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Title	Origin of the intense positive and moderate negative atmospheric electric field variations measured during and after Antarctic blizzards
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12	
13	Abstract
14	There is an atmospheric electric field (AEF) or an electric potential gradient (PG) in fair weather

between the Earth's surface and the mesosphere/ionosphere, which is positive. During 15 16 blizzards/snowstorms in the polar regions, an intense positive AEF/PG in the order of 10^3 V/m of 17 the same polarity in fair weather was observed using an electric field mill at 1.4 m in height. In 18 contrast, a moderately negative AEF/PG variation after a blizzard was observed in 2015 at Syowa 19 Station, Antarctica. The negative variation, where the magnitude ranged from tens to hundreds of 20 V/m, gradually recovered into the positive AEF/PG for more than 40 minutes. According to various 21 studies on blowing/drifting snow dynamics and electricity in laboratory experiments and field 22 observations, snow particles colliding with the snow surface are charged, and the charge of saltating 23 and suspended particles during the snowstorm is negative on average. To verify the AEF/PG 24 observed during and after the blizzards, we numerically estimated the electric field surrounding the 25 conductive sensor unit of the electric field mill using a three-dimensional Poisson equation. Under 26 blizzard conditions, the polarity of the estimated AEF/PG was the opposite of that of the observed 27 AEF/PG. From the noise study of the field mill, we deduced that the positive AEF/PG variations 28 were caused by the collision of negatively charged snow particles with the electric probe on the 29 sensor unit. Just after the blizzard, the number of snow particles measured at 4.4 m in height clearly 30 decreased, and the camera image showed clear visibility. From this evidence, we modeled the 31 suspended and saltating negatively charged snow particles that had fallen onto the ground surface 32 and then constructed a charge layer of the snow particles softly attaching to the ground, which 33 slowly discharged following the study on the electrical resistance of the powders. The three-34 dimensional Poisson calculation based on the model reproduced a moderately negative AEF/PG. 35 Thus, we elucidated that the origins of the intense positive and moderate negative electric fields 36 during and after blizzards are the charged snow particles colliding with the electric probe on the 37 sensor unit and the negative snow layers softly attached to the ground, respectively. These results

38 are applicable to studies on dust storm electrification on Mars' and Earth's deserts, snowstorm 39 electrification in the polar regions, and high mountains, such as Mt. Fuji in Japan, and turbulent 40 electrification for industrial dust, which provides the identification of intense electrification and 41 storms.

42

43 Keywords

44 Atmospheric electric field; Potential gradient; Electric field mill; Blizzard; Antarctica; Charged45 snow particles.

46

47 1. Introduction

48 There is an atmospheric electric field (AEF) in fair weather between the Earth's surface 49 and the mesosphere/ionosphere. The magnitude of the AEF at the ground surface is around 100 50 V/m in fair weather at sea level (MacGorman and Rust, 1998; Harrison, 2013; Williams and Mareev, 2014). The AEF transports atmospheric ions originating from atmospheric molecules 51 52 ionized by cosmic rays and natural radionuclides as air-earth currents (i.e., a weak electric current 53 flow from the mesosphere/ionosphere to the ground surface). Negative charges are transported 54 from the negatively polarized bottom of clouds to Earth's surface via negative ground-to-ground 55 lightning, which occurs constantly all over Earth. The positive charges in thunderclouds are 56 transported into the mesosphere/ionosphere, generating an electric potential difference in relation 57 to Earth. The negatively charged precipitation also transports negative charges to Earth's surface 58 (Liu et al., 2010). This electrical circuit on Earth is called the global electrical circuit 59 (MacGorman and Rust, 1998; Harrison, 2004; Williams and Mareev, 2014). The electric potential 60 difference between Earth's surface and the mesosphere/ionosphere, which forms a massive 61 global-scale spherical capacitor, is around 250 kV (Markson, 2007). The downward (geocentric 62 direction) of the vertical AEF is conventionally defined as positive. In other words, it is a positive 63 AEF under fair-weather conditions. This definition is adopted in many studies of atmospheric 64 electricity and many papers. 65 With the electric field vector and the electric potential expressed as **E** and *V*, respectively,

66 E is given as follows:

67

$\boldsymbol{E} = -\boldsymbol{\nabla} \boldsymbol{V}. \tag{1}$

When only the vertical *z*-axis is discussed, as in the case of the AEF in fair weather, equation (1)is expressed as follows:

- $F_z = -\frac{dV}{dz}.$ (2)
- 71 Here, we introduce the electric potential gradient (PG), which is a scalar quantity:
- 72 $PG = E_z.$ (3)
- 73 In this case, PG and E_z have the same magnitude. Therefore, PG has also been used in some papers

as a general expression because it is positive, like the AEF in fair weather (e.g., Harisson, 2013;
Aplin, 2018; Nicoll et al., 2019). The present paper follows this definition for AEF/PG unless
otherwise noted.

77 According to the World Meteorological Organization (1966), blowing snow was defined 78 as snow raised by the wind to moderate heights above the ground, reducing horizontal visibility at 79 eye level. The same source defined a snowstorm as a meteorological disturbance giving rise to a 80 heavy fall of snow, often accompanied by strong winds, and a blizzard as a violent winter storm 81 lasting at least 3 hours. It is combined with below-freezing temperatures and extremely strong wind 82 laden with blowing snow, which reduces visibility to less than 1 km. Blizzards at Syowa Station, 83 Antarctica (69°00'S, 39°35'E) have been identified by the criteria described in Sato and Hirasawa 84 (2007), including visibility of less than 1 km and wind velocity of more than 10 m/s continuing for 85 more than 6 hours. The blizzard at Syowa Station is regarded as a weather event as defined by these 86 criteria.

