Observation of the Electric Potential Gradient at the Surface in Winter Fogs (Electrical Properties of Winter Fog: Part I)

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Abstract

In winter fogs, when the polluted air or liquid fog came over, the potential gradient increased positively to several times of normal value. This increase in the potential gradient was explained by the decrease of the air conductivity.

Accompanying with the glaciation of those liquid fogs, the positively enhanced potential gradient decreased to the normal values or even negative values.

About the decrease due to the glaciation following mechanisms are considered. Ice crystals carried preferentially the negative charge. The conductivity of the air increased by the removing submicron aerosols due to the growth of ice crystals (Facy effect).

At times, it was observed that when the snowfall stopped, the potential gradient abruptly increased to positive high values. About the mechanism, it was considered that the residual positive space charge was gravitationally separated from the negative snow crystals, then the positive space charge was brought down to the surface by downdraft between snow clouds.

1. Introduction

Ice phase precipitation plays important roles in thunderstorm activities. Phillips (1967) considered that the appearance of ice phase might trigger the electrification of the precipitation elements.

In order to study of electrical phenomena accompanying the glaciation of supercooled cloud droplets, the authors carried out some observation of the atmospheric electrical property accompanying the glaciated fog in the severe cold season, because it is considered that the glaciated fog corresponds to the condition at the top of thunderclouds, and the continuous observation of fog on the ground is easier than in the cloud.

The electrical properties of fog have been studied by many workers as reviewed by Dolezalek (1963). However, almost all of those studies were concerned about fog in a liquid phase, except that by Ohtake (1970), because the study of the electric properties of fog containing the ice phase was difficult. Phillips (1967) studied the air conductivity in foggy air in a big tank. He found that the conductivity increased due to

the glaciation of fog particles.

The authors carried out the measurement of the surface electric potential gradient, the vertical distribution of the potential gradient, the point discharge current and antenna-earth current, both in supercooled and frozen fogs. The present paper, Part I, mainly describes the results of the observation of the atmospheric potential gradient at the surface.

2. Observation site and methods

At Asahikawa City, which is located at the center of Hokkaido island, northern Japan, as shown in Fig. 1 (a), it is often seen that supercooled fog droplets change to ice crystals on a calm and cloudless night in winter.

The observation was carried out in the period from 28 January to 23 February 1968, on an open flood sole (ordinarily dried portion) of the Ishikari River, into which warm waste water comes from a paper mill, as shown in Fig. 1 (b) and (c).

On calm and cloudless nights during the observation period, the air temperature decreased to about -30°C due to the radiation cooling.

Fig. 1. Observation site

Fig. 2. (a) System of measuring for surface electric potential gradient, (b) details of the insulator system.

However, the river remained unfrozen because of the hot waste water from the big paper mill upstream. Therefore dense steam fog was formed over the stream. With the descent of air temperature from about -15°C , the supercooled fog droplets were often glaciated to ice crystals like "diamond dusts".

The observation site was set at the center of the spacious flood sole covered with fallen snow, to avoid the effect of the point discharge from trees and buildings. In Fig. 1 (c), two $\times$ marks and a square mark indicate the location of two masts for measuring the electric potential and the observation hut, respectively, as shown in Fig. 2 (a). Those observation points were at least 200 m away from both banks. During the observation period, westerly or southern wind was predominant at the ground surface of the flood sole as shown by the wind rose at the bottom of Fig. 1 (c). The west and northwest wind brought steam fog from the stream, and sometimes south or southeast wind brought polluted air mass from the downtown of the city.

An electrometer of Benndorf type was used for the measurement of electric potential. A collector with Po 210 equalizer was set on the center of a wire horizontally stretched at a height of 6 m above the snow surface. The wire was electrically isolated from the masts and connected to the electrometer in the observation hut, as shown in Fig. 2 (a). The electric insula-

tors were specially devised with drying agent of silicagel, as shown in Fig. 2. (b). In order to avoid leakage, after the passing of dense fog, the insulators were exchanged for new ones. The fog conditions were observed with the beam of a handy searchlight: namely, whether fog was present or not, the phase of fog was frozen or not, fog concentration was roughly high or low, and also the direction of the wind.

