Studies of Physical Structure of Fog

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Abstract

Some results on the drop size distribution of radiation fog near the ground at Asahikawa measured by gravity settling method are presented in Part 1. The concentration of small droplets with radii below 20 microns gradually increases until 10 to 50 minutes after the formation of the fog, then it has nearly constant value. At the base of the thick fog the large droplets with radii larger than 50 microns appear at the later stage of the development of the fog. In the shallow fog, on the other hand, the increase or decrease of the concentration of large and small droplets occurs concurrently.

The influence of air temperature on the structure of fog is also studied. It is found that when the air temperature is above freezing the mean volume radius is 12.5 to 15 microns. In the majority of the cases when the air temperature is below -5°C the mean volume radius is about 7.5 microns. In the winter fog the low liquid water contents between 10^{-4} and 10^{-2} g/m³ are frequently found. It is suggested that in winter fog a large number of very fine particles are present and obscure the visibility.

The measurements by means of a hand operated impactor and water-blue dye coated film reveal that many small droplets of radii less than 2 microns are present frequently in winter fog especially in smog and steam fog. Their results are shown in Part 2. It is further found that the local difference of the structure of fog and the effect of river steam are small in well developed radiation fog.

Part 1. Structure of Radiation Fog near the Ground

1.1 Introduction

The physical structure of fog and stratus cloud is one of the important problems in meteorology, particularly concerning with smog. Although the samplings of fog- and cloud-droplets have been made by many investigators, few systematic investigations of the physical structure of fog and stratus cloud have been undertaken.

As Asahikawa is situated in a basin radiation fog frequently occurs and annual mean value of fog day is about 90 days. Moreover, severe smog frequently occurs in winter. Therefore the study of radiation fog is also of practical importance for the prevention of smog.

In the period from September, 1957 to February, 1958, the measurements of the size

distribution of radiation fog droplets were made on the ground. The gravity settling method was employed for the sampling (Okita, 1961).

1.2 Observations on September 11, 1953

As fog occurred at about 0200 JST the droplet samplings were made from 0339 JST at Shunkocho (Fig. 1.1). Fig. 1.2 shows the variation of the concentration of fog droplets in several size groups. At the top of the figure the mean volume radius (M.V.R.) and maximum droplet radius (M.D.R.) in each sample are also shown. From the figure it is found that small droplets with radii below 20 microns show no large variation in concentration. The larger droplets, on the other hand, appeared in the later stage of the development of the fog and gradually increased in concentration. The concentrations of the large droplets were at their maximum

Fig. 1.1. Asahikawa.

H.W.T.: Hokusei watch tower

G.U.: Gakugei University

H.M.S.: Hokusei middle school

A.B.: Asahi bridge

A.M.O.: Asahikawa Meteorological Observatory

Fig. 1.2. Variation of concentrations of radiation fog droplets on Sep. 11, 1957.

Range of radius (μ)

● 3-5	□ 25-35
× 5-10	■ 35-50
○ 10-15	⊕ 50-75
+ 15-20	▽ 75-100
△ 20-25	

from 0631 to 0701 JST, when the droplets of radius as large as 85 microns were found. It is interesting to note that at 0732 JST, when the fog was dissipating, the rate of decrease of the droplet concentration was the same irrespective of fog size. It may be said that Fig. 1.2 is a typical example of the variation of droplet size and concentration at the base of deep radiation fog.

1.3 Observations on September 22, 1957

At Shunkocho fog appeared at about 0340 JST, then the samplings were made from 0349 JST. The fog layer, however, did not develop upward with estimated thickness between 50 and 100 m. Fig. 1.3 indicates that the increase or decrease of the concentration of large and small droplets occurred concurrently. The concentration increased till about 0500 JST, then it gradually decreased. Such a variation will be typical for shallow fog.

Fig. 1.3. Variation of concentrations of radiation fog droplets on Sep. 22, 1957.

Symbols in the figure are the same as in Fig. 1.2.

