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Title	A Further Study on the Internal Structure of Graupel
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Citation	Journal of the Faculty of Science, Hokkaido University. Series 7, Geophysics, 7(3), 227-238
Issue Date	1983-02-10
Doc URL	http://hdl.handle.net/2115/8737
Type	bulletin (article)
File Information	7(3)_p227-238.pdf

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Jour. Fac. Sci., Hokkaido Univ., Ser. VII (Geophysics), Vol. 7, No. 3, 227–238, 1983.

A Further Study on the Internal Structure of Graupel

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(Received October 12, 1982)

Abstract

Studies were made by the thin section method in order to ascertain the contributing factors to the internal structure of graupel particles. The thin sections of graupel particles were classified into three types of internal structures, that is porous ice with small crystals, porous ice with large crystals and compact ice with large crystals. It was found that the three types of internal structures were related to the vertical distribution of temperature in cloud. In order to verify the observational results, they were compared with the contributing factors to the ice structure of accreted ice formed in a similar process as the growth of graupel particles. The result was that the contributing factors to the appearance and crystal size of graupel particles coincided fairly with those of accreted ice, respectively. Therefore the temperature conditions which classified the internal structure of graupel particles is considered to be all right in a sense.

1. Introduction

It is considered that the internal structures of graupel particles reflect the meteorological conditions in the cloud in which graupel particles grew. For example, they are such conditions as environmental temperature, the impact velocity of cloud droplets, liquid water content, the size distribution of cloud droplets and so on. By a simultaneous study of the internal structures of graupel particles and meteorological conditions in the cloud, contributing factors to the internal structure can be found. Previously, contributing factors to the appearance, crystal size, crystallographic orientation, bubble size and bubble concentration of the accreted ice have been clarified by accretion experiments (e.g. Macklin, 1962; Brownscombe and Hallett, 1967). Accordingly, the observational results regarding the contributing factors to the internal structure of graupel particles can be verified by the results of these accretion experiments.

The classification and contributing factors of internal structure regarding graupel particles which grew under the colder climate such as Sapporo (43°03′N, 141°20′E) were studied in a previous paper (Harimaya, 1977). As the result, it was shown that the size of the component with the same crystallographic orientation (hereinafter crystal) was as small as about 100 μm under temperature condition below −5°C at the ground and crystal was as large as about several mm under temperature condition above −5°C. In these cases, the condition of temperature was limited to +2°C. In order to study the classification and contributing factors of internal structure regarding graupel particles which grew in the warmer cloud, similar observation was carried out at Wajima (37°23′N, 136°54′E) where the climate is warmer. In this paper, the results will be described and the contributing factors also will be considered regarding the internal structure of all graupel particles observed by this time.

2. Observational results

In the present study, many thin sections of graupel particles were made and they were observed under a polarization microscope in the same manner as carried out by Harimaya (1976). The graupel particles which fell simultaneously were composed of the same internal structure, thus the internal structure could be related to the meteorological conditions in the cloud in which graupel particles grew. At first, the thin sections of graupel particles were classified with special attention to the characteristics of internal structure such as appearance and crystal size. The reference to porous ice here is of a ice which has numerous vacancy. In contrast, compact ice has no vacancy. On the other hand, the reference to large crystals here actually is of a crystal size of several mm and small crystals are about 100 μm. Combining the appearance with the crystal size, the internal structures are classified into four types of characteristics and all types of internal structures were observed in the present study. The thin sections of porous ice with small crystals and porous ice with large crystals are shown in Figs. 1 and 2, respectively. It is seen that the both thin sections have numerous vacancy in appearance and a considerable difference in crystal size. On the other hand, the thin sections of compact ice with small crystals and compact ice with large crystals are shown in Figs. 3 and 4, respectively. Both are different in crystal size, but they are full of ice in appearance as compared with porous ice shown in Figs. 1 and 2.