3. Results

Since Asahikawa City is located at the center of a basin, it is almost always windless in the city. On such a calm night, radiation fog and steam fog were often formed above the warm surface of the river.

The conditions of a typical foggy night are as follows. It was required for the fog to appear that the air temperature should be lower than -10°C by the time of sunset. At around 1800 JST, the air temperature decreased suddenly to -20°C and a soft breeze ($1.0\sim 2.0\text{m/s}$) produced a dense fog over the surface of the warm water. At this time, the steam fog was diffused and soon disappeared above the water surface. As the air temperature fell farther down beyond -20°C , the fog moved horizontally and was gradually accumulated on the flood sole surrounded by the banks with a height of about 5m. This seems to be due to the fact that the surface inversion progressed with time. At this stage, the fog began to be glaciated partially.

Fig. 3. Comparison of change of electric potential with air temperature immediately before fog.

Sakurai (1969) reported about the fog in Asahi-kawa that the concentration of ice crystals became higher than that of supercooled fog droplets as time elapsed, only ice crystals being observed at sunrise, and after that all of them fell out so that the visibilities became better.

Remarkable phenomena were picked out from the data on the surface potential gradient, and are shown in Fig. 3 to Fig. 8. In these figures, the potential gradient is compared with changes in air temperature and status of the fog.

3.1. Positive peak of the potential gradient accompanying the polluted air

In Fig. 3, the change of the potential gradient was compared with that of the air temperature, although in this case fog was not observed just after the time of sunset. In this figure, it is noted that each quick drop in air temperature

Fig. 4. Comparison of change of electric potential with the air temperature at foggy time.

Fig. 5 Time change of potential gradient at foggy time, and accompanying meteorological conditions. Schematic symbols are explained in the text. (15-16 Feb. 1968)

shown by A, B, ..., K correlates to the peak of the potential gradient lifting indicated by A', B', ..., K' respectively, and the values of these peaks are two or three times larger than those in fair weather, as shown by a horizontal broken line in the figure.

Similarly, Fig. 4 shows the changes during the foggy time. It is also noted that the drops in air temperature shown by A, B and C in the upper half of the figure correspond to the peaks of the potential gradient lifting A', B' and C' in the lower half.

In addition to the change of the potential gradient and air temperature, the behavior of fog and the wind direction are shown schematically in the lower half of Fig. 5, where the black dots and white triangles mean the presence of the liquid phase fog and the ice crystal fog respectively, and the number of these marks represents the grade of the concentration of fog particles. The hatched area at the bottom of the figure shows the change of the depth of the fog layers. The values greater than +500 V/m were scaled out in the record of the electrometer.

It is seen in the figure that in the period from 00^h 08^m to 00^h 50^m the potential gradient rose above +500 V/m. It is noted that the air temperature was dropping in the period. Because the southern wind was prevalent during the period, as shown in the wind direction at the center of the figure, it is considered that the dropping of air temperature was due to the advection of the cold air to the observation point from downtown. As seen in Fig. 1, the observation point was immediately south of the warm stream, and the air then was heated by the warm water. This view is supported from the change in thickness of the fog layer around 0015; namely a heavier cold air parcel came under the fog layer and lifted up its base by a height of 15 m.

3.2. Changes of the potential gradient accompanying winter fogs

There were three remarked phenomena in the surface potential gradient accompanying winter fogs.

3.2.1. Enhancement of the positive potential gradient by liquid phase fog

As pointed out by many workers, it was

Fig. 6. Time change of the potential gradient with fog. (14 Feb. 1968)

observed that the potential gradient was lifted up to positive values higher than normal when a liquid fog was coming.

In Fig. 6, the authors note the peaks of the potential gradient at 2240 and 2330. The wind direction was north or northwest at those times. Therefore the fog came from the hot water surface, situated to the north, and the air temperature rose by 0.4~0.5°C in each case. The concentration of the liquid phase fog increased, while ice crystals were hardly seen. Accordingly it was considered that the sharp rise in the potential gradient was caused by the fog in liquid phase, which came directly from the warm water surface to the observation point.