1.4 Observations on September 23, 1957

At Shunkocho fog occurred at about 0404 JST. The concentration of small droplets increased until 0456 JST, then it had nearly constant value (Fig. 1.4). The droplets with

Fig. 1.4. Variation of concentrations of radiation fog droplets on Sep. 23, 1957. Symbols in the figure are the same as in Fig. 1.2.

radii between 25 and 50 microns appeared 20 to 50 minutes after the occurrence of the fog. The droplets of radii larger than 50 microns appeared at the later stage of the fog development. This type of variation is similar to that on September 11. However, as the maximum droplet radius, 54 microns, is smaller than that on September 11, it is supposed that the fog layer is less deep on September 23 than on September 11.

1.5 Observations on January 16 and February 7, 1958

Fig. 1.5 shows two examples of the variation of droplet size distributions of winter fog. Fog occurred at about 2100 JST of

January 16, 1958 and the samplings were made between 2210 and 2250 JST on the 30 m high Hokusei Watch Tower (Fig. 1.1). The fog first appeared at some level above the ground and then descended to the ground. It is interesting to note that despite the air temperature as low as -10°C the large droplet with radius 63 microns was found in the fog. The liquid water contents were between 0.2 and 0.45 g/m^3 . The high concentration of small droplets as many as 300 cm^{-3} was observed.

As fog occurred at about 0500 JST on February 7, 1958 the samplings were made from 0538 to 0639 JST on the roof of the Hokusei Middle School at 20 m above the ground (Fig. 1.1). Many small droplets with radii below 5 microns were also found. It is of interest to note that at about 0603 JST the concentration of smaller droplets rapidly decreased concurrently with the appearance of larger droplets of radii above 15 microns, then the concentration returned to its original value as the large droplets disappeared. However, it is uncertain what happened at that time.

1.6 The influence of air temperature on the structure of fog

Comparing Figs. 1.2 to 1.4 with Fig. 1.5 it is found that when the air temperature is above 5°C very few small droplets with radii below 5 microns are present in the fog. When the air temperature is below -10°C , on the other hand, such small droplets are contained in concentration above 100 cm^{-3} . For the droplets with radii above 10 microns the concentration is usually larger in autumn than in winter-fog.

The relationship between the mean volume radius (M.V.R.) of fog droplets and mean air temperature shown in Fig. 1.6 also indicates more clearly the above results. The data in the figure are obtained in the period from 1952 to 1957 for autumn fogs and from 1958 to 1960 for winter fogs. The gravity settling method gives inaccurate values for the concentration of small droplets of radii below 3 microns (Okita, 1961). Then the mean volume radius, which is unaffected by the inaccuracy of the measurement of small droplet concentration, is used to represent

Fig. 1.8. Relationship between mean air temperature and liquid water content of radiation fog.

seems to be a feature of winter shallow fog.

According to the Radford's diagram (Houghton and Radford, 1938) which relates liquid water content and horizontal visibility, the minimum liquid water content corresponding to the maximum value of visibility, 1,000 m, in fog is 0.02 g/m^3 . Then it is suggested that in winter fog a large number of very fine particles are present and obscure the visibility.

Part 2. The Observations of Size Distribution of Small Droplets in Radiation and Other Fogs

2.1 Introduction

The investigation of small droplets with radius about one micron in cloud and fog is one of the important subjects of cloud physics. Usually the investigators have found very few such small droplets. But according to the Eldridge's indirect measurements of droplet size distribution by means of infrared transmissometer (Eldridge, 1957) small droplets with radii about 0.5 micron are contained in growing stratiform cloud in concentration more than 10,000 per cm^3 . Kumai (1951) found many small particles in the branches of dendritic ice crystals by means of electron-microscope. He further supposed that the particles are the nuclei of minute cloud droplets which are collected by the ice crystals while the latter are growing. Kamiyama and Moriguchi (1952) made the

droplet samplings on the fine methylmethacrylate fibre in sea fog. They found that the number of small droplets of size 0.3–1.2 microns captured on the fibre was about ten times as large as the number of ordinary fog droplets.