87 In blowing snow conditions, including snowstorms and blizzards, an intense positive 88 AEF/PG accompanied by high-frequency fluctuations was observed using an electric field mill. 89 Gordon and Tylor (2009) measured the AEF/PG for 80 days in Amundsen Bay, Canada (70°03'N, 90 126°18'W) and observed intense positive variations of the AEF/PG during blowing snow events. 91 In a polar observation, Kikuchi (1970) reported an intense positive AEF/PG observed during a 92 blizzard at Syowa Station. Although the wind velocity and magnitude of the AEF/PG were 93 correlated in previous studies (e.g., Kikuchi, 1970; Gordon and Tylor, 2009), the origin of the 94 positive AEF/PG was unclear.

95 The dynamics of blowing snow involve the dynamics of snow drifting near the snow 96 surface. During snow drifting, the dynamics of snow particles produces an electrical charge, 97 categorized into the following three modes: saltation, suspension, and surface creep (Nemoto and 98 Nishimura, 2004). Saltation refers to snow bouncing at the snow surface and/or pushing one 99 particle out of another; suspension refers to snow migrating without touching the ground surface; 100 and creeping refers to snow migrating, frequently in contact with the snow surface. When a 101 snowstorm begins, the snow particles on the snow surface migrate as the wind speed increases, 102 causing creep. The creep of the particles develops into saltation, which generates suspension 103 (Anderson, 1987; Nemoto and Nishimura, 2004). When the snowstorm terminates, the suspended 104 and saltating particles diminish.

105 Snow particles that collide with the snow surface are charged. Maeno et al. (1985) 106 executed a laboratory experiment to collide positively and negatively charged snow seeds with 107 snow surfaces under horizontal wind blowing inside a horizontal wind tunnel. The blowing snow 108 particles were negatively charged, regardless of the initial seed polarity. The charge-to-mass ratio 109 of the snow particles after the collision was -0.1 to -0.3μ C/kg. As described below, the amount 100 of negative charge measured in the laboratory experiment was two orders of magnitude smaller than that observed in the field. Omiya and Sato (2011) examined the correlation between the electric charge of snow particles and their saltation in the same type of laboratory experiment as Maeno et al. (1985). They showed that the negative charge of snow particles accumulated with an increase in saltation occurrences. This means that the saltation in the laboratory experiments was smaller than that in the field because of the limited length of the wind tunnel.

116 In 1967 and 1968, Wishart (1968) measured the amount of charge on snow particles 117 during the snowstorms at Byrd Station, Antarctica (80°00'S, 119°30'W), using a Faraday cage and 118 a charge electrometer. He conducted two observation campaigns for different height measurements. 119 The first observation showed that the charge-to-mass ratio of snow particles ranged from -1.4 to 120 $-7.7 \,\mu$ C/kg at a wind velocity of 4.5 to 6.5 m/s in an air temperature of -5 to -6° C and a height of 121 50 cm; this corresponded to a wind velocity of 6.5 to 9 m/s at a height of 10 m. The second The 122 second observation showed that the charge-to-mass ratio comprised roughly negative constant 123 values, $-0.05 \ \mu\text{C/kg}$ at a wind velocity of 4.5–6.5 m/s, air temperature of -9 to -12°C (snow 124 temperature of -10 to -13 C), and height of 15 cm, corresponding to a wind velocity of 7.5–9 m/s 125 and a height of 10 m. Schmidt et al. (1999) measured the charge amount of 11 individual drifting 126 snow particles at Chimney Park, Wyoming, USA, and measured both positive and negative charges. 127 The charge-to-mass ratios of six negatively charged snow particles and five positively charged 128 snow particles ranged from -12 to $-208 \,\mu\text{C/kg}$ and 1 to $72 \,\mu\text{C/kg}$, respectively. Burrows and Hobbs 129 (1970) measured the charge of 3,654 snow particles passing through an induction coil during a 130 light snowfall at an altitude of 2,025 m on Mt. Olympic, Washington, USA, and showed that the 131 proportions of positively and negatively charged snow particles were 52% and 48%, respectively. 132 The charge amounts per snow particle were on the order of 10^{-14} to 10^{-12} C. In Sapporo, Japan, 133 Asuma et al. (1988) measured the electric charge of individual precipitation particles on the ground 134 and at altitudes of 100 m and 200 m using a moored balloon at a wind speed of less than 6 m/s. 135 They showed that positively and negatively charged precipitation particles were dominantly found 136 in the sky and near the ground surface, respectively. The charge amounts per snow particle were in the order of 10^{-13} to 10^{-12} C. Therefore, both the positively and negatively charged snow particles 137 138 were measured for suspended snow particles in the field observations. However, the dominant 139 charge was statistically negative for the particles that were saltating and suspended during 140 snowstorms in field observations (Wishart, 1968; Latham and Montagne, 1970; Schmidt et al., 141 1999).

The studies described above have shown that although snow particles in wind tunnel experiments controlled for saltation were negatively charged, both positively and negatively charged particles were observed in the snow particles where saltation could not be confirmed in the field. The charge-to-mass ratios of the particles observed in the field observations were two orders of magnitude larger than those measured in the laboratory experiments. These results suggest that collisions between the snow particles and the snow surface should generate a larger negative charge accumulation on the particles; they imply that the difference in charge-to-mass
ratios between field and laboratory experiments was caused by the difference in the number of
collisions owing to the different lengths of saltation.