3.2.2. Recovery from the enhanced positive potential gradient to normal values with the glaciation of the liquid phase fog

It was noted that the enhanced positive

Fig. 7. Time change of the potential gradient with fog. The marks in the fog layer at the bottom show that the fog was perfectly glaciated or perfectly in liquid phase respectively. (17 Feb. 1968)

potential gradient which was mentioned above decreased to the normal values ($+100\text{V/m}$) when the liquid phase fog transformed into an ice phase fog. For example in the glaciation at 2250 and 0000 in Fig. 6, it is noted that each high positive potential gradient which was enhanced by the liquid fog rapidly decreased and became the normal value ($+100\text{V/m}$). It is seen also in Fig. 5 that, in the case of the glaciation at 2345 and 0230, the potential gradient decreased from the value higher than $+500$ to $+100 \sim +300\text{V/m}$.

In Fig. 7, similar phenomena are seen. There was only a liquid phase fog until 0100, and the potential gradient was two or three times larger than the normal values. When the air temperature began to decrease fast at the rate of 4°C per hour, *i.e.*, at 0110, glaciation began, and it was completed by 0200. Corresponding to the glaciation, the potential gradient began to decrease gradually to normal values ($+100\text{V/m}$),

Fig. 8. Time change of the potential gradient with fog. (16 Feb. 1968)

in spite of the polluted air coming from the south. However, in this series, the potential gradient increased up to $+370\text{V/m}$ temporarily at 0220. This temporary increase may be due to two effects. One is the effect of polluted air from downtown. Another is that of the liquid fog.

At 0235, the liquid phase fog had disappeared and the potential gradient decreased to $+270\text{V/m}$. But the liquid fog appeared again at 0300, then the potential gradient began to increase.

3.2.3. Abnormal drops of the potential gradient accompanying the glaciation of fog in liquid phase

Accompanying the glaciation from supercooled to ice fog, it was found that positive potential gradient enhanced by the liquid fog was not only restored to the normal values, but also dropped to zero or even negative values. For example, it is noted in Fig. 7 that the positive potential gradient dropped beyond the normal values and crossed the zero line at 0150. At that time, almost all the liquid phase fog which already existed changed into ice fog, and the air temperature increased considerably, and the top of the glaciated fog layer rose. At the surface, the concentration of ice fog was relatively low at the time, then increased gradually with the falling of the ice crystals. The average air

Fig. 9. Time change of the potential gradient with snowfall. (14 Feb. 1968)
Symbols are described in the text.

temperature was about -23°C for the duration of this glaciation.

In the case of Fig. 8, the liquid fog and ice fog alternately came to the observation point. When the ice fog came, the potential gradient dropped, arriving at zero or even negative values. At those times the air temperature was about -18°C .

3.3. Change of the surface electric potential gradient in snowfall on a calm night

Fig. 9 shows an example of the time change of the potential gradient when snowfall occurred in the presence of a fog on a calm night. The fog was considerably glaciated at -15°C until 2400 on 13th, when the observation site was suddenly covered by a snow cloud with its base 100 to 300 m above the ground surface. The air temperature began to increase after 0130 as shown in the upper part of the figure and snow crystals began to appear within the ice fog.

It was a full-moon night. The white circles in the middle of Fig. 9 indicate that the full moon could be seen clearly, and those crossed with three horizontal lines, that the moon was dimly

seen through thin clouds. In the period without any of those symbols no moon could be seen due to an overcast of thick clouds. By the use of the moon and visual observation, cloud thickness was roughly measured. The result of measurement is schematically shown by two curves at the bottom of the figure. The asterisks indicate the fall of single dendritic snow crystals and those with smaller ones the fall of snowflakes. The number of the symbols in a column shows the grade of concentration of the falling snow crystals.

It is seen in the figure that the positive potential gradient decreased in the period from 0100 to 0150, as the cloud became thick compared with the time earlier than 0100, and the potential gradient even took negative values at 0130.