As described in Part 1 it is supposed that winter fog, especially "smog", contains such small droplets. Then the investigations of the size distribution of small droplets were done in radiation and other fogs using the water-blue film technique (Okita, 1958).

2.2 Sampling technique

The measurements of the small droplets in fog were made by means of following technique. The hand operated impactor with hole diameter one mm shown in Fig. 2.1 was

Fig. 2.1. Impactor.

used for the collection of the droplets. A thin water-blue dye coated celluloid film with area $1 \times 1 \text{ cm}^2$ was attached to a glass slide and placed under the hole. The fog droplets were collected on the film when fog air was drawn by means of a hand-operated glass syringe. The volume of the syringe was 20 cm^3 . Usually 10 to $1,000 \text{ cm}^3$ of fog air was drawn depending on the density of the fog. The samplings of the droplets were always made in Asahikawa.

It is frequently mentioned that if the air is drawn through a narrow hole, rapid increase of air velocity would result in adiabatic cooling of the air, then condensation would take place in the air stream. Then a brief estimation of the effect of the cooling will be made. Usually 10 cm^3 of fog air is drawn in one second, so that the mean air velocity at the hole of diameter one mm is 12.7 m/sec . If it is assumed that the air is saturated and is cooled adiabatically the supersaturation of 0.006 to 0.008 per cent will be attained if the air temperature is between 0 and -20°C . However, as the time for the air to pass through the hole is only 10^{-3} second or less, even if the nucleation occurs, the time is not

enough for the new droplets to grow to one-micron size droplets. This conclusion is confirmed by the measurements in the fog on October 22, 1959 and on September 29, 1960, when very few droplets of radii between 0.5 to 2 microns were found even when the fog was growing.

The collection efficiency of the impactor was measured by Ranz and Wong (1952), their result being shown in Fig. 2.2. In the

Fig. 2.2. Collection efficiency of impactor according to Ranz and Wong.

figure the collection efficiency is plotted against $\sqrt{\phi} = (C \rho_p v_0 / 18 \mu D_c)^{1/2} D_p$, where C is the empirical correction factor for the resistance of air opposed to the movement of small particles, which is expressed by $C = 1.00 + 0.16 \times 10^{-4} / D_p$.

ρ_p is the density of aerosol particles in g/cm^3 , v_0 the velocity of aerosol jet in cm/sec , D_p the effective diameter of aerosol particle in cm , μ the viscosity of air in poise and D_c is the diameter of round jet in cm . If the fog air of volume 10 cm^3 is drawn through a round hole of diameter one mm in one second the mean air velocity at the hole is 12.7 m/sec . The figure shows that the droplets of radii above 1.4 microns are completely captured. The collection efficiency is about 50 per cent for one micron-radius droplets. Therefore the droplet concentrations shown in the following figures, which are obtained under the assumption that the collection efficiency is unity, give only relative values for the droplets of radii below 2 microns and it is likely that more small droplets are present in the fog.

2.3 Observations on December 10, 1959 (winter fog associated with air pollution)

As fog occurred at about 2200 JST on December 10, 1959 the droplet samplings were made from to 2200 to 2314 JST at Shunkocho (Part 1, Fig. 1.1). The smoke from the chimneys of many houses was mixed with the fog, so that the fog may be called "smog". It is found that large carbon particles of diameters above 10 microns are contained in about half of the stains of large fog droplets with radii above 12.5 microns. These large carbon particles would act as the nuclei of the large droplets.

Fig. 2.3. Droplet size distribution at 2250 JST, Dec. 10, 1959.

One example (2250 JST) of droplet size distributions is shown in Fig. 2.3. In the figure the size distributions obtained by gravity settling method is also shown (Okita, 1961). These two methods give the same concentration for droplets of radii between 3 and 5 microns. For the droplets with radii larger than 5 microns gravity settling method gives larger concentration than by impactor method, which indicates that the collection efficiency of the impactor reduces also for large droplets. The gravity settling method gives inaccurate result for the small droplets of radii less than 3 microns, which is due to the fact that the fall velocity of the small droplets is very small.