When the graupel particles composed of compact ice were collected at the

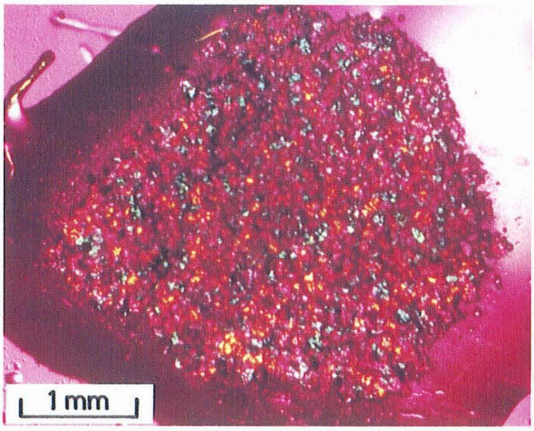

Fig. 1 Thin section of a graupel particle composed of porous ice with small crystals.

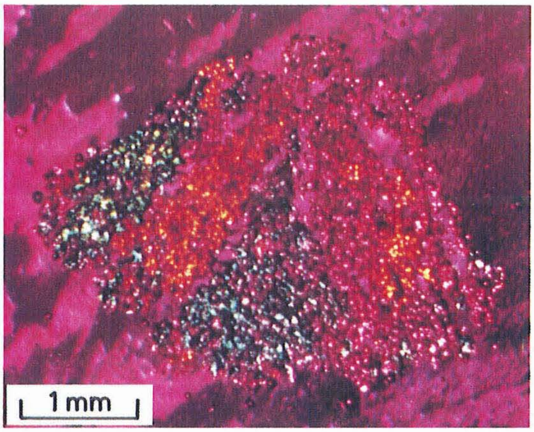

Fig. 2 As in Fig. 1 except for porous ice with large crystals.

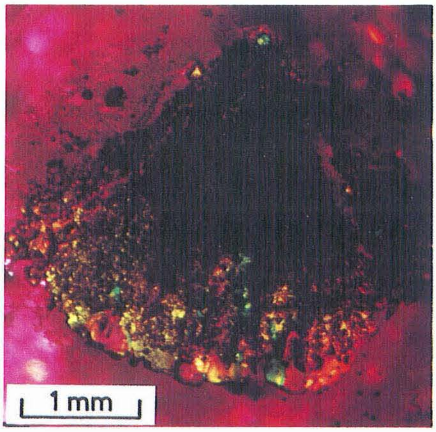

Fig. 3 As in Fig. 1 except for compact ice with small crystals.

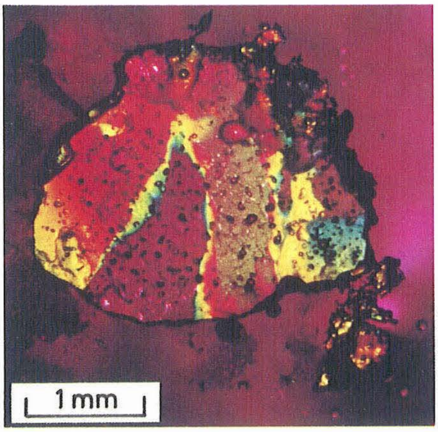

Fig. 4 As in Fig. 1 except for compact ice with large crystals.

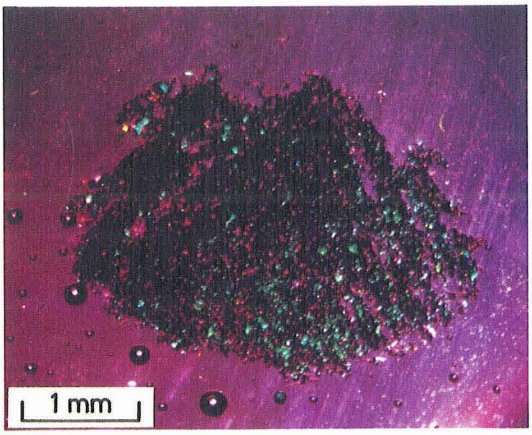

Fig. 5 As in Fig. 1 except for porous ice with large crystals.

