



Measurements of positive ions and air-Earth current density at Maitri, Antarctica

Devendraa Siingh,^{1,2} Vimlesh Pant,¹ and A. K. Kamra¹

Received 4 October 2006; revised 1 April 2007; accepted 4 May 2007; published 13 July 2007.

[1] Simultaneous measurements of the small, intermediate and large positive ions and air-Earth current density made at a coastal station, Maitri (70°45'52"S, 11°44'03"E, 130 m above sea level), at Antarctica during January–February 2005, are reported. Although small and large positive ion concentrations do not show any systematic diurnal variations, variations in them are almost similar to each other. On the other hand, variations in intermediate positive ion concentrations are independent of variations in the small/large positive ions and exhibit a diurnal variation which is similar to that in atmospheric temperature on fair weather days with a maximum during the day and minimum during the night hours. No such diurnal variation in intermediate positive ion concentration is observed on cloudy days when variations in them are also similar to those in small/large positive ion concentrations. Magnitude of diurnal variation in intermediate positive ion concentration on fair weather days increases with the lowering of atmospheric temperature in this season. Scavenging of ions by snowfall and trapping of α -rays from the ground radioactivity by a thin layer of snow on ground is demonstrated from observations. Variations in intermediate positive ion concentration are explained on the basis of the formation of new particles by the photolytic nucleation process.

Citation: Siingh, D., V. Pant, and A. K. Kamra (2007), Measurements of positive ions and air-Earth current density at Maitri, Antarctica, *J. Geophys. Res.*, 112, D13212, doi:10.1029/2006JD008101.

1. Introduction

[2] Electrical state of the atmosphere is mostly determined by atmospheric ions. Their movements under electrical/non-electrical forces cause the flow of conduction and convection currents that determine their spatial and temporal distributions at any place. Concentrations and mobilities of these ions range over four orders of magnitude and are generally governed by the processes which generate and destroy them. The aerosol particles and trace gases ubiquitously present in the atmosphere play a major role in their evolution. Temporal and spatial variations of ions have been studied at several places [Wait and Torreson, 1934; Norinder and Siksna, 1953; Misaki, 1961; Jonassen and Wilkening, 1965; Misaki *et al.*, 1972]. Dhanorkar and Kamra [1991, 1992, 1993] have extensively studied the diurnal and seasonal variations of different categories of ions and their relative contributions to the atmospheric electric conductivity at a tropical land station, Pune. Hörrak *et al.* [2000, 2003] categorize the atmospheric ions in five different categories and study their properties at a midlatitude station, Tahkuse, Estonia. Hirsikko *et al.* [2005], from their measurements made at a station in southern Finland, observe that the concentrations and growth rates of the atmospheric ions and particles displayed a seasonal variability.

[3] Concentration of atmospheric ions over land areas is determined by several sources and sinks. Further, characteristics of these ions on land areas in tropical and midlatitude regions are grossly modified by the naturally and anthropogenically produced pollutants. So, their contributions to atmospheric electric conductivity are complex. However, at clean places such as over open oceans and polar regions, contributions of different types of ions to the atmospheric electric conductivity is mainly determined by the rate of small ion generation and concentration of background aerosols. The inverse relationship observed between the atmospheric electric conductivity and aerosol concentration has therefore been often used as an index of background air pollution at such places [Cobb and Wells, 1970; Kamra and Deshpande, 1995; Deshpande and Kamra, 2002].

[4] Antarctica provides a unique site which is practically free of anthropogenic pollution. Since more than 98% of the continent is covered by ice, the ionization produced by the ground radioactivity and its emissions which is a major source of ionization near the ground, is almost nil. However, being located near the South Magnetic Pole and as a result, the lines of force of Earth's magnetic field being perpendicular to the Earth's surface, the continent is exposed to a greater flux of high-energy particles which are known to penetrate and produce more ionization in the lower atmosphere than at other sites at lower latitudes. Therefore the sources and sinks of ions and their transport in the Antarctic environment are much different than those in the tropics and midlatitudes. Although measurements of several atmospheric electric parameters have often been made [e.g., Kasemir,

¹Indian Institute of Tropical Meteorology, Pune, India.

²Now at Institute of Environmental Physics, University of Tartu, Tartu, Estonia.



Figure 1. Ion counter installed at Maitri.

1972; Byrne *et al.*, 1993; Burns *et al.*, 1995; Bering *et al.*, 1998; Deshpande and Kamra, 2001; Virkkula *et al.*, 2005], to the author's knowledge, no measurements of atmospheric ions of different categories have so far been made at Antarctica. Knowledge of atmospheric ions is important not only to understand the electrical state of the atmosphere but also in understanding the global electric circuit [Roble and Tzur, 1986; Tinsley, 2000; Rycroft *et al.*, 2000; Singh *et al.*, 2004; Siingh *et al.*, 2007], nucleation and growth characteristics of aerosol particles [Tinsley and Heelis, 1993; Carslaw *et al.*, 2002; Harrison and Carslaw, 2003; Nadykto and Yu, 2003; Hirsikko *et al.*, 2005], monitoring of background air pollution [Cobb and Wells, 1970; Kamra and Deshpande, 1995], and in understanding the solar-terrestrial relationships [Markson, 1978; Markson and Muir, 1980].

[5] Here, we present our simultaneous measurements of the small, intermediate, and large positive ions and air-Earth current density made at Maitri ($70^{\circ}45'52''\text{S}$, $11^{\circ}44'03''\text{E}$, 130 m above mean sea level), Antarctica in January–February 2005 during the 24th Indian Scientific Expedition to Antarctica.

2. Instrumentation and Measurement Site

[6] Positive ion concentrations were measured with an ion counter of the type described by Dhanorkar and Kamra

[1991] and shown in Figure 1. It consists of three coaxial Gerdiens condensers through which the air is sucked with a single fan. Table 1 details the measurements of all the three condensers. Ranges of mobility covered by each condenser are described in Table 2.