151 Negative (upward) AEF/PG has been observed on the ground when the polarity of the 152 dominant charge above the field mill is negative, such as in thunderstorm events (e.g., Suzuki et 153 al., 2011). Similary, multiple negatively charged snow particles during the snowstorm were 154 suspended around the sensor unit of the electric field mill that measured AEF/PG. Therefore, one 155 may surmise that the electric field direction was from the electrical probe of the sensor unit to the 156 negatively charged snow particles. In this case, the measured value was negative, as was the case 157 just below the thundercloud. It is not clearly understood why positive AEF/PGs were measured 158 during the blizzard/snowstorm.

159 An intense positive AEF/PG exceeding 10 kV/m was reported at Syowa Station during 160 blizzards (Kikuchi, 1970). In addition, as described below, a moderate negative AEF/PG of -30161 to -110 V/m was observed with a duration of 50 to 100 minutes, just after the blizzard on several 162 occasions. In this study, we show the time series of the AEF/PG, the wind velocity, and the number 163 of snow particles during the intense positive AEF/PG in the blizzard, as well as the moderate 164 negative AEF/PG just after the blizzard. Furthermore, we demonstrated the numerical calculation 165 of the AEF/PG formed by the distribution of the negatively charged snow particles to investigate 166 the origin of the positive and negative AEF/PG variations during and after the blizzard, respectively. 167 We discuss how to construct the intense positive AEF/PG during the blizzard and the moderate 168 negative AEF/PG just after the blizzard.

169

170 **2. Observation**

171 In this study, we used the data of the AEF/PG, the wind velocity, the number of 172 precipitation particles (NPP), and still images recorded by a live camera at Syowa Station in 2015. 173 Syowa Station is located on East Ongul Island, about 4 km east of Antarctica. Fig. 1 shows the 174 location of Syowa Station and the observation points in the station. The electric field mill measures 175 the magnitude and polarity of the AEF/PG estimated from the amount of electric charge on the 176 electrical probes (stators), which are alternately shielded and exposed by a grounded rotor 177 (MacGorman and Rust, 1998). We used a Boltek EFM-100 electric field mill to observe the 178 AEF/PG. The time resolution of the measurement was 2 Hz; the median value of 120 measured 179 values was taken as 1-minute representative values for the analysis. The sensor unit was installed 180 at a height of 1.4 m, and the electric probe of the sensor unit faced not the zenith but the ground 181 (an inverted sensor) to avoid noise originating from snow precipitation and rainfall.





Fig. 1. (a) Location of Syowa Station, Antarctica, (b) observation points in the station, and (c) sensor photos of the atmospheric electric field (AEF)/potential gradient (PG) and the number of precipitation particles (NPP). The AEF/PG and NPP in (b) denote the location of the electric field mill to observe the AEF/PG and the laser precipitation monitor (LPM) sensor to observe the number and size of precipitation particles, respectively. The time-lapse image and the wind indicate the live camera and the location of the wind velocity sensor, respectively. Visibility (VIS) denotes the observation point for visibility.

192 The AEF/PG measured by an electric field mill does not correspond to the ambient 193 AEF/PG in fair weather because the electric lines of force are concentrated around the conductive 194 field-mill sensor, causing the intense AEF/PG. In addition, the electric conductive environment 195 around the sensor also modulates the AEF/PG around the sensor. Hence, in general, the calibration 196 is conducted, comparing the field mill for the observation and the field mill embedded in the ground 197 (See Tsurudome et. al, 2013). Note that this calibration is effective for fair-weather observation and 198 thunderstorms with a high cloud bottom. The calibration factor of the field mill for the present 199 study (0.20) was obtained by the comparative observations described in MacGorman and Rust 1998). The measurement range of the present field mill was ± 20 kV/m. Therefore, the observed 201 range of AEF/PG was $\pm 4,000$ V/m, which is ± 20 kV/m multiplied by the calibration factor.

202 The wind velocity data were 1-minute data provided by the Japan Meteorological Agency. 203 The NPP, by size, was measured using a laser precipitation monitor (LPM). The sensor was 204 installed at a height of 4.4 m. When the particles fell through the laser sheet between the laser 205 emission part and the intensity detector, the size of the laser shadow behind the particles one by 206 one was measured (Hirasawa et al., 2018). In this study, we used the 1-minute data of the number 207 of particles and assessed the number of particles in the different classes measured as a distribution 208 of snow particles before, during, and after the blizzard. The diameter of the precipitation particles 209 was recorded as 22 diameter classes (i.e., 22 bins) by the LPM. However, we recategorized the 210 particle diameter into the following four classes, because the major diameter of the precipitation 211 particles was less than 0.500 mm: 0.125 mm or less, 0.250 mm or less, 0.375 mm or less, and more 212 than 0.375 mm.

213 Regular observations of visibility were carried out eight times a day (i.e., every 3 hours). 214 When there was an abrupt change in the weather, such as before and after the blizzard, a temporary 215 observation was also conducted. To confirm the blizzard, we used time-lapse images provided by 216 the live camera recording every 5 minutes (Figs. 5 and 7), which was installed 140 m away from 217 the AEF/PG observation point (Fig. 1). The visibility to identify the blizzard was ocularly observed 218 500 m away from the live camera. In addition, visibility was not measured in a specified direction 219 but in the direction with the most visibility. Therefore, the view direction of the live camera did not 220 always coincide with that of the visibility observation. This may have caused differences in the 221 timing of the start/end of the blizzard between the ocularly assessed visibility and the still images 222 recorded by the live camera.