It is also seen that two peaks of cloud thickness correspond to two minima in the change of the potential gradient at 0105 and 0135. After 0135, the snowflakes which fell from those clouds arrived at the ground, while the potential gradient increased slowly to positive values, and remained at values two or three times the normal one during the continuous snowfall. The

air temperature remained steady at -13.5°C , because the observation site was covered by the snow cloud. There was hardly a fog to be seen above the water surface of the river, but ice crystals were observed in considerable numbers. The snowfall steadily continued up to 0340, when it stopped and a full moon came out. It is noted that the cloudless period A'-B' corresponds to the abnormally enhanced positive potential gradient A-B and that the cloudless moments C' and D' at 0450 and 0500 respectively correspond to the sharp peaks C and D in the potential gradient change.

The diameters of the snow crystals which fell in the present case were 3 to 4 mm and the crystals were mostly dendritic crystals without riming and partially contained stellar type crystals with diameters of about 1 mm. Ice crystals of the hexagonal plate type with a size of several hundred microns were always seen in the nearly same concentration as that of the ordinary ice fog. There were few chances at which the electric charge of the falling snow crystals could be measured by means of the Farady cage with the vibrating reed type electrometer. The sign of the electric charge on the snow crystals were all negative. It was windless at the surface but the cloud above moved considerably fast with the wind aloft during the period.

4. Considerations

The important results of our observation about winter fogs are the following three: the sharp peaks in the positive potential gradient with a rapid drop in air temperature, the increase in the potential gradient with the occurrence of liquid fog, and the decrease with the occurrence of ice fog. The following discussions are offered about these results and the field pattern during snowfall.

4.1. Sharp peaks of the positive potential gradient

a: Due to increase in humidity

Although no visible fog appeared yet in the case of Fig. 3, the relative humidities were thought so high as near the saturation values, because the air temperature was falling lower and lower. Misaki *et al.* (1969) pointed out that the atmospheric conductivity was decreased 30 or 60 minutes before the visible fog appeared. They explained these phenomena as follows. It

may be considered that when many invisible small particles (submicron particles) were formed in such high humidity conditions, small ions were lost through diffusing over the surface of such particles, and then only larger ions remained. Therefore the ion spectrum shifted up from the small ion ranges to the larger ones. It results in decreasing the densities of small ions and the atmospheric conductivity, and then increasing the potential gradient in turn.

b: Due to the polluted air

It is considered that the rapid drops of air temperature were due to the advection of a cold air parcel, because the air on the flood sole near the hot water was warmer than that near by. In case of Fig. 5, the cold air parcel was brought by a southerly wind. Because the air was cleaner on the flood sole than elsewhere, the advection of the cold air means the advection of polluted air from downtown. The increase of the potential gradient due to the polluted air was pointed out by Magono and Orikasa (1960). The authors will consider why the potential gradient was raised by the polluted air.

Two factors are involved in the mechanism of the positive peak due to polluted air. First, since the conductivity of polluted air is low, in other words, the columnar resistance near the surface in polluted air is large, then the potential gradient is enhanced if the air-earth current is constant. Secondly, it is considered that an urban air parcel carries the positive space charge as found by Mühleisen (1958), and therefore the positive space charge makes the positive potential gradient increase.

4.2. Increase in the potential gradient accompanying by a liquid fog

It has been reported by many workers (see Dolezalek, 1963) that the liquid phase fog enhance the potential gradient positively. To explain this process, the results by Misaki (1970) and Ohtagaki, Kanazawa and Misaki (1969) are useful. They assert that small ions are lost through diffusing over the surface of not only fog particles but also smaller invisible particles which were formed under a high relative humidity. It is considered that the potential gradient would be enhanced due to the decrease in the air conductivity in the fog.

4.2. Decrease in the potential gradient accompanying glaciation of fog

a: Recovery to the normal positive value

It is well known that when fog is glaciated the visibility is considerably improved. This may be because many fog particles change into a small number of large ice crystals. As calculated by Phillips (1967), increase in the size of the particles strikingly decreases the total surface of particles over which small ions diffuse in the presence of an extraneous electric field under the conservation of water content. Therefore the concentration of small ions is high in glaciated fog, and the potential gradient will return to the normal values, even if the potential gradient was enhanced in a liquid fog.