[7] Several steps were taken to minimize the effects of the harsh Antarctic weather on our measurements. Nonmagnetic stainless steel was used for fabricating the ion counter. All electronic components used for making the electronic cir-

Table 1. Dimensions and Other Parameters of Three Condensers of the Ion Counter

Dimensions/Constants	Small Ion Condenser	Intermediate Ion Condenser	Large Ion Condenser
Length of the outer electrode, m	0.4	0.8	1.2
Length of the inner electrode, m	0.2	0.5	1.0
Diameter of the outer electrode, m	0.098	0.06	0.038
Diameter of the inner electrode, m	0.076	0.037	0.022
Potential applied, V	15	100	600
Critical mobility, $\text{m}^2 \text{V}^{-1} \text{s}^{-1}$	0.766×10^{-4}	1.2×10^{-6}	0.97×10^{-8}
Flow rate, l s^{-1}	8.6	1.8	0.29

Table 2. Mobility and Size Ranges of Ions

Category	Small Ions	Intermediate Ions	Large Ions
Mobility range, $\text{m}^2 \text{V}^{-1} \text{s}^{-1}$	$>0.77 \times 10^{-4}$	1.21×10^{-6} to 0.77×10^{-4}	0.97×10^{-8} to 1.21×10^{-6}
Diameter range, nm	<1.45	1.45–12.68	12.68 to ~ 130

country were of military grade which can operate well up to subfreezing temperatures of -40°C . Coaxial cables with Teflon insulation were used for carrying signals from ion counter to the data logger. To minimize the effect of strong winds on the suction rates in condensers, ion counter was placed with its condensers perpendicular to the prevailing wind direction.

[8] To check the stability of the instrument, zero-checking of individual condensers were performed periodically by grounding the inputs. No appreciable zero-shift was observed in fair weather and even in light snowfall. Whenever the snowfall continued beyond a few hours, zero was found to shift and observations were discontinued.

[9] Air-Earth current density is measured with a 1 m^2 flat-plate antenna kept flush with the ground and is shown in Figure 2. The inputs from all the three condensers of the ion counter and the air-Earth current plate are amplified with separate amplifiers placed close to the sensors and then fed through coaxial cables to a data logger placed in a nearby hut.

[10] Measurements were made at Maitri located in the Schirmacher oasis in the Dronning Maud Land, East Antarctica. The east trending oasis is exposed over an area of 35 km^2 with 16 km length and a maximum of 27 km width. It has a lake and then steep cliffs toward the ice shelf and is covered by polar ice on the southern side. The area is dominantly covered by sandy and loamy sand type of soil. Measurements of Rn^{222} and small ions made at Maitri show that their atmospheric concentrations close to ground are very low and not much different from that over sea [Ramachandran and Balani, 1995].

[11] Figure 3 shows the location of Maitri ($70^\circ45'52''\text{S}$, $11^\circ44'03''\text{E}$, 130 m above sea level) at the Antarctic continent, the location of instruments at the Maitri station and a scatter polar diagram of 3-hourly surface winds for the period of observations at Maitri. Maitri is located $\sim 80 \text{ km}$ south of the coastal line. Prevailing direction of winds is southeasterly. Ion counter was placed on the ground with the inlet of the small and intermediate positive ion con-