The figure indicates that the fog occurred in polluted air contains small droplets of radii below two microns in concentration

above several hundred per cm^3 of air. This type of size distribution continued more than two hours, which reveals that the small droplets were stable in the fog. The air temperature at 2230 JST was -13.7°C .

Findeisen (1932) measured the droplet size distribution of radiation fog occurred in winter at Hamburg by means of photographic method. One of his distributions is shown in Fig. 2.4. His distribution curve has a peak with droplet radius below 2 microns. The result obtained by Liddell and Wootten (1957) in winter fog at Porton shown in Fig. 2.5 also indicates that more than half of the droplets have radii below one micron. Therefore, from these observations it is concluded that the presence of very small droplets with radii one to two microns is one of the characteristics of winter fog, especially of smog.

Fig. 2.4. Droplet size distribution of radiation fog at Hamburg, Jan. 13, 1931.

Fig. 2.5. Droplet size distribution of fog at Porton, Dec. 15, 1540 hr, 1954.

2.4 Observations on December 3, 1959 and on March 13, 1960 (frontal fog)

As a cyclone passed over Hokkaido on

December 3, 1959, steady rain fell at Asahikawa, the three-hour intensity of the rain being 5.2 and 2.5 mm from 1500 to 1800 JST and 1800 to 2100 JST respectively. At about 1730 JST fog occurred in the rain and although Asahikawa was in the center of the cyclone there was little wind. The samplings of fog droplets were made from 1740 to

Fig. 2.6. Droplet size distribution at 1814 JST, Dec. 3, 1959.

Fig. 2.7. Droplet size distribution at 0253 JST, Mar. 13, 1960.

1818 JST at Shunkocho. One of the droplet size distributions is shown in Fig. 2.6. The air temperature at 1800 JST was -1.9°C .

A cyclone also passed over Hokkaido and light rain fell in the midnight of March 12 to 13, 1960, its intensity between 2400 and 0300 JST being 0.3 mm. Thin fog occurred at midnight and there was little wind. The air temperature at 0300 JST was 2.7°C . The samplings of fog droplets were made at about 0300 JST and one of the measured droplet size distributions is shown in Fig. 2.7.

The records of radio-sounding made at Sapporo show the temperature inversions with top at about 140 and 320 m at 2100 JST of December 3, 1959 and of March 12, 1960 respectively. Therefore it may be supposed that the temperature inversion was present also over Asahikawa. The staffs of the Asahikawa Local Meteorological Observatory said that they frequently observed the cold air stagnating in the lowest layer over the Kamikawa Basin. Therefore the fog seems to be of frontal fog type intensified by nocturnal radiation. It is further noticed that the size distributions on these days have the same form. Therefore it may be concluded that the distributions shown in Figs. 2.6 and 2.7 are typical in frontal fog. These distributions also indicate the relatively high concentrations of small droplets.

2.5 Observation on October 22, 1959 and On September 29, 1960 (autumn fog)

Shallow fog occurred at about 0150 JST

on October 22, 1959 at the ground of the Gakugei University (Part 1, Fig. 1.1) but it disappeared at about 0210 JST. After 0223 JST the fog appeared again and developed. The air temperature at 0235 JST was 0.7°C . The samplings of fog droplets were made at 0159 and 0230 JST, their results being shown in Fig. 2.8.

Fog occurred at about 0407 JST on September 29, 1960 at Shunkocho. The thickness of the fog was estimated to be 30 to 40 m as the stars were visible through the fog. One of the droplet size distributions (at 0411 JST) is shown in Fig. 2.9. The air temperature at 0300 JST was 2.8°C .

Fig. 2.9. Droplet size distribution at 0411 JST, Sep. 29, 1960.

It is evident from Figs. 2.8 and 2.9 that the concentration of small droplets in the initial stage of radiation fog in autumn is very small.