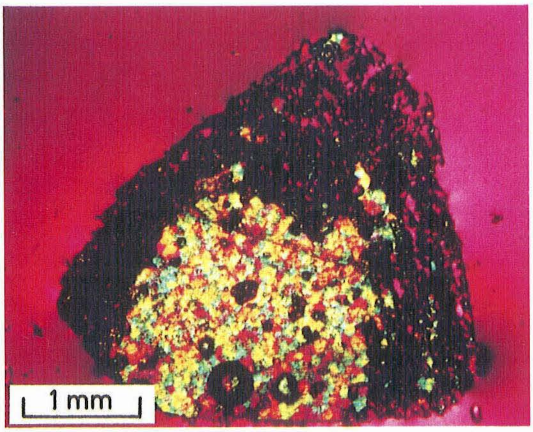

Fig. 6 As in Fig. 1 except for compact ice with small crystals.

ground, their surfaces were melting and wet. If the graupel particles contain liquid water, they were recrystalized in the process of making thin sections in which the graupel particles are refrigerated below 0°C. Such recrystalized ice is of necessity distinguished from the original ice of graupel particles in the classification of internal structure. Therefore the recrystalized ice was checked as follows. Graupel particles which fell simultaneously were collected at the ground. Ten of them were used to make thin sections and the others were left for the next experiment. It was shown that all of them were composed of porous ice with large crystals. An example of the thin section is shown in Fig. 5. It is seen that the thin section is composed of porous ice with large crystals, because it has numerous vacancy in appearance and has the size of itself in crystal size. The thin section in Fig. 6 was made by the ordinary method in a cold room after the graupel particles collected previously were exposed to warmer environment with temperatures of 20°C for the short time and were melted somewhat. It is seen in Fig. 6 that the halves of the components changed to the compact ice with small crystals after the graupel particles were melted slightly and refrigerated again. When other graupel particles were exposed to warmer environment for a longer time, all of the components changed to compact ice with small crystals. The result was that the porous ice changed to compact ice in appearance and the crystal size always became small in the process of making thin sections in which the graupel particles were refrigerated below 0°C if they contain liquid water. Therefore, the compact ice with large crystals is the original ice of graupel particles, but whether it is original ice or recrystalized ice can not be distinguished with regard to the compact ice with small crystals. In the following analysis, the compact ice with small crystals was excluded from discussion regarding ice structure.

Next, the relation between the internal structure and environmental temperature was studied. Fig. 7 shows the vertical distributions of temperature below the cloud top at the time when graupel particles were observed. The height of cloud tops was determined from the vertical distributions of temperature and humidity. The broken lines show the vertical distributions of temperature at the time when graupel particles composed of porous ice with small crystals fell, the solid lines indicate porous ice with large crystals and the dotted line indicates porous ice with medium crystal, respectively. On the other hand chain lines indicate compact ice with large crystals. It is seen in Fig. 7 that the characteristics of the internal structure were clearly classified by the vertical distribution of temperature in the clouds. That is to say, as the temperature in cloud changes from a cold region to a warm region, the internal structures of graupel particles changes from porous ice with small crystals to porous ice with large crystals and compact ice with large crystals in that order.