**Figure 2.** Air-Earth current plate antenna installed at Maitri.

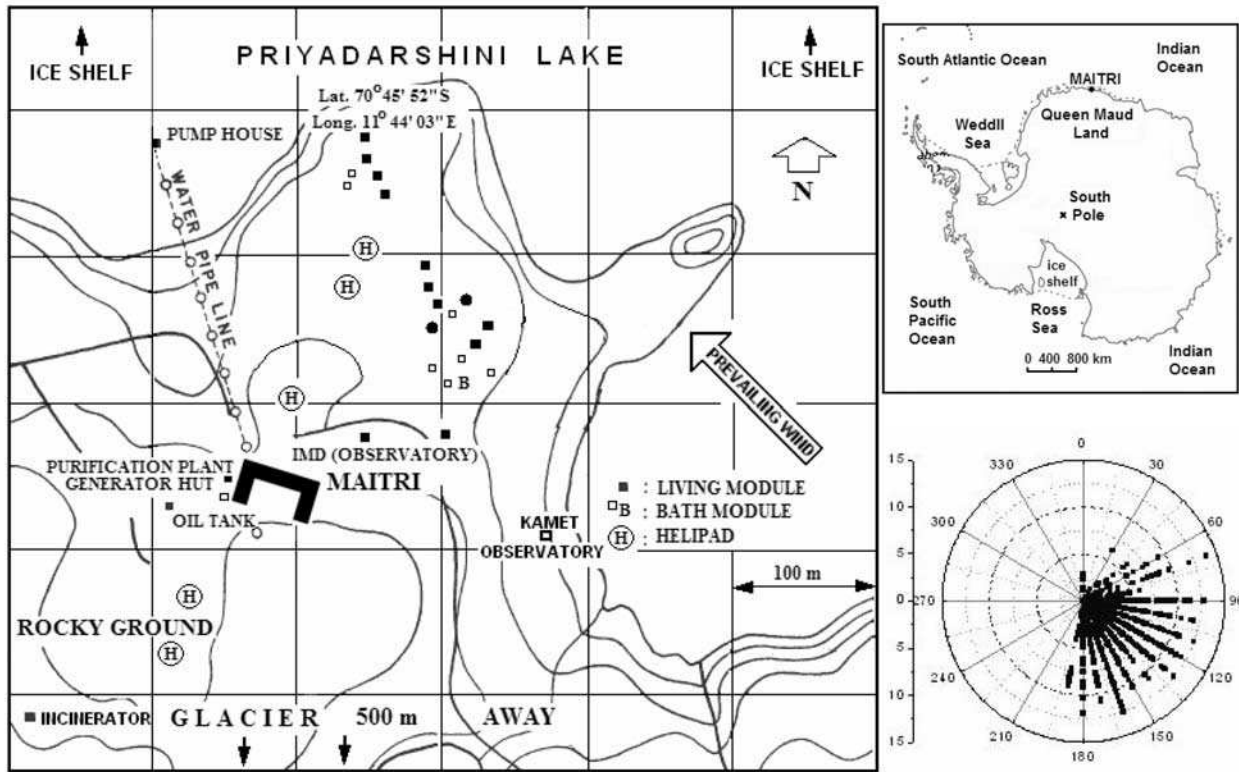


Figure 3. Map of Antarctica, showing the location of Maitri station. Location of instruments (Kamet observatory) at Maitri and the wind rose showing the magnitudes and directions of wind speed during the January to February 2005 period.

densers at 50 cm and large ion condenser at 60 cm above the ground. The air-Earth current plate was placed flush with the ground. The single storied building of Maitri station, the generators, gas plant and incinerator are about ~300 m away in the southwest direction from the instruments so that any pollutants released from them have no or little chance of reaching the site of measurements with the prevailing winds.

3. Observations

3.1. Daily Average Concentrations of Ions

[12] Figure 4 shows the daily average values of the small, intermediate, and large positive ion concentrations and air-Earth current density for the entire period of measurements at Maitri. Vertical bars show the standard deviations. Concentrations of small, intermediate and large positive ions vary in the ranges of 2 to $6 \times 10^2 \text{ cm}^{-3}$, 7×10^2 to $3 \times 10^3 \text{ cm}^{-3}$, and from 5×10^3 to $1.2 \times 10^4 \text{ cm}^{-3}$ respectively and the air-Earth current density varies from 0.5 to $1.6 \times 10^{-12} \text{ A m}^{-2}$ during this period. Values of all categories of ions start increasing between the Julian day 15 to 18 and, except for a dip observed around Julian day 22, are 1.5 to 2 times larger up to the Julian day 45 as compared to the periods immediately before or after this period. Variations in air-Earth current during this period follow similar trend. In comparison to continental stations in the Northern Hemisphere, these values are roughly 50–80% lower than that at a tropical station, Pune [Dhanorkar and Kamra,

1992] and more than those at midlatitude station at Tahkuse [Hörrak et al., 2003] in the Northern Hemisphere. In particular, the intermediate positive ion concentration at Maitri is about an order of magnitude higher than those at Tahkuse in this season.

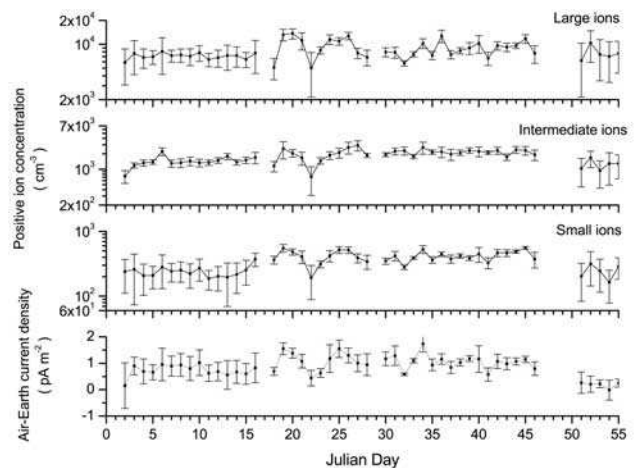


Figure 4. Daily average values of the small, intermediate, and large positive ion concentrations and air-Earth current density for Julian days in 2005. Vertical bars show the standard deviations.

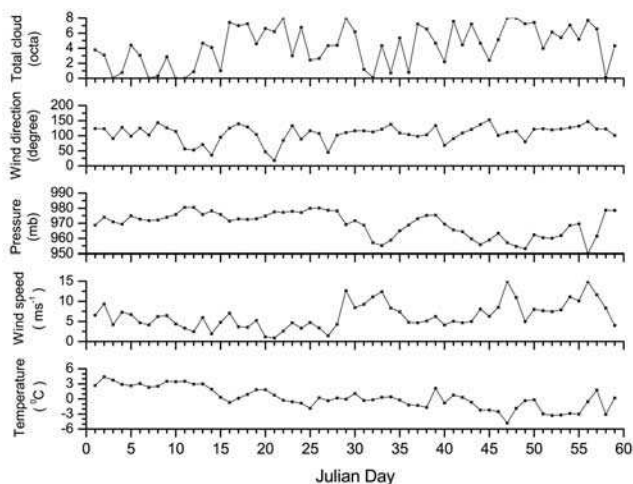


Figure 5. Daily average values of meteorological parameters.

[13] The variations in electrical parameters do not show much similarity with the variations in meteorological parameters at Maitri (Figure 5). The daily average atmospheric temperature, however, from Julian day 15 to 47 drops by 4°C, from 2°C above freezing point to 2°C below freezing point. Very strong winds prevailed after 1800 UT and the station experienced snowfall during the night of Julian day 46.

[14] A characteristic feature in our measurements is 2–4 hours periods when the small and large positive ion concentrations simultaneously increase or decrease by about an order of magnitude. Air-Earth current density also shows a similar change during these periods. However, intermediate positive ion concentration does not necessarily show any

corresponding change. Figure 6 shows two examples of such changes when the intermediate positive ion concentration does not show (Figure 6a) or shows (Figure 6b) changes similar to, small/large positive ion concentrations. Such changes are not associated with change in any of the 3-hourly observed meteorological parameters at Maitri. Further, an examination of the 5-day back trajectories around and during such events does not show any significant change in the place of origin of the air mass. However, association of such changes with changes in the high-energy particle fluxes which may cause change in ionization and thus increase the small ion concentrations, cannot be ruled out. The corresponding changes in large positive ion concentration may follow because of the ion-aerosol attachment process.