223 Fig. 2 shows the time series of the AEF/PG variations observed at Syowa Station from 224 January to December 2015. Positive AEF/PGs were frequently observed, whereas negative electric 225 fields were only occasionally seen. A positive AEF value exceeding 1 kV/m often lasted for several 226 hours, whereas a negative value rarely lasted for more than 1 hour. Fig. 3 shows the relationship 227 between the wind velocity and the AEF/PG from January to December 2015. As the wind velocity 228 increased, the AEF/PG value and its variability increased. Indeed, below a wind velocity of 6 m/s, 229 the AEF/PG value and its variability were smaller than those of the large wind velocity. Minamoto 230 and Kadokura (2011) employed a threshold of 6 m/s for the criteria to identify fair-weather 231 conditions. We note that when the wind velocity exceeded 26 m/s, the values of the 75th and 90th 232 percentiles of the observed values were almost equivalent because of the saturation of the

233 measurement.



234

Fig. 2. Time series of 1-minute data of the AEF/PG and wind velocity in 2015 at Syowa Station. There are two data gaps, which are in January and from the middle of April to the beginning of May. The numbers below the AEF/PG panel correspond to the events of negative AEF/PG variations after the blizzard, as listed in Table 1.

239



Fig. 3. Box-and-whisker plot for the relationship between wind velocity and the AEF/PG from
January to December 2015. The whiskers and downside/middle/upside of the box indicate 10th,
25th, 50th, 75th, and 90th percentile values from the bottom. The class width of the wind velocity

244 was 2 m/s. The upper limit corresponding to a saturated value of the AEF/PG measurement was 245+4,000 V/m.



247Fig. 4. Number of particles, AEF/PG, and wind velocity of 0 UT to 24 UT on September 23, 2015. 248(a) Number of particles in different particle size classes. The green, blue, red, and black lines 249 indicate the number of particles with a diameter of 0.125 mm or less, 0.25 mm or less, and 0.375 250mm or less, as well as the total number of particles. (b) AEF/PG. (c) Wind velocity. The blue and 251 red bars denote the period of the blizzard and still images shown in Fig. 5, respectively.



Fig. 5. Still images recorded every 5 minutes by the live camera from 0814 UT to 0839 UT on September 23, 2015.

255

256 Fig. 4 shows the time series of the number and size of snow particles, AEF/PG, and wind velocity 257 on September 23, 2015, as an example of a blizzard period. The start and end of the blizzard were 258 recorded at 0818 UT and 1550 UT, respectively (Oshiki, 2016). The wind velocity exceeded 6 m/s 259 at 0810 UT and reached 20 m/s at 0900 UT. The AEF/PG and the number of particles increased 260 rapidly around 0630 UT and 0700 UT, respectively. Note that we did not describe the origin of the 261 enhancement of AEF/PG around 0300 UT not related to the increase in the number of snow 262 particles and the wind. The origin was unknown, and similar variations were barely observed. Fig. 263 5 shows the still image of the live camera recording every 5 minutes from 0814 UT to 0839 UT on 264 September 23, 2015. The visibility dropped between 0819 UT and 0824 UT. When the blizzard 265 started at 0818 UT, the wind velocity was 16.5 m/s. Figs. 4 and 5 indicate that the number of 266 particles measured by the LPM increased and the visibility decreased as the wind velocity increased. 267

Table 1. Six events of moderately negative AEF/PG variation after a blizzard in 2015. They were

satisfied with the conditions that the number of particles measured by the LPM was less than 500

and a negative AEF/PG was observed for more than 30 minutes. The start and end times of the

271 negative AEF/PG after the blizzard are shown in the table. The minimum of the AEF/PG

272 indicates the minimum value of the 5-minute running mean of the AEF/PG. The time constant τ is

273 the period from the observed to the minimum value of the 5-minute running mean of the

274 AEF/PG, $|E_{min}|$, to the value of $|E_{min}|/e$. The temperature refers to the hourly value observed

during the negative AEF/PG.

	Date (2015)	Start time (UT)	End time (UT)	Duration [min.]	Min. of AEF/PG [V/m]	Time constant τ [minutes]	Lowest wind velocity [m/s]	Highest wind velocity [m/s]	Temperature [°C]
1	Feb. 8	3:57	4:48	52	-32.9	17	2.9	4.3	-3.8 (04UT)
2	Jul. 19	2:41	3:42	62	-39.4	36	5.9	7.1	-11.5 (03UT)
3	Jul. 19	4:39	5:24	46	-29.8	6	7.3	7.3	-12.0 (05UT)
4	Jul. 29	10:06	11:44	99	-101.2	58	3.8	8.2	-6.8 (14UT)
5	Aug. 10	16:06	17:21	76	-110.8	30	5.6	11.2	-15.7 (17UT)
6	Aug. 15	14:42	15:33	52	-63.1	14	5.3	8.9	-13.7 (15UT)

276



Fig. 6. Number of particles in different classes, AEF/PG, and wind velocity from 0000 UT to 2400
on July 29, 2015. The color of the lines is the same as in Fig. 4. The blue and red bars denote the
period of the blizzard and still images shown in Fig. 7, respectively.



283

Fig. 7. Still images recorded every 5 minutes by the live camera from 0934 UT to 0959 UT on July
285 29, 2015.