Recently Sakurai (1969) reported that the water content in foggy air was mostly conserved under the phase change from liquid to ice at Asahikawa City. According to his result in a typical case, the supercooled fog droplets with an average diameter of $5\text{ }\mu\text{m}$ of concentration with 100 per cm^3 transformed into ice particles with an equivalent diameter of about $50\text{ }\mu\text{m}$ of concentration 0.1 per cm^3 , and the conservation of water content was maintained.

Based on these data, it is considered that the total surface of the fog particles is reduced to 10% due to the glaciation. Since ice crystals fall more easily under gravitational force than fog droplets, the mass of fog particles is reduced. Then because of the decreasing of the total surface of the fog particles for the above-mentioned reasons, the numbers of small ions increase so that the potential gradient recover the normal values.

As said by Misaki *et al.* (1969), not only the fog droplets but also the submicron aerosol particles are considered to play a role in decreasing air conductivity by capturing small ions, and their effect may be greater than that of the fog particles.

Consequently, it is considered that the effect of the decrease in submicron air-borne particles due to Facy effect by the growth of ice crystals is much greater than is usually expected, as supposed from the sharp peaks in fogless time in Fig. 3.

b: Decreasing to zero or negative value

It was sometimes observed that after the

glaciation of fog, the positive potential gradient decreased from the normal value to zero or even negative values. We will consider the mechanism. There are many indications that ice crystals are charged negatively. The liquid fog and ice phase fog occurred alternately there and it was noted that the negative potential gradient corresponded to the ice fog as shown in Figs. 7 and 8. If the ice crystals carry preferentially the negative electric charge, and if the region of ice crystals are separated from the liquid fog, then a negative potential gradient will be established by the space charge due to negative ice crystals.

Takahashi (1970) showed experimentally that the surface of ice during its growth at about -20°C carries a positive charge. If that is the case, the surface of air-borne ice crystals will collect preferentially negative ions in the air during their fall, and then the ice crystals are charged negatively at those air temperatures. In a recent laboratory experiment, Magono & Iwabuchi (1972) observed that the ice crystals of hexagonal plate were charged negatively at -18°C . Ohtake (1970) reported that the ice fog slightly tended to be attracted toward the positive electrode in a high-tension field. These facts support the authors' view that ice crystals carry negative electric charges.

Taking account of those evidences, the authors consider that ice crystals are charged negatively in the phase transition from liquid to ice phase and then the negative potential gradient is formed due to the negative space charge of the ice crystals.

4.4. Changes in the field pattern by snowfall

It was observed that when a snow cloud became thick, the potential gradient was lowered, and when snow crystals from the cloud arrived at the surface, the potential gradient returned to positive values. When the snowfall stopped, the cloud overcast disappeared for a short time, and the potential gradient was increased to abnormally high positive values.

The low stratus snow clouds shown in Fig. 9 are considered to be only the extension of an ice fog layer, because they are very thin and low, and snow crystals in each stage, with sizes as small as ice fog crystals, fell from the cloud.

Fig. 10 shows a schematic picture to explain the time change in Fig. 9 according to Magono & Orikasa (1966)'s model. The time changes of

Fig. 10. A schematic picture of the electrification of the snow cloud.

the potential gradient, of the air temperature and of the cloud cover are simplified. And there, the change of air temperature give evidence of cloud layer existence. The electric charge of falling snow crystals is considered to be always negative, because the charge of snow crystals measured was all negative. It was assumed that ice crystals carry preferentially a negative charge in the growing process in the cloud as similar as winter fog electrification, and then they left the positive space charge in the cloud as shown in Fig. 10. Then the time change of the potential gradient on the ground may be as follows.