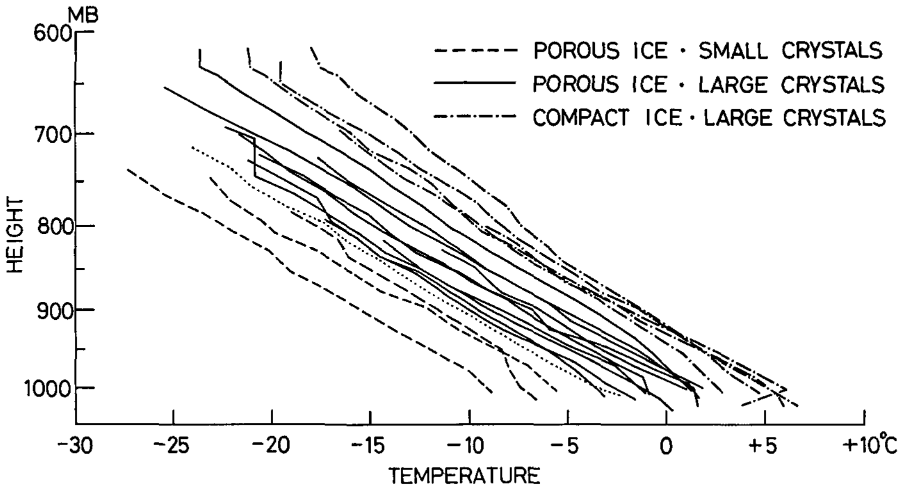

Fig. 7 Relation between characteristics of internal structure of graupel particles and vertical distributions of temperature below cloud tops.

3. Consideration

In a previous section, the characteristics of internal structure were clearly classified by the vertical distribution of the temperature in the clouds. Compared with the contributing factors to the ice structure of accreted ice, the observational result can be verified. The result by Macklin (1962) was adopted as the appearance of accreted ice and the result by Brownscombe and Hallett (1967) as the crystal size.

In their diagrams, the surface temperature was adopted as one of the contributing factors to the ice structure, therefore the surface temperature of growing graupel particles was required in the comparison with the ice structure of accreted ice. The surface temperature was calculated as follows, using the same equations as adopted in the calculation of graupel growth by Harimaya (1981). In the cloud, the growth rate of a graupel particle in given by

$$\frac{dM_r}{dt} = \pi a^2 EL(V-v) , \tag{1}$$

where,

M_r: mass which the graupel particle gains through accretion of cloud droplets,

a : major semi-axis of a graupel particle,

E : collection efficiency of cloud droplets by a graupel particle,

L : liquid water content of cloud droplets,

V : terminal falling velocity of a graupel particle,

v : terminal falling velocity of accreted cloud droplets.

During the growth of the graupel particle, the release of latent heat by freezing of the accreted droplets causes the surface temperature of the graupel particle to rise above that of its environment. When the latent heat is dispersed by sublimation (evaporation), conduction and forced convection from such a ventilated graupel particle, we have

$$\{L_c+c_w(T-T_m)+c_i(T_m-T_s)\}\frac{dM_r}{dt}$$
$$=4\pi CDF(\rho_s-\rho)L_s+4\pi CKF(T_s-T)\,, \qquad (2)$$

where,

L_c : latent heat of freezing,

c_w : specific heat of water,

c_i : specific heat of ice,

T : ambient temperature,

T_m: melting temperature of ice,

T_s : surface temperature of a graupel particle,

C : electrostatic capacity of a graupel particle,

D : coefficient of diffusion of water vapor in air,

F : ventilation factor of a graupel particle during fall,

ρ_s : saturation vapor density over ice at the surface of a graupel particle,

ρ : ambient vapor density,

L_s : latent heat of sublimation,

K : thermal conductivity of air.

Based on the equations (1) and (2), the surface temperature (T_s) of a graupel particle is obtained from the meteorological conditions in the cloud and the size of a graupel particle.

Numerical calculations were performed by using equations (1) and (2) as follows. In this calculation, the cloud was assumed to be always saturated with respect to liquid water. The meteorological conditions in the cloud were assumed to be constant with time. In order to express graupel particles as a single shape, their shape was treated as a sphere. The falling velocity of graupel particles was obtained from the result measured by Kajikawa (1975). The values of spheres obtained by Langmuir (1948) was used as collection efficiencies. The empirical results obtained by Kinzer and Gunn (1951) were adopted as the ventilation factor. Since the position where the graupel particles grew could not be determined exactly, it was assumed that the growth layers of graupel particles were in the lower halves of cloud layers. The value of 1 g/m^3 was adopted as the liquid water content in the cloud, which is a typical value in the snow cloud during winter. The size distribution with five grades based on the observational result (Sasyo et al., 1967) was used as the size distribution of cloud droplets in the cloud.