2.6 Observations on March 16, 1960 (steam fog)

Steam fogs frequently occur over the Ishikari River in cold winter. From 0615 to 0715 JST on March 16, 1960 the samplings of steam fog droplets were made on the bank near the Asahi Bridge (Part 1, Fig. 1.1). The droplet size distribution (0640 JST) shown in Fig. 2.10 indicates that more than 80 per cent by number of the droplets are of less than 2 micron radius. Therefore it is evident that radiation and steam fog have quite different physical structure. The air temperature during the samplings was about -14.3°C .

Fig. 2.8. Droplet size distributions on Oct. 22, 1959.

Fig. 2.10. Droplet size distribution at 0640 JST, Mar. 16, 1960.

2.7 Observations on January 22, 1959 (ground fog)

In the period of 0834 to 0850 JST a shallow ground fog about 1.5 m thick developed over Hokumoncho and other area (Part 1, Fig. 1.1). Visibility in the fog was between 200 and 300 m. Several samplings were made in the fog. Fig. 2.11 is one of the droplet size dis-

Fig. 2.11. Droplet size distribution at 0840 JST, Jan. 22, 1959.

tribution of the ground fog. The ground fog consisted of the droplets of radii less than 2.5 microns and has the similar structure as steam fog. The air temperature during the observations was about -10.0°C .

2.8 Observations on March 30 and on October 29 in 1959 (fog in dissipating stage)

On March 30, 1959 fog occurred at about 0220 JST but gradually dissipated after 0730

Fig. 2.12. Droplet size distribution at 0748 JST, Mar. 30, 1959.

Fig. 2.13. Droplet size distribution at 0711 JST, Oct. 29, 1959.

JST. The samplings were made from 0745 to 0759 JST. In this case and on October 29 the impactor with the diameter of hole 3 mm was used. During the samplings the visibility was about one km and the air temperature about 3.0°C. Fig. 2.12 shows the droplet size distribution at 0748 JST.

Fog was formed at 0310 JST on October 29, 1959, but it began to dissipate at about 0700 JST. The droplet samplings by means of large hole impactor were made between 0711 and 0732 JST. Fig. 2.13 shows the droplet size distribution at 0711 JST. The mean visibility during the samplings was about 500 m and the air temperature at 0700 JST was 6.6°C.

The distributions shown in Figs. 2.12 and 2.13 have the same form with a peak with radius about 1.5 microns. However, as it is supposed that the collection efficiency of one micron-size droplets by the large hole impactor is considerably small, it is expected that more droplets of this size were present in the fog.

2.9 Observations on March 10, 1960

Fog occurred at about 0100 JST on March 10, 1960. The samplings of fog droplets were made at three different places in the Asahi-kawa City to examine the local difference of the structure of the fog. The places are Shunkocho (residential quarter), city office

(central part of city) and the Asahi Bridge (river side) (see Fig. 1.1). Both the impactor and gravity settling methods were employed.

Three examples of droplet size distributions are shown in Figs. 2.14 (a) to (c) and Table 2.1 lists some properties of the fog. There were rather few small droplets of radii less than 2 microns. Comparing with the size distributions on December 10 shown in Fig. 2.3 it is concluded that numerous small droplets are formed in the polluted air in the evening. However, at midnight and in the early morning, when the chimneys of most of the houses do not emit smoke, the concentration of both the smoke and small droplets gradually decreases. The values of visibility in the table are calculated from the droplet size distributions using the equation

$$V = \frac{3.91}{k_s}, \quad k_s = K_s \pi \Sigma r^2 n \quad (2.1)$$

where V is visibility, k_s scattering coefficient, r droplet radius and n is droplet concentration. The value of K_s is approximately equal to 2 for large fog droplets. The calculated values are approximately in agreement with the the observed visibility.

Table 2.1 shows that there is little difference of the structure of fog at three different places, except that the values of mean volume

Fig. 2.14. Droplet size distributions on Mar. 10, 1960.

Table 2.1 Data of fog on March 10, 1960.