3.2. Diurnal Variations

[15] At Maitri, concentrations of small and large positive ions do not show any systematic diurnal variations on fair weather days. However, they exhibit a very high degree of similarity in variations among themselves. For example, Figure 7 shows diurnal variations of the concentrations of three categories of positive ions and the air-Earth current density on a typical fair weather day, 10 January 2005. On this day, atmospheric pressure varied from 971 to 973 hPa with no trace of cloud throughout the day, except for moderately strong southeasterly winds during night and morning hours. Winds were calm or very light and temperature gradually increased from -1°C at 0100 UT, attained a maximum of 6°C at 0900 UT and then decreased to 2°C at 2400 UT. Sunshine lasted for almost all the 24 hours of the day. Small positive ion concentrations on this day were less than $3 \times 10^2 \text{ cm}^{-3}$ and were minimum at about 0900 UT. Large positive ion concentrations, though more than an order of magnitude higher, closely follow the variations in small positive ion concentration. The intermediate positive

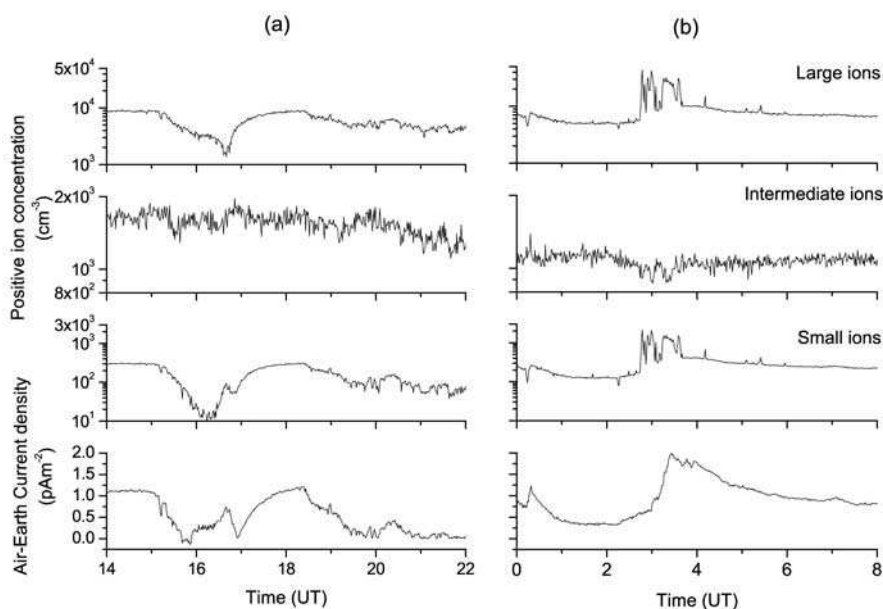


Figure 6. Variations in small, intermediate, and large positive ion concentrations and air-Earth current density on (a) 12 January and (b) 3 January 2005.

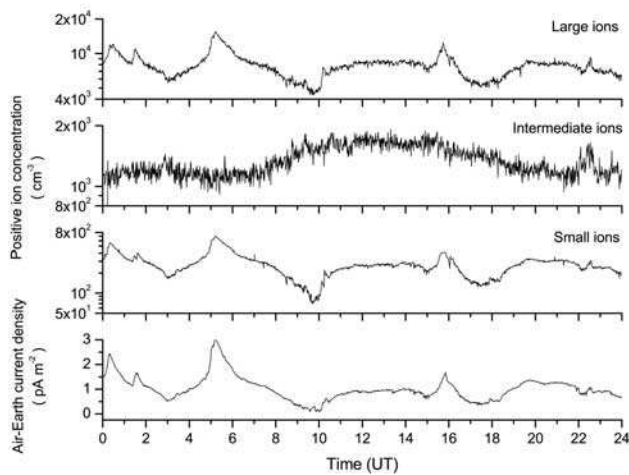


Figure 7. Diurnal variations of small, intermediate and large positive ion concentrations and air-Earth current density on a fair weather day, 10 January 2005.

ion concentrations change little in the range of 1 to $2 \times 10^3 \text{ cm}^{-3}$ and vary independent of variations in small/large positive ion concentrations. In contrast to the small/large positive ion concentrations, the diurnal variation in intermediate positive ion concentrations are much regular and generally follow the trend in atmospheric temperature and are comparatively higher during the day than the night hours. The air-Earth current density varies from 0 to $1.8 \times 10^{-12} \text{ A m}^{-2}$ and almost exactly follows the variations in small/large positive ion concentrations.

[16] During afternoons, the values of small and large positive ion concentrations at Maitri are comparable to those observed at tropical station, Pune [Dhanorkar and Kamra, 1993] and at midlatitude station, Tahkuse [Hörrak et al., 2003]. However, the maxima observed in the morning hours at Pune are not observed at Maitri. The day and night values also do not show much systematic difference at Maitri as at Pune and Tahkuse. On the other hand, the

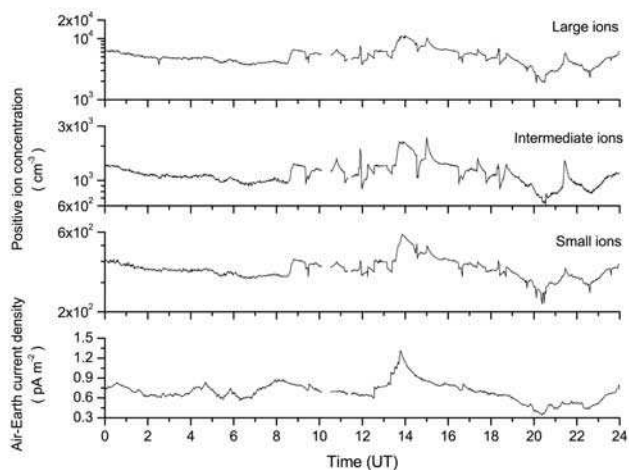


Figure 8. Diurnal variations of small, intermediate and large positive ion concentrations and air-Earth current density on a cloudy day, 18 January 2005.