At first, the contributing factors to the appearance were studied. In Fig. 8, the results of the present study are superimposed on the diagram

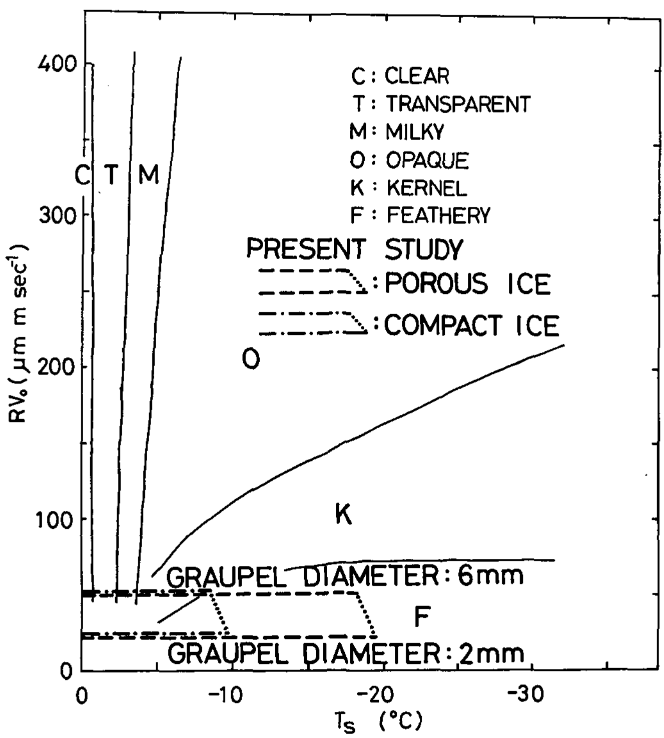

Fig. 8 The dependence of the appearance regarding graupel particles on the parameter RV_0 and the surface temperature superimposed on the diagram regarding accreted ice by Macklin (1962).

regarding the contributing factors to the appearance of accreted ice measured by Macklin (1962). The abscissa and ordinate show the surface temperature and the product of impact speed and droplet radius, respectively. The marks of C, T, M, O, K and F indicate six kinds of appearance such as clear, transparent and milky ice, and opaque, kernel and feathery rime. That is to say, they are clear ice, with virtually no air entrapped; transparent ice, with moderate amounts of air entrapped in fairly large bubbles; milky ice, with considerable amounts of air enclosed as small bubbles; opaque rime, dull and white, which crumbled rather than cracked; kernel rime, similar in appearance to kernels of corn on a cob, and feathery rime, a deposit similar to kernel rime but of a more open and fragile structure. Based on the surface temperature and the product of impact speed and droplet radius regarding graupel particles with 2～6 mm in diameter observed in present study, porous ice and compact ice are shown as the regions surrounded with broken lines and chain lines, respectively. As it is considered that porous ice corresponds to kernel and feathery ice, and compact ice corresponds to clear, transparent, milky and opaque ice, it is seen from Fig. 8 that the contributing factors to the appearance of graupel particles coincided fairly well with that of accreted ice. Therefore the temperature condition which distinguished porous ice from compact ice in Fig. 7 is considered to be all right in a sense.

Next, the contributing factors to the crystal size were studied. In Fig. 9, the results of the present study are superimposed on the diagram regarding the contributing factors to the crystal size of accreted ice measured by Brownscombe and Hallett (1967). The ordinate and abscissa show the air temperature and surface temperature which is replaced with the liquid fraction of spongy ice under the condition above 0°C, respectively. Thin broken lines show the boundary between the small crystals and large crystals of accreted ice, which is displaced to lower temperatures for small droplets. Based on the air temperature and surface temperature of graupel particles with 2～6 mm in diameter observed in present study, small crystals and large crystals are shown as the regions surrounded with thick broken lines and thick solid lines, respectively. It is seen from Fig. 9 that the contributing factors to the large crystals of graupel particles coincided perfectly with that of accreted ice, but the contributing factors to the small crystals of graupel particles did not coincide in part with that of accreted ice. As a whole, the contributing factors to the crystal size of graupel particles coincided fairly well with that of accreted ice. Therefore the temperature condition which distinguished small crystals from large crystals in Fig. 7 is considered to be all right in a sense.