When negatively charged ice crystals fall, a positive polarity is established within the cloud layer as shown in the overcast stage in Fig. 10. Therefore the cloud base consisting of snow crystals is electrified negatively, and it bares directly to the surface and approaches there, then the surface potential gradient becomes more and more negative, owing to the approach of negative space charges due to negatively charged ice and snow crystals. After the snow crystals carrying a negative charge arrive at the surface, the negative charge leaks out to the ground. And as the process progresses, the residual positive

space charge aloft becomes predominant, then the surface potential gradient gradually increases toward the positive values as shown in the snowfall stage in Fig. 10. When the visible cloud has disappeared, only positive space charge is left aloft. Therefore the fair weather normal values will be recovered. But the several folds larger than the normal value seen in the cloudless stage in the figure has not yet been explained. As possible reasons for this abnormal lift of the potential gradient accompanying cloud disappearance, the following may be mentioned. Firstly the sheathing-layer effect which was suggested by Eden and Vonnegut (1965), is out of the question, because there are no cloud particles to reduce the conductivity. The positive space charge aloft affects the surface potential gradient directly. Secondly, it may be considered that there is a relative downdraft in the cloudless region rather than in the cloud region, so an air parcel containing a positive space charge comes down to the surface, enhancing the positive potential gradient. This enhancement will be diminished exponentially as indicated by the broken line, but the curve was sharply cut by the presence of another new cloud overcast

according to Fig. 9.

5. Concluding remarks

In Asahikawa City in winter are seen steam fogs and their glaciation. And there we have observed some atmospheric electrical phenomena pertaining to winter fogs.

5.1. When humidity in the air increased and become near saturation, although no fog was observed, the electric potential gradient increased in positive values to two or three times the normal value.

A possible reason for this is that many sub-micron particles originate from high humidity.

5.2. When the polluted air came, the positive potential gradient increased. Pollution particles are considered to capture small ions and reduce the conductivity of the air, and to carry a positive charge originally.

5.3. As known up to date, with the coming of liquid fog, the potential gradient was enhanced positively. It was considered that this was because fog particles captured the small ions, but Misaki (1970) says that so many submicron particles originate in fog and are more effective to reduce the conductivity of the air than fog particles.

5.4. When the liquid fog was glaciated, the positively enhanced potential gradient due to the fog recovered the normal value, and furthermore sometimes it decreased to zero or even negative values. The reasons for this are considered to be as follows. On the phase transformation of fog from liquid to ice under the conservation of liquid water content, the size of particles generally becomes large, and the concentration decreases. This results in reducing the total surface over which small ions diffuse and diminish in their number, and ice crystals more rapidly fall out than supercooled droplets to diminish in their number. Then the small ions become abundant, and the air conductivity and the potential gradient recover from the influence of liquid fog and return to normal values. Furthermore submicron particles are considered to dissipate. It is considered that the ice crystals carry the negative charge preferentially at about -18 or 20°C , being gravitationally separated from fog

to leave there the opposite positive charge.

5.5. It is noted specially that when the snowfall stopped, the potential gradient abruptly increased to a positive high value. This may be explained by the residual positive charge after Magono and Orikasa's model (1966).

By the dissipation of cloud particles, the shielding effect was removed, and space charges are able to flow freely. And some downdraft brings them near the surface from the cloud level.

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冬霧の中での地上電位傾度の観測 (冬霧の電氣的性質. その1)

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1968年、旭川にて冬霧の中での地上電位傾度の観測を行った。

汚染された空気と水霧が来ると電位傾度が晴天値の数倍になった。この増加は主に大気の電気伝導度の減少によるものと説明された。

また、この水霧が氷化する際に、すでに正に高まった電位傾度が減少し晴天値から更に負電場にまで達するのがみられた。この減少のメカニズムとして、まづ氷晶が選択的に負電荷を帯びることによるためと更に氷晶の成長によりエアロゾル粒子が除かれるため (Facy 効果) 大気の電気伝導度が水霧時より増加するためと考えた。

たまたま観測された降雪に際し、降雪が止み雲がなくなると電位傾度が急に正の高い値へ増加するのがみられた。これは負に帯電した雪が重力的に降下し分離して残った正の空間電荷が雲の切れ間では自由になり下降流により地上へ運び込まれることによるものと説明した。