286

Fig. 6 shows the time series of particle size distribution, AEF/PG values, and wind velocity from 0000 UT to 2400 UT on July 29, 2015. The blizzard ended at 0920 UT (Oshiki, 2016). The negative AEF/PG started at 0952 UT, and the negative values remained from 1001 UT to 1238 UT. Meanwhile, the NPP measured by the LPM at a height of 4.4 m was under 500. The recovery of visibility was recognized from the still images shown in Fig. 7. The AEF/PG values reached a minimum just after the blizzard ended and gradually recovered. The high-frequency fluctuation was not found in the recovery period.

Thirty blizzards were identified at Syowa Station in 2015 (Yamamoto et al., 2015; Oshiki, 2016). Among them, six events of similar negative variations in AEF/PG were found, as shown in Fig. 2. Table 1 lists the six events in 2015 that satisfied the conditions in which the negative AEF/PG values remained for more than 30 minutes and the number of particles measured by the 298 LPM was less than 500. The date, start/end time, duration, minimum AEF/PG, time constant, 299 lowest/highest wind velocity, and temperature for each event are also shown. The time constant τ 300 for the recovery of the negative AEF/PG was estimated from the period of the observed minimum 301 value of the 5-minute running mean of the AEF/PG, $|E_{min}|$, to the value of $|E_{min}|/e$, where e is the 302 base of the natural logarithm. Although there was no significant correlation between the 303 lowest/highest wind velocities or temperatures and the time constant τ , correlations between the 304 minimum AEF/PG $|E_{min}|$ and time constant τ were obtained. Fig. 8 illustrates the semi-logarithmic 305 relationship of the time constant τ and the minimum of the 5-minute running mean of the AEF/PG 306 $|E_{\min}|$. From these six events, the correlation coefficient between the time constant τ and the log 307 $|E_{\min}|$ of the minimum AEF/PG was 0.65.



308

309 Fig. 8. Relationship between the minimum value of the 5-minute running mean of the AEF/PG and 310 the time constant τ in the six events satisfied the conditions that the number of particles measured 311 by the LPM be less than 500 and a negative electric field was observed for more than 30 minutes, 312 as listed in Table 1. The horizontal axis is the time constant τ , the period from the observed 313 minimum value of the 5-minute running mean of the AEF/PG, $|E_{min}|$, to the value of $|E_{min}|/e$. The 314 minimum value of the 5-minute running mean of the AEF/PG is logarithmically shown on the 315 vertical axis. The gray line is a regression line. The correlation coefficient between the time 316 constant τ and the log $|E_{\min}|$ is 0.65.

317

318 **3. Calculations**

Several previous papers have numerically investigated the electric field distribution formed by charged particles, such as snow and sand particles. Schmidt and Dent (1993) estimated the electric field intensity perpendicular to the surface when charged snow particles were arranged in a hexagonal configuration on the surface. They obtained an electric field of 1,000 V/m and 20 V/m at heights of 1–2 cm and 10 cm, not considering the charge of the snow particles suspended in the air. Gordon and Tylor (2009) proposed a model of the electric field formed by suspended snow 325 particles. They found that the electric field intensity was proportional to the particle number density 326 distribution in the model. However, the correlation coefficient r between the electric field intensity and the snow-particle density in the field was relatively small, at $r^2 = 0.13$ to $r^2 = 0.66$. The 327 328 researchers concluded that the intensity of the electric field was likely influenced by various other 329 origins, such as snow conditions, the distribution of blowing snow density, and the history of 330 suspended particles. Zheng et al. (2004) constructed a theoretical model for calculating the electric 331 fields produced by charged sand particles, considering the saltation, suspension, and creep of the 332 particles. The result of the calculation, in which the charge-to-mass ratio of sand particles was -60 333 μ C/kg, similar to the charge-to-mass ratio of snow particles, showed that an upward electric field 334 (i.e., a negative AEF/PG), exceeding 100 kV/m, was obtained just above the surface of the sand 335 layers. The electric field decreased quickly to zero, while the height increased. Then, the polarity 336 of the electric field changed (i.e., positive [downward]).

337To verify the electric field distribution formed by the negatively charged snow particles338suspended in the snowstorm, we numerically solved the three-dimensional Poisson equation. This339is shown in equation (4):

$$\frac{\partial^2 \varphi(\mathbf{x}, \mathbf{y}, \mathbf{z})}{\partial \mathbf{z}^2} = -\frac{\rho(\mathbf{x}, \mathbf{y}, \mathbf{z})}{\varepsilon_0} = -\frac{dE(\mathbf{x}, \mathbf{y}, \mathbf{z})}{d\mathbf{z}},\tag{4}$$

341 where $\varphi(x, y, z)$, $\rho(x, y, z)$, and E(x, y, z) are the electric potential, charge density, and electric field, 342 respectively; *x* and *y* are the horizontal components; and *z* is the vertical height from the ground.

340

Although a downward (geocentric) direction is conventionally defined as positive in the studies of atmospheric electricity, as introduced in Section 1, we define the upward direction as positive in this numerical calculation. In this section, not AEF/PG but the electric field is used to describe the calculated electric field in the Poisson equation because the horizontal components are also required to calculate the electric field around the sensor.