intermediate positive ion concentrations at Maitri are about an order of magnitude higher than that at Tahkuse. The intermediate positive ion concentrations at Maitri are comparable to the afternoon values but much lower than the morning maxima values at Pune. Diurnal variation of intermediate ion concentrations shows a distinct maximum at all the three locations but at different times, e.g., during 0600–0800 UT at Pune, during 1200 to 1300 UT at Tahkuse and during 0900–1600 UT at Maitri. Unlike at Pune or Tahkuse the maxima at Maitri is much broader and is almost flat for several hours in the afternoon.

[17] In sharp contrast to the diurnal variations on fair weather days, the intermediate ion concentrations on cloudy days do not show any maximum in the afternoon hours and follow the variations in small/large positive ion concentrations (Figure 8). For example, on 18 January 2005, the sky remained covered for the entire day with more than 6 octa of clouds. Southeasterly winds of $2\text{--}5 \text{ m s}^{-1}$ and temperatures from -2 to $+3^\circ\text{C}$ prevailed over the station. Concentrations of all categories of positive ions were comparatively small and showed much smaller variability during the whole day. Variations in air-Earth current density on such cloudy days closely follow the variations in either category of positive ions.

3.3. Effect of Snowfall

[18] Snowfall, just like rainfall, is considered to be an effective scavenger of atmospheric aerosols and ions. Our observations at Maitri provide several good cases of its demonstration. For example, Figure 9 shows that with the start of snowfall at about 0400 UT on the Julian day 22 the concentrations of all categories of ions fall by about an order of magnitude and continue to be low until 0800 UT when observations had to be discontinued because of heavy snowfall. During this period, sky remained overcast with southeasterly winds remaining below 5 m s^{-1} and atmospheric temperatures in the range of 0 to -2°C . Lowest values of the ion concentrations encountered during this period are 10 ions cm^{-3} for small positive ions, $10^2 \text{ ions cm}^{-3}$ for intermediate positive ions and $3 \times 10^2 \text{ ions cm}^{-3}$

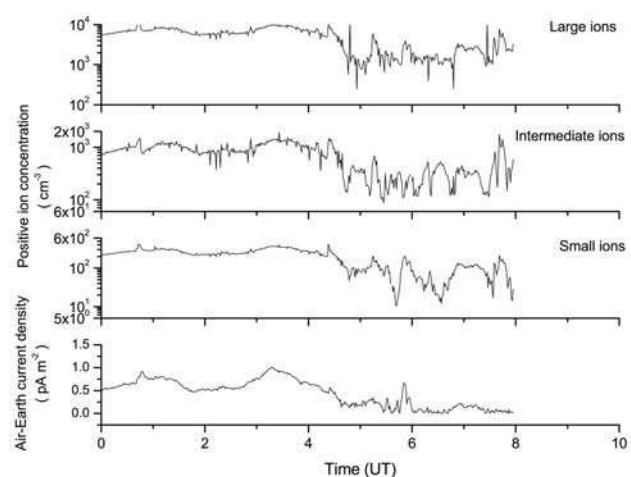


Figure 9. Change in concentrations of positive ions and air-Earth current density due to snowfall on 22 January 2005.

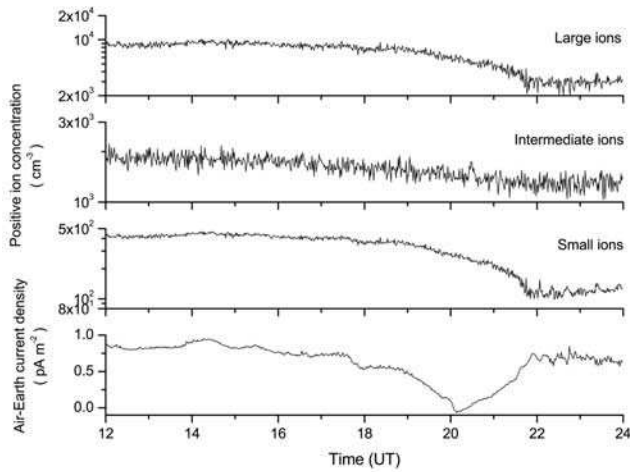


Figure 10. Change in concentrations of positive ions and air-Earth current density during a blizzard on 15 February 2005.

for large positive ions. Although ion concentrations in each category fall, time variations in one category need not exactly follow the variations in other category. Air-Earth current density also falls to very low or almost zero value during the period of snowfall.

3.4. Effect of Blizzard

[19] *Simpson* [1919] observed that blizzards are intensely electrified and produce high positive potential gradients on the ground. In our observations we observe that whenever

high winds are accompanied with some snowfall, i.e., atmospheric temperature are below freezing point, positive ion concentration of all the three categories begin to decrease about 3–4 hours before the appearance of snow. For example, on 15 February 2005, winds begin to strengthen at 1800 UT and snowfall started from 2255 UT. Concentrations of all the three ion categories begin to decrease at 1830 UT and decrease by approximately 2–4 times by 2200 UT (Figure 10). Although blizzard continued for the next two days, our observations could not be continued beyond midnight on 15 February when wind speed exceeded 30 m s^{-1} .