Place	Shunkocho				
Time (JST)	0237	0300	0320	0348	0406
L.W.C. g/m^3	0.087	0.30	0.097	0.27	0.085
M.V.R. μ	10	12	10.5	11	10
Droplet Concentration cm^{-3}	42	69	41	65	44
Visibility m	300	99	270	100	280
Max. Droplet Radius μ	27	27	27	25	36
Min. Droplet Radius μ	1	1	1.7	—	2
S.D.C. cm^{-3} $r < 2\mu$	5.7	0.6	1.7	—	0

Place	City Office			Asahi Bridge	
Time (JST)	0502	0516	0526	0602	0612
L.W.C. g/m^3	0.14	0.14	0.13	0.19	0.16
M.V.R. μ	10	9	11	13.5	13
Droplet Concentration cm^{-3}	51	65	65	38	31
Visibility m	170	160	180	240	200
Max. Droplet Radius μ	23	18	28	32	27
Min. Droplet Radius μ	2	2	1.2	1.5	3
S.D.C. cm^{-3} $r < 2\mu$	0	0	2.8	1.3	0

L.W.C.: Liquid Water Content, M.V.R.: Mean Volume Radius,
S.D.C.: Small Droplet Concentration

radius are larger at the Asahi Bridge than at the other two places. It indicates that even in winter fog the local difference of the structure of fog is very small if the fog is well developed. At the Asahi Bridge the samplings were made at about seven meters above river surface. It is frequently mentioned that river has large influence on the formation of fog. But our observations indicate that the influence, even if it exists, is small in well developed radiation fog.

2.10 Summary

The measurements by means of a hand operated impactor and water-blue dye coated film reveal that many small droplets of radii less than 2 microns are frequently present in winter fog especially in "smog". The concentration of the small droplets formed in the evening in polluted air gradually decreases, then very few such small droplets are found in the early morning of the following day. It is further found that the local difference of fog structure and the effect of river steam are small in well developed radiation fog.

References

- Eldridge, R.G. (1957): Measurements of cloud drop-size distribution. *Journ. Met.*, **14**, 55-59.
- Findeisen, W. (1932): Messungen der Grösse und Anzahl der Nebeltropfen zum Studium der Koagulation inhomogenen Nebels. *Beitr. Geo-phys.*, **35**, 295.
- Houghton, H.G. and W.H. Radford (1938): On the Measurement of Drop Size and Liquid Water Content in Fogs and Clouds. *Papers Phys. Ocean. Met.*, **6**, No. 4.
- Kamiyama, K. and M. Moriguchi (1952): The Collection of Fog Droplets upon Fine Fibre and Absorption of Infra-Red Ray by Fog Droplets. *Journ. Met., Res.*, **4**, Suppl., 43-53 (in Japanese).
- Kumai, M. (1951): Electron microscope study of snow-crystal nuclei. *Journ. Met.*, **8**, 151-156.
- Liddell, H.F. and N.W. Wootten (1957): The detection and measurement of water droplets. *Quart. Journ. Roy. Met. Soc.*, **83**, 263.
- Okita, T. (1958): Water-blue film method for measurement of cloud and fog droplets. *Journ. Met. Soc. Japan*, **36**, 164-165.
- Okita, T. (1961): Size distribution of large droplets in precipitating clouds. To be published in *Tellus*.

Ranz, W.E. and J.B. Wong (1952): Jet impactors
for determining the particle-size distributions

of aerosols. Arch. Ind. Hyg. Occup. Med., 5,
464.

霧の物理的構造について

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旭川でウオーターブルーフィルム法を用いて霧粒の調査を行なった。気温が 0°C 以上の時には mean volume radius は $12.5\sim 15\mu$ であるが、気温が -5°C 以下になると mean volume radius は約 7.5μ となる。また冬霧の場合には霧水量は $10^{-4}\sim 10^{-2}\text{ g/m}^3$ でも霧の状態のことがしばしばみられる。このような場合には微粒子が多数存在することが考えられる。

一方インパクトターを用いて霧の中の小滴を観測した。その結果 smog と呼ばれるような冬の霧や蒸気霧中には半径 2μ 以下の小滴が多く存在することがわかった。またよく発達した放射霧中では川の蒸気の影響があまり大きくないこともわかった。