348 The computational domain of 6 m in the horizontal direction (x and y components) and 349 2 m in the vertical direction (z-component) was set. Although the prevailing wind direction was set 350 in the y-axis (Fig. 9), the charge distribution $\rho(x, y, z)$ was regarded as uniform in the horizontal x 351 and y components because the constant wind velocity substantially carried the constantly charged 352 snow particles. In addition, the wind velocity concerned was much smaller than the electric field 353 propagation velocity (i.e., the velocity of light); the charge distribution was practically time-354 independent (i.e., static). It must be noted that the electrical conductivity modification caused by 355 the snow particles was negligible; Shumilov et al. (2005) showed that no significant change in 356 atmospheric conductivity during the snowstorm was found at sites of high latitude in Russia. In the 357 calculations, the electric field mill and its metal mounting support (Fig. 1) are conductors and are 358 grounded, setting their potential to be zero and forming the boundary conditions shown in Fig. 9. 359 To reproduce the AEF/PG in fair weather (i.e., 100 V/m in the geocentric direction), a positive 360 charge layer was installed at the top of the computational domain as a boundary condition.





Fig. 9. Conductor for the boundary condition (i.e., the sensor unit of the electric field mill and the pipe for mounting the sensor) shown in the Poisson calculation. The sensor was mounted at a height of 1.4 m. The cross-sections of the Poisson calculation results (shown in Figs. 11 and 13) correspond to the red plane in (a). The vertical component z of the Poisson calculation results (shown in Figs. 12 and 14) corresponds to the red and blue lines in (b). The computational domain is 6 m in the horizontal x- and y-directions and 2 m on the vertical z-axis.

369 The negative charge density originating from the snow particles was given as an initial condition, 370 multiplying the number density distribution of the snow particles by the average amount of charge 371 per snow particle. For simplicity, we assumed that the charge amount of each snow particle was 372 constant. Omiya et al. (2011) measured the charge-to-mass ratios of snow particles at different 373 temperatures and particle sizes in the wind tunnel experiment and estimated that the electric charge per snow particle was -2×10^{-14} C under the conditions of air temperature at -10 C and a particle 374 375 size of 0.3 mm. The median charge per snow particle at Byrd Station was -5×10^{-14} C when the 376 wind velocity at the height of 50 cm was between 4.5 and 6.5 m/s (Wishart, 1968).

Fifty-seven percent of the wind direction was north-northeast, northeast, and eastnortheast at Syowa Station (Sato and Hirasawa, 2007). Northeast wind prevailed during blizzards. When maximum wind speed was observed, the wind directions were north-northeast, northeast, and east-northeast in 29 out of the 30 blizzards identified in 2015 at Syowa Station (Yamamoto et al., 2015; Oshiki, 2016). The ocean extends to the northeast of Syowa Station. The sea surface was frozen during the period of analysis in this paper (Ushio, 2015; Miura, 2016). During the blizzard, many snow particles were negatively charged because they migrated into Syowa Station with

- repeated saltations at the snow surface on the sea ice. The charge amount of the snow particles depends on the transported length with snow surface collisions (Omiya and Sato, 2011). This implies that the charge accumulated with multi-collisions. Therefore, we considered the possibility that the charge amount in the calculation would be larger and smaller than that in previous studies (Wishart, 1968; Omiya and Sato, 2011). The charge amounts were given by -1×10^{-13} , -1×10^{-14} , and -1×10^{-15} C per snow particle.
- We used the density distribution of snow particles observed at Halley Station, Antarctica, obtained by Mann et al. (2000). They measured the snow-particle number flux and presented the 10-minute mean profile of snow particle number density into eight wind speed bins ranging between 10 and 17 m/s (1.0 m/s bin width). These profiles showed that the number density of snow particles decreased with height following a power law. We formulated the number of snow particles per unit volume, $n_w(z)$, as a function of height, *z*, for each wind velocity bin *w*, as depicted in Mann et al. (2000), with the constant values a_w and b_w shown as follows:
- 397 $n_w(z) = 10^{k_w(z)}$, where $k_w(z) = a_w z + b_w$. (5)
- For w = 15-16 m/s, we derived the coefficients of $a_w = -0.67$ and $b_w = 6.37$. Fig. 10 shows the height distribution of the number of snow particles per 10^{-6} m³ (1 cm³).
- 400



401 Number of snow particles per 10⁻⁶ m⁻³

402 Fig. 10. Height distribution of the number density of snow particles depicted in Mann et al. (2000)

403 for the Poisson calculation. The horizontal and vertical axes denote the number of snow particles

404 per 10^{-6} m³ and the height (i.e., z), respectively.

406 The sensor of the electric field mill was installed at 1.4 m in height and mounted downward using 407 a metal pipe (Fig. 1). The measured value of the grounding resistance of the sensor was 100 Ω . 408 Assuming that the constant permittivity and conductivity of the snow surface are ε and κ , the 409 relaxation time T_{relax} is represented by the following equation (Harrison et al., 2016):

410

$$T_{relax} = \varepsilon/\kappa. \tag{6}.$$

411 Gow (1968) sampled snow and ice on the surfaces and in the boreholes at several sites in Antarctica 412 and Greenland and measured their electric conductivity. The conductivity of the snow and ice was 413 1 to 2×10^{-4} S/m at inland sites. The conductivity at Little America V (78°11'S, 162°12'W), located on the Ross Ice Shelf near the sea, was about 6×10^{-4} S/m. The relative permittivity measured at a 414 415 depth of 1 m in Antarctica was between 1.4 and 2.0 (Sugiyama et al., 2010). Since the permittivity of the air was 8.9×10^{-12} F/m when the conductivity was assumed to be 10^{-4} , the relaxation time 416 was about 10^{-7} seconds, which was negligible. The sensor unit of the electric field mill and the 417 metal pipe mounting the sensor unit (Fig. 9) were grounded. The three-dimensional Poisson 418 419 calculations were carried out with the above charge and conductor distribution as initial and 420 boundary conditions.