3.5. Effect of Snow-Covered Ground

[20] α - and β -rays emitted from the ground are primary sources of ionization close to ground. α -rays are emitted by the radioactive decay of radon. The soil around Maitri is found to have a uranium (U^{238}) content varying from 0.036 to 0.364 ppm which is very small in comparison to the range of levels of 1.47 to 4.07 ppm estimated from various types of Indian soil [*Ramachandran and Balani, 1995*]. In the region free of human activity, such as at Maitri, presence of U^{238} in the soil is mainly attributed to geochemical processes. These emissions can be effectively trapped by a thin layer of ice over ground. During the period of our observations, ample opportunity was provided when the Earth’s surface at Maitri was completely bare or covered with a layer of snow. The snow that deposited on the ground during the snowfall on 22–23 January 2005 completely covered the ground but melted away and left the ground bare by 25 January 2005. Figure 11 shows the positive ion concentrations and air-Earth current density on 23 and

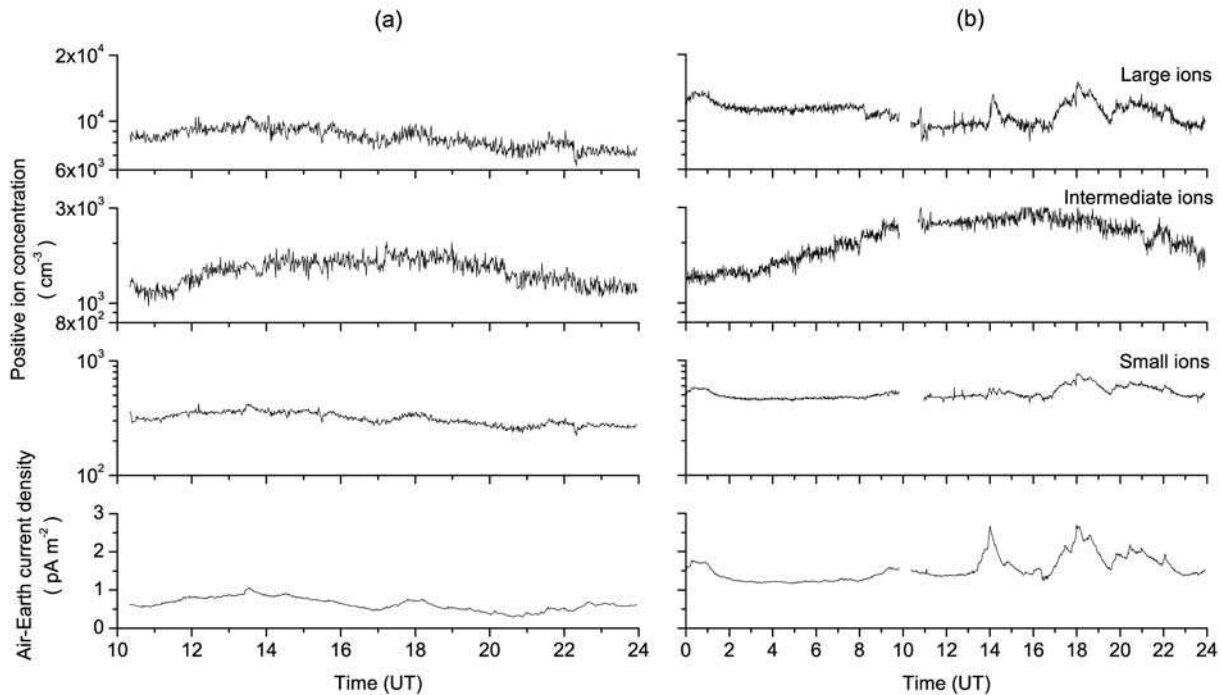


Figure 11. Diurnal variations of the small, intermediate and large positive ion concentrations and air-Earth current density on two fair weather days when the ground (a) was covered with snow on 23 January 2005 or (b) was bare on 25 January 2005.

25 January 2005 when the ground was completely covered or bare, respectively. Both days were otherwise marked with fair weather and bright sunshine. Concentrations of all categories of positive ions increase by 100 to 400% on 25 January. An important feature of observations is almost uniform concentration of about 3×10^2 ions cm^{-3} of small positive ions throughout the day on 23 January when the ground is covered with snow.

4. Discussion

[21] The small ions produced in the atmosphere soon get attached to aerosol particles and form large ions. In the absence of any other mechanisms directly producing large ions, the variations in small and large ion concentrations are therefore expected to closely follow each other. The close parallelism observed here between the small and large positive ion concentrations during the fair weather periods strongly supports this fact that the ion-aerosol attachment process is the only dominant source for the production of large ions at Maitri. It also demonstrates almost total absence of any effect due to the ions or aerosols produced from anthropogenic sources on land on the Antarctic measurements. Further, almost parallel variations in the air-Earth current density and small/large positive ion concentrations confirm the fact that the air-Earth current is mainly determined by the small ions. The electric field measurements made in 1997 in the same season at this station show that its diurnal variation exhibits a maximum at 1300 UT and another secondary maximum at 1900 UT with its daily average value as 83 Vm^{-1} [Deshpande and Kamra, 2001]. During the same season, the mean total conductivity value is $2.1 \times 10^{-14} \text{ Sm}^{-1}$ [Deshpande and Kamra, 2001].

[22] Large ion concentrations in our observations are certainly higher than the expected at a clean site, like Maitri. Some of the likely reasons for this observation are as follows: (1) Being a coastal station, some of the marine aerosols being generated over ocean may be transported to the site, this being especially so during the periods when the cyclonic storms revolving around the Antarctic continent penetrate up to the Maitri station, which happens quite frequently. (2) Some of the intermediate ions being generated over ice glacier south of the Maitri grow to the large ion size during their transportation to Maitri with the prevailing wind from southeast. (3) Ion counter is placed with its inlet 60 cm above the ground which is bare in this season at Maitri. High winds prevailing at Maitri can strip off some dust particles from the sandy and loamy sand type of soil. Such dust particles, though expected to be large in size, may carry multiple charges so as to be counted as large ions.