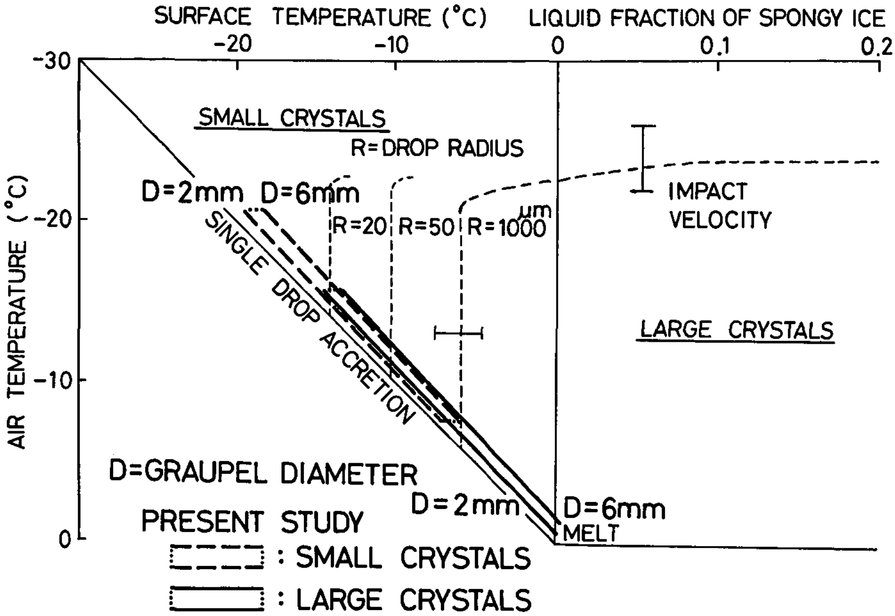

Fig. 9 The dependence of the crystal size regarding graupel particles on the air temperature and surface temperature superimposed on the diagram regarding accreted ice by Brownscombe and Hallett (1967).

The reason why the contributing factors regarding graupel particles did not coincide in part with that regarding accreted ice is considered to be due to the assumption in which the growth layers of graupel particles were in the lower halves of cloud layers. If the position where the graupel particles grew can be determined exactly, it is considered that the contributing factors regarding graupel particles will coincide perfectly with that regarding accreted ice.

4. Conclusion

Many thin sections of graupel particles were made in order to study the contributing factors to the internal structure of graupel particles. At first, the thin sections of graupel particles were classified with special attention to the characteristics of internal structure. The results were that the thin sections were classified into three types of internal structures such as porous ice with small crystals, porous ice with large crystals and compact ice with large crystals. Next, the relation between the internal structure and environmental temperature was studied. The three types of internal structures were clearly classified by the vertical distribution of temperature in the clouds.

In order to verify the observational results, they were compared with the contributing factors to the ice structure of accreted ice formed in a similar process as the growth of graupel particles. In the diagrams by accretion experiments, the surface temperature was adopted as one of the contributing factors to the ice structure, therefore that of growing graupel particles had to be obtained by calculation. In the comparison, the contributing factors to the appearance and crystal size of graupel particles coincided fairly well with those of accreted ice, respectively. Therefore the temperature condition which classified the characteristics of the internal structure is considered to be all right in a sense. But, the contributing factors to the internal structure of graupel particles did not coincide in part with those of accreted ice. The reason is considered to be due to the assumption in which the growth layers of graupel particles were in the lower halves of cloud layers. If the position where the graupel particles grew can be determined exactly, it is considered that the contributing factors to the internal structures of graupel particles will coincide perfectly with those of accreted ice.

Acknowledgements

The author wishes to express his hearty thanks to staff members of Wajima Meteorological Observatory for offering conveniences to his observation. The expense of this work was defrayed by a Fund for Scientific Research from the Ministry of Education, Science and Culture of Japan.

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