Fig. 11 shows the electric field distribution on the plane (red plane in Fig. 9a) across the sensor unit of the electric field mill. The electric field in fair weather without and with the sensor unit is shown in Fig. 11a and b, respectively. Fig. 11c shows the electric field with the sensor unit in the distribution of snow particles (i.e., during the blizzard), based on the observation of Mann et al. (2000). The electric charge was -1×10^{-14} C per snow particle.

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Fig. 11. Electric field in the three-dimensional Poisson calculation. A cross-section (red plane in Fig. 9a) across the sensor unit is shown. The arrows indicate the direction and magnitude of the electric field. The area of the conductor corresponding to the sensor unit and metal pipe is shaded. The calculation results are as follows: (a) in fair-weather without the sensor unit, (b) in fair-weather with the sensor unit, and (c) during the blizzard with the electric charge amount of -1×10^{-14} C per snow particle, with the sensor unit.





436 Fig. 12. Vertical distribution of the *z*-component of the electric field in the three-dimensional 437 Poisson calculation. The number density of snow particles during the blizzard as an initial 438 condition was based on Mann et al. (2000). The red, black, and blue lines indicate the calculation 439 results for the charge amounts of -1×10^{-13} , -1×10^{-14} , and -1×10^{-15} C per snow particle,

respectively. (a), (b) The z-component of the electric field along a vertical line (red line in Fig.
9b) through the sensor unit. There is a conductor of the sensor unit from 1.4 m to 1.7 m in height.
(c), (d) The z-component of the electric field along a vertical line (blue line in Fig. 9b), not
passing through the sensor unit. The wide and narrow ranges of the AEF/PG are shown in (a), (c),
and (b), (d), respectively.

445

446 When the direction of the electric field is from outside to inside the sensor electrode of 447 the electric field mill, it is positive. In other words, the arrows heading to the field mill at the 448 undersurface of the sensor indicate a fair-weather electric field. Fig. 11b shows the calculated 449 electric field reproducing the positive electric field in fair weather. Conversely, the electric field 450 heading away from the sensor electrode was measured as a negative electric field. The result of the 451 calculation shown in Fig. 11c during the blizzard did not provide the electric field heading away to 452 the sensor unit. From this result, the negative electric field was expected to be measured by the 453 calculation but not observed in the field. Therefore, the intense positive electric field observed 454 during the blizzard, shown in Figs. 4 and 6, was not reproduced.

455 Fig. 12 shows the distribution of the electric field on the z-axis during the blizzard. The 456 z component of the calculated electric field on the vertical line passing through the sensor unit (red 457 line in Fig. 9b) and on the line not passing through the sensor unit (blue line in Fig. 9b) are shown 458 in Fig. 12a and 12b, respectively. The calculation results with electric charge amounts of -1×10^{-13} , -1×10^{-14} , and -1×10^{-15} C per snow particle are shown as red, black, and blue lines, respectively. 459 460 The electric field of the z-component was negative, and this corresponds to arrows heading away 461 at the undersurface of the sensor just below the electric probe of the sensor unit in Fig. 11. In this 462 case, the output value of the electric field mill was negative. The magnitude of the electric field 463 varied widely depending on the charge amount of the snow particles.

The electric field showed a downward direction just below the electric probe of the sensor unit, corresponding to the electric field from the inside to the outside of the sensor unit, as shown in Fig. 11. In this case, the output value measured by the electric field mill was negative. The magnitude of the electric field varied widely depending on the charge amount of the snow particles.

469

470 **4. Discussion**

The observed AEF/PG values and calculated electric field values during blizzards were different. The installation method for the electric field mill is described in Section 6.1.2 of MacGorman and Rust (1998). They mentioned that the electric probe of the sensor unit facing downward into the ground (inverted sensor) effectively avoided the electrical noise caused by the charged particles attached to the sensor when charged particle precipitation, such as rain and snow, was falling. Ogawa (1973) estimated that the electric field caused by rain precipitation was 1 kV/m, 477 based on the measurement of the electric current generated by raindrops reported by Ogawa (1960).
478 From the estimation, the polarity of the electric field was opposite to that of the charge of the
479 raindrops. Moreover, the inverted sensor in the condition of the blizzard was ineffective at avoiding
480 the charged snow particles attaching to the sensor because the suspended and saltating snow
481 particles were reachable, even to the inverted sensor. Thus, we concluded that the positive intense
482 AEF/PG values observed during the blizzard were apparent electric field measurements because
483 of collisions of charged snow particles with the sensor electrodes.

