loss to ground was very substantially increased; we estimated \( 0.2 - 0.3 \text{ g kg}^{-1} \text{h}^{-1} \), on average, depending on the exchange coefficient, compared with the condensation rate of about
0.1 g kg\(^{-1}\) h\(^{-1}\). This has the effect of reducing the mean liquid water content in the fog and appears to account for the decrease in amplitude and period of the fluctuations after 2118h. The decreased liquid water content will increase the depth of fog being cooled radiatively and so reduce the mean lapse rate within the fog, the depth of any convective layer and the enhancement of liquid water content near the fog top. The effect of the decreases in convective motion, together with the smaller mean drop size and eddy exchange coefficient, is to reduce the effective loss to ground to around 0.1 g kg\(^{-1}\) h\(^{-1}\), close to the condensation rate. Thus the radiative cooling can restore the higher liquid water content. A still lower exchange coefficient during this period would further enhance this effect. A return to large amplitude, low frequency, fluctuations eventually ensues. There is no correlation between surface temperature fluctuations and these regimes so no direct evidence is available for any effect of the convection on entrainment into the fog top.

Figure 6 shows droplet spectra for the periods 2058 to 2118h, a period of strong fluctuation in water content, and 2119 to 2130h, one of much smaller fluctuations. It is apparent that the major difference between them is the rather higher concentration of larger drops in the higher liquid water content region. The total drop counts were about 20% higher in the period with lower water content compared to the higher liquid water content periods, supporting the suggestion that then the rate of droplet loss to ground was less than the rate of nucleation of new drops in the low liquid water content period; while in the periods of high liquid water content the relative magnitudes of these two effects were reversed. It is expected that the nuclei activated would have been entrained from above the top of the fog.

![Figure 6. Measured size distributions for the periods:](image)

- **A** 2058h to 2118h
- **B** 2119h to 2130h

(f) **The evolution of the drop spectra**

A model was developed to examine the growth of the droplet spectrum in the radiation field described in section (l). The interaction between radiation and the droplets was modelled using the method developed by Roach (1976). The vertical depth of the fog was varied as appropriate and the radiation field at each level in the fog was calculated taking account of the screening effect of the droplets at higher levels as suggested by Oliver et al. (1976). The level of supersaturation was calculated from application of the growth equation
to all droplet sizes. Initial spectra consisted either of those observed in the fog or ones chosen to investigate particular aspects of the effect of radiation on the droplet growth.

The effects of gravitational sedimentation and eddy diffusion of droplets through the fog were included in this model. The same wide range of exchange coefficients was used as described earlier, in order to simulate the wide range of stability suggested by the various regimes observed in the fog.

The main conclusion from these calculations were that it was not possible to produce droplets of radii larger than about 15 μm radius with drop concentrations close to those observed, and that the drop size distribution was only weakly dependent on altitude within the fog. Both these results were obtained over the full range of exchange coefficient profiles used. It is also clear that the liquid water content was a maximum close to the fog top.

The drop size distributions observed in the regions of maximum and minimum liquid water content, during the early period of fluctuations, are presented in Fig. 7. This shows that many more large droplets were present in the high liquid water content regions. Other workers (e.g. Pinnick *et al.*, 1978 and Goodman 1977) have made drop size distribution measurements as a function of height in radiation fog. They found substantially higher mean drop radii in the high liquid water content region near the fog top, in contradiction to the prediction of the radiative cooling model.

![Figure 7](image)

**Figure 7.** Measured size distributions for the regions of maxima (×) and minima (■) of liquid water content during the period 2058 to 2118h.

It is clear that the lifetime of the larger droplets in the fog is insufficient for the distribution shown to have been produced by coalescence between droplets of radii not exceeding 15 μm.

(g) Possible mechanisms for the development of large droplets near the fog top

Immediately above the convective region in the fog an inversion layer will exist, produced by radiative cooling at the fog top. Although on this occasion the air well above the surface was dry, near the fog top the radiative cooling inversion would be expected to contain saturated or nearly saturated air. It is therefore proposed as mentioned before, that the strong turbulent and convective motions generated in the unstable layer below the fog
top resulted in the downward entrainment of some of this moist warmer air. As this is mixed with the colder air in the fog a supersaturation will be developed locally. This will result in the growth of small drops on nuclei present in the entrained air. Due to the small size of these, however, they will be inefficient at absorbing the excess water vapour, and larger droplets mixed in from the pre-existing fog will have much higher mass growth rates. As the admixed air is diluted (as the entrained eddies decay) the water available per unit volume of entrained air will decrease and the numbers of pre-existing droplets affected will increase, thereby reducing the growth rate of each one. The ability of this entrained air to produce large drops will therefore be strongly dependent on the ratio of eddy dissipation time to the time taken for the droplets to grow to a given size. No information is available on this point but it would seem likely that it is a maximum in the most strongly convective case, when entrainment rate and scale are a maximum; which is when the largest droplets were detected.