[23] Another factor that may contribute to large ion concentration is the formation of some doubly and multiply charged aerosols during ion-aerosol interactions. These multiply charged aerosol particles even though larger in size as compared to large ions can be collected in large ion condenser because of their higher mobilities and be counted as large ions. The percentage of multiply charged ions in the aerosols plays a significant role only in very pure air having aerosol concentration of $<5000 \text{ cm}^{-3}$ [Hogg, 1934a, 1934b]. Moreover, multiply charged ions gain in importance only when radius of the particles exceeds 10 nm [Israel, 1970; Fuchs, 1964]. The environmental conditions

at Antarctica where aerosol concentrations are low and aerosols generally consist of aged particles are suitable for the formation of such multiply charged ions. However, percentage of such multiply charged ions is not likely to exceed 20% of singly charged ions [Hogg, 1934a, 1934b; Fuchs, 1964] and is not included in our calculations.

[24] On the contrary, almost independent behavior of the variations of intermediate positive ion concentrations at Maitri suggests that the mechanism responsible for their production is independent of the mechanism responsible for small/large positive ion production. Moreover, the observations that the variations in intermediate positive ion concentration and atmospheric temperature are almost parallel to each other on the fair weather days and this parallel behavior between the two parameters disappears on cloudy days, strongly suggest that the mechanism responsible for the production of intermediate positive ions is strongly dependent on the solar radiation. Supporting this is the fact that in spite of different surface conditions on the two days in Figure 11 the diurnal variations in the intermediate positive ion concentration and surface temperature on both days are similar because both are fair weather days and have plenty of solar radiation throughout the day. With the abundance of solar radiation, sulphate and low humidity conditions present in the Antarctic environment the production of intermediate ions can occur by nucleation process. Hörrak *et al.* [1998] suggested that cluster ions can grow into intermediate size ions through ion-induced nucleation processes, i.e., accumulation of environmental vapors under proper conditions.

[25] The decrease observed in all types of positive ion concentrations and the air-Earth current density during snowfall indicates that snow particles effectively scavenge the ions. The fact that the air-Earth current density almost reduces to zero value indicates that scavenging of atmospheric ions is almost total at that time. The observations that the decrease in different ion categories is not always parallel to each other are likely to result from the nonuniform rate of scavenging of the ions of different sizes.

[26] The observed decrease in all categories of positive ion concentrations when the ground is covered by a thin layer of snow shows an effective trapping of α and β rays from the ground by a thin layer of snow. Though small but rather distinct difference in small ion concentration over a snow-covered or bare ground supports the observations of Ramachandran and Balani [1995] that radioactive emissions from the rocks at Schirmacher are low and almost comparable to that of seawater. Further, almost constant concentration of small positive ions throughout the whole day when the ground is covered with snow indicates almost uniform production of small ions by cosmic rays and γ rays in the lower atmosphere.

[27] **Acknowledgments.** Authors express their gratitude to National Centre for Antarctic and Ocean Research (NCAOR) and Department of Ocean Development (DOD) for participation in the 24th Indian Antarctic Expedition. The meteorological data provided by India Meteorological Department are thankfully acknowledged. D.S. would like to thank DST, Government of India, under the BOYSCAST programme (with reference SR/BY/A-19/05).

References

Bering, E. A., A. A. Few, and J. R. Benbrook (1998), The global electric circuit, *Phys. Today*, (Oct. 1998), 24–30.