484 After a blizzard, the suspended and saltating snow particles fell onto the snow surface 485 with a negative charge. Although the relaxation time of the charge on the solid snow surface was 486 negligible, as shown in equation (6), the charged snow particles softly attaching to the surface took 487 a certain time to discharge. Sims et al. (2003) calculated the discharge decay-time constant (i.e., 488 the time to reach the charge of 1/e) for various powders on the surface. The discharge decay times 489 of the Mars dust simulants and acrylic polymer powders were about 5 minutes and 150 minutes, 490 respectively. We carried out the Poisson calculation under the initial condition that a thin layer of 491 negatively charged snow particles was covered on the snow surface (Figs. 13 and 14). The results 492 of the Poisson calculations shown in Fig. 13 indicated that when the negative charge density for 493 the thin layer on the surface was -1×10^{-8} C/m², an electric field heading away from the field mill 494 sensor was reproduced. Fig. 14 shows that when the negative charge density was -1×10^{-7} C/m² 495 or -1×10^{-8} C/m², the calculated electric field was opposite to that of -1×10^{-9} C/m². Assuming 496 that the distribution of the number density of snow particles followed that of Mann et al. (2000) 497 and that the electric charge per snow particle was -1×10^{-14} C, the charge density layer on the 498 surface became -5.5×10^{-8} C/m² when the suspended and saltating snow with the negative charge 499 from the ground to 1.0 m fell into the surface.





502 Fig. 13. Electric field with the negatively charged snow-particle layer on the surface of -1×10^{-8}

503 C/m² on the cross-section (red plane in Fig. 9a) across the sensor unit is shown. The arrows

504 indicate the direction and magnitude of the electric field. The area of the conductor

505 corresponding to the sensor unit and metal pipe is shaded.



507

508 Fig. 14. Vertical distribution of the electric field *z*-component with the initial condition of which 509 the negatively charged snow particle layer on the surface is shown. The red, black, and blue lines 510 indicate the calculation results, in which the charge densities are -1×10^{-7} , and -1×10^{-8} C/m², 511 -1×10^{-9} , respectively. (a), (b) The *z*-component of the electric field along a vertical line (red

line in Fig. 9b) through the sensor unit. There is a conductor of the sensor unit from 1.4 m to 1.7
m in height. (c), (d) The z-component of the electric field along a vertical line (blue line in Fig.
9b), not passing through the sensor unit. The wide and narrow ranges of the AEF/PG are shown
in (a), (c), and (b), (d), respectively.

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517 The live camera was located more than 100 m away from the sensor unit of the electric field mill. 518 The height of the camera (30 m) was higher than that of the electric field mill sensor (1.4 m). 519 Therefore, it was difficult for the still images recorded by the camera to verify the presence of 520 powdered snow on the ground because of insufficient image resolution. The LPM sensor for 521 measuring the NPP, shown in Figs. 4 and 6, was mounted at a height of 4.4 m, and the snow 522 particle layer was not measured. However, the origin of the negative electric field just after the 523 blizzard was explained, assuming that the presence of the snow-particle layer originated from the 524 falling of suspended and saltating snow particles to the ground.

525 We found a correlation between the duration of the negative AEF/PG and the magnitude 526 of the electric field: The larger the magnitude of the negative electric field value was, the longer 527 the duration of the negative AEF/PG value became. This correlation was understandable when we 528 speculated about the relationship between the time required for the discharge of the snow particles 529 softly attaching to the snow surface and the amount of electric charge of the snow particles. 530 However, monitoring the distribution of snow particles and the electric charge of the particles just 531 above the ground surface may enable us to verify this speculation, as it remains a problem for 532 future consideration.

533 Although the electric field mill is generally used for the observation of AEF/PG, the 534 measurements do not reflect the signal originating from the charged particle distribution, 535 particularly under severe conditions, such as in desert and polar regions. Nicoll et al. (2020) 536 observed a positive AEF/PG exceeding 7 kV/m, generated by charged desert dust at Al Ain in the 537 United Arab Emirates. Renno et al. (2008) developed an electric field mill for Mars. They 538 mentioned that a typical dust storm on Mars, such as with a charge density of 10^{-8} C/m³ and a wind 539 velocity of 20 m/s, generates an electric field of about 11 kV/m. Therefore, to monitor the AEF/PG 540 in a dusty environment, signals caused by the collisions of charged particles must be discriminated 541 from the signal of ambient AEF/PG. Furthermore, the measurements of the electric field mill are 542 applicable to automatic storm monitoring because the magnitude of the measured noise is possibly 543 correlated to that of the storm. For instance, the start and end times of blizzards, such as the events 544 at Syowa Station, have generally been identified from ocular observation. However, the electrical 545 observation using the field mill offers unmanned monitoring because the intense positive electric 546 field may be related to visibility. In further application, observations with the field mill were also 547 useful for snow drifting studies in areas with high mountains, such as the Alps and Mt. Fuji, to 548 mitigate snow avalanches (Gauer, 2001) and turbulent electrification monitoring for industrial dust

549 to avoid explosions.

550

551 **5. Conclusion**

552 We investigated the origin of the intense positive AEF/PG during blizzards/snowstorms and the 553 moderate negative AEF/PG just after a blizzard at Syowa Station, Antarctica. A Poisson calculation 554 with the negatively charged snow particles surrounding the sensor unit did not reproduce the 555 observed intense positive AEF/PG during the blizzard. This implies that the intense positive PG 556 during the blizzard should be the apparent electric field variation originating from the suspended 557 and saltating snow particles attached to the sensor. The moderate negative AEF/PG just after the 558 blizzard was reported for the first time. When a moderate negative electric field was observed, the 559 number of snow particles dropped at a point higher than the sensor unit of the electric field mill. 560 We modeled that the charge of the snow particles that had fallen and softly attached to the ground 561 on the ground surface remained during the negative AEF/PG. The Poisson calculation in the model 562 reproduced the negative electric field. Thus, we showed that the origins of the intense positive and 563 moderate negative electric fields during and after blizzards are the charged snow particles colliding 564 with the electric probe on the sensor unit and the negative snow layers softly attached to the ground.

565

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