It follows from dimensional arguments that the eddy exchange coefficient $K$ is related to the turbulent energy dissipation rate, $\varepsilon$, and a characteristic length scale $\lambda$ by

$$K \sim \varepsilon^{1/2} \lambda^{4/3}$$

and that the characteristic decay time $T$ of an eddy of size $\lambda$ is given by

$$T \sim \varepsilon^{-1/2} \lambda^4$$

Further, the time constant for droplet growth by condensation between radii, $r_0$ and $r_1$ at the temperatures of interest is

$$T_g \sim \left\{(r_1 + z)^2 - (r_0 + z)^2\right\}/2S$$

where $z$ (about 5 $\mu$m) is the length associated with the condensation coefficient, $r$ is in $\mu$m and $S(\%)$ is the supersaturation.

To estimate the growth of the most favoured drops, i.e. those entering the warm (initially drop free) region shortly after entrainment, we compare $T$ and $T_g$. If $\lambda \sim 30$ m and $K \sim 1$ m$^2$ s$^{-1}$, then $T \sim 10^3$ s. For a 15 $\mu$m radius drop to grow to 25 $\mu$m in a time comparable to this requires a value of $S$ of about 0.2% over this period in the vicinity of the most favoured drops. Such supersaturations could be generated by temperature differences around 2°C. Since this supersaturation will be developed primarily in the vicinity of entrained filaments of cold drop-filled air entering the warm blob it is unlikely that sufficient new nuclei from the warm air will be activated – and then grow sufficiently – to deplete significantly the water available to the growing drops.

Detailed modelling work is planned to calculate the size distribution of drops generated by the mixing of the two saturated parcels by eddy diffusion. The argument presented above, however, suggests that it may be possible for a small number of the drops in the fog to grow to the size observed without the need for them to be confined to the region of strong radiative cooling throughout their growth history.

An alternative mechanism suggested by Roach (private communication) is that a fraction of the larger droplets in the fog may, as a result of the weak convective motions, make several excursions to the fog top where they would grow rapidly due to radiative cooling. If we consider the droplet growth equation appropriate to this mechanism

$$\frac{dr}{dt} = \frac{1}{f_1(T)} \left\{S - f_2(T)R\right\}$$

whose $f_1(T)$ and $f_2(T)$ are temperature dependent coefficients and $R$ is the net radiative loss per unit absorption efficiency (about 60 $\text{W m}^{-2}$). By using appropriate values for $f_1(T)$ and
$f_s(T)$ at about $-7^\circ C$ and assuming that $S \sim 0.05\%$ we find that a drop will increase its radius from 15 to 25 $\mu m$ in about 15 minutes.

Evidence from Pilie et al. (1975) implies that vertical velocities present within the fog are typically $0.3 m/s$ or less, once the convective regime has become established. If the liquid water content at the top of the fog is about $1 g/m^2$ then this suggests an absorption depth of 16 m for terrestrial radiation. Thus the time spent by a parcel of fog in the radiation cooling zone will be about 100 s, and 9 circulation cycles would be required for the radius to increase from 15 to 25 $\mu m$. This seems unlikely in view of losses to ground by sedimentation and eddy diffusion.

3. CLEARANCE OF THE FOG

As mentioned, it is probable that the sky above Meppen was completely clear of cloud up to the time of arrival of the sharply defined frontal cloud sheet. It has been suggested that the onset of snow followed this closely at about 2315 h.

The period from 2245 to 2315 h was characterized by strong periodic fluctuations in water properties and a broad drop size distribution. By 2321 h a substantial reduction in the numbers of small droplets had occurred but the larger droplets remained in roughly the same concentration. The evolution of the drop spectra in 15 minute time intervals from 2321 h onwards is shown in Fig. 8.

![Figure 8. Measured size distribution for three time intervals during the clearance of fog:](image)

As the cold front approached there was no increase in geostrophic windspeed at the surface (or any level below the 900 mb pressure level) and the observed surface wind also remained roughly constant at $1.5 m/s$. Consequently there is no evidence of increased downward entrainment through the inversion layer due to increased turbulence.

The major effect of the frontal cloud cover would be to substantially reduce the rate of radiative cooling from the fog top. Hence the net radiative cooling of the fog may be replaced by warming from the surface, due to the soil heat flux, as reported by Brown and Roach. In this case the warming was probably by upward eddy diffusion of heat. The large decrease in the concentration of small droplets in the fog up to 2321 h was probably due to evaporation associated with this effect. On this occasion, however, the ground was very
cold and snow covered, and this process probably soon became much less important. Beyond this time the major change is an increasing rate of loss of larger droplets, the smallest size categories remaining almost unchanged. This suggests that loss to ground and scavenging of the larger droplets by the falling snow had become the major modes of fog dispersal. Table 1 indicates that no noticeable rise in surface temperature occurred during the period of dispersal. This confirms the suggestion that sedimentation was more important than warming, by radiation, of the now more stable fog from the ground; which would also have the effect of preferentially evaporating the larger drops.

It is interesting to note that a total heat flux of 15–20 W m\(^{-2}\) during the 50 minute period of observed dispersal would have been sufficient to evaporate the 120 m deep fog. This supports the suggestion of a soil heat flux of no more than 10 W m\(^{-2}\).

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