- Burns, G. B., M. H. Hesse, S. K. Parcell, S. Malachowski, and K. D. Cole (1995), The geoelectric field at Devis station, Antarctica, *J. Atmos. Terr. Phys.*, *57*, 1783–1797.
- Byrne, G. J., J. R. Benbrook, E. A. Bering, A. A. Few, G. A. Morris, W. J. Trabucco, and E. W. Paschal (1993), Ground-based instrumentation for measurements of atmospheric conduction current and electric field at the South Pole, *J. Geophys. Res.*, *98*(D2), 2611–2618.
- Carslaw, K. S., R. G. Harrison, and J. Kirkby (2002), Cosmic rays, clouds, and climate, *Science*, *298*, 1732–1737.
- Cobb, W. E., and H. J. Wells (1970), The electrical conductivity of oceanic air and its correlation to global atmospheric pollution, *J. Atmos. Sci.*, *27*, 814–819.
- Deshpande, C. G., and A. K. Kamra (2001), Diurnal variations of atmospheric electric field and conductivity at Maitri, Antarctica, *J. Geophys. Res.*, *106*, 14,207–14,218.
- Deshpande, C. G., and A. K. Kamra (2002), Atmospheric electric conductivity measurements over the Indian Ocean during the Indian Antarctic Expedition in 1996–1997, *J. Geophys. Res.*, *107*(D21), 4598, doi:10.1029/2002JD002118.
- Dhanorkar, S., and A. K. Kamra (1991), Measurement of mobility spectrum and concentration of all atmospheric ions with a single apparatus, *J. Geophys. Res.*, *96*, 18,671–18,678.
- Dhanorkar, S., and A. K. Kamra (1992), Relation between electrical conductivity and small ions in the presence of intermediate and large ions in the lower atmosphere, *J. Geophys. Res.*, *97*, 20,345–20,360.
- Dhanorkar, S., and A. K. Kamra (1993), Diurnal variations of the mobility spectrum of ions and size distribution of fine aerosols in the atmosphere, *J. Geophys. Res.*, *98*, 2639–2650.
- Fuchs, N. A. (1964), *The Mechanics of Aerosols*, 408 pp., Elsevier, New York.
- Harrison, R. G., and K. S. Carslaw (2003), Ion-aerosol-cloud processes in the lower atmosphere, *Rev. Geophys.*, *41*(3), 1012, doi:10.1029/2002RG000114.
- Hirsikko, A., L. Laakso, U. Horrak, P. P. Aalto, V. M. Kerminen, and M. Kulmala (2005), Annual and size dependent variation of growth rates and ion concentrations in boreal forest, *Boreal Environ. Res.*, *10*, 357–369.
- Hogg, A. R. (1934a), Atmospheric electric observations, *Gerl. Beitr. Geophys.*, *41*, 1–31.
- Hogg, A. R. (1934b), Some observations of the average life of small ions and atmospheric ionization equilibria, *Gerl. Beitr. Geophys.*, *41*, 32–54.
- Hörrak, U., J. Salm, and H. Tammet (1998), Bursts of intermediate ions in atmospheric air, *J. Geophys. Res.*, *103*, 13,909–13,915.
- Hörrak, U., J. Salm, and H. Tammet (2000), Statistical characterization of air ion mobility spectra at Tahkuse Observatory: Classification of air ions, *J. Geophys. Res.*, *105*, 9291–9302.
- Hörrak, U., J. Salm, and H. Tammet (2003), Diurnal variation in the concentration of air ions of different mobility classes in a rural area, *J. Geophys. Res.*, *108*(D20), 4653, doi:10.1029/2002JD003240.
- Israel, H. (1970), *Atmospheric Electricity*, vol. I, Israel Program for Sci. Translations, Ltd., Natl. Sci. Foundation, Washington, D. C.
- Jonassen, J., and M. H. Wilkening (1965), Conductivity and concentration of small ions in the lower atmosphere, *J. Geophys. Res.*, *70*, 779–784.
- Kamra, A. K., and C. G. Deshpande (1995), Possible secular change and land-to-ocean extension of air pollution from measurements of atmospheric electrical conductivity over the Bay of Bengal, *J. Geophys. Res.*, *100*, 7105–7110.
- Kasemir, H. W. (1972), Atmospheric electric measurements in the Arctic and Antarctic, *Pure Appl. Geophys.*, *100*, 70–80.
- Markson, R. (1978), Solar modulation of atmospheric electrification and possible implication for the Sun-Weather relationship, *Nature*, *273*, 103–105.
- Markson, R., and M. Muir (1980), Solar wind control of the Earth's electric field, *Science*, *208*, 979–990.
- Misaki, M. (1961), Studies on the atmospheric ion spectrum, II, Relation between the ion spectrum and the electrical conductivity, *Pap. Meteorol. Geophys.*, *12*, 261–276.
- Misaki, M., M. Ohtagaki, and I. Kanazawa (1972), Mobility spectrometry of the atmospheric ions in relation to atmospheric pollution, *Pure Appl. Geophys.*, *100*, 133–145.
- Nadykto, A., and F. Yu (2003), Uptake of neutral polar vapor molecules by charged particles: Enhancement due to dipole-charge interaction, *J. Geophys. Res.*, *108*(D23), 4717, doi:10.1029/2003JD003664.
- Norinder, H., and R. Siksnia (1953), Variations of the concentration of ions at different heights near the ground during quiet summer nights at Uppsala, *Ark. Geophys.*, *1*, 519–541.
- Ramachandran, T. V., and M. C. Balani (1995), Report on the participation by the Bhabha Atomic Research Centre in the Tenth Indian Expedition to Antarctica, *Scientific Report on Tenth Indian Expedition to Antarctica*, *Tech. Publ. 8*, pp. 159–180, Dept. of Ocean Devel., Govt. of India, New Delhi, India.
- Roble, R. G., and I. Tzur (1986), The global atmosphere electrical circuit, in *The Earth's Electrical Environment*, edited by E. P. Krider and R. G. Roble, pp. 206–231, Natl. Acad. Press, Washington, D. C.
- Rycroft, M. J., S. Israelsson, and C. Price (2000), The global atmospheric electric circuit, solar activity and climate change, *J. Atmos. Solar Terr. Phys.*, *62*, 1563–1576.
- Singh, D., V. Gopalakrishnan, R. P. Singh, A. K. Kamra, S. Singh, V. Pant, R. Singh, and A. K. Singh (2007), The atmospheric global electric circuit: An overview, *Atmos. Res.*, *84*, 91–110.
- Simpson, G. C. (1919), *British Antarctic Expedition 1910–1913*, 326 pp., Thacker, Spink and Co., England.
- Singh, D. K., R. P. Singh, and A. K. Kamra (2004), The electrical environment of the Earth's atmosphere: A review, *Space Sci. Rev.*, *113*, 375–408.
- Tinsley, B. A. (2000), Influence of solar wind on the global electric circuit, and inferred effects on the cloud microphysics, temperature, and dynamics in troposphere, *Space Sci. Rev.*, *94*, 231–258.
- Tinsley, B. A., and R. A. Heelis (1993), Correlations of atmospheric dynamics with solar activity: Evidence for a connection via the solar wind, atmospheric electricity and cloud microphysics, *J. Geophys. Res.*, *98*, 10,375–10,384.
- Virkkula, A., M. Vana, A. Hirsikko, P. A. Aalto, M. Kulmala, and R. Hillamo (2005), Air ion mobility and aerosol particle size distributions at the Finnish Antarctic research station Aboa, in *Abstracts of the European Aerosol Conference 2005*, edited by W. Maenhaut, 698 pp., Elsevier, New York.
- Wait, G. R., and D. W. Torrison (1934), The large-ion and small-ion content of atmosphere at Washington, D. C., *J. Geophys. Res.*, *39*, 111–119.

A. K. Kamra and V. Pant, Indian Institute of Tropical Meteorology, Pune 411 008, India. (kamra@tropmet.res.in)

D. Siingh, Institute of Environmental Physics, University of Tartu, 18, Ulukooli Street, Tartu 50090, Estonia.