Ann. Geophysicae 16, 1544–1551 (1998) © EGS – Springer-Verlag 1998

Annales Geophysicae

Effects of geomagnetic activity on the mesospheric electric fields*

A. M. Zadorozhny and A. A. Tyutin

Novosibirsk State University, Pirogova 2, Novosibirsk 630090, Russia

Received: 2 February 1998 / Revised: 13 May 1998 / Accepted: 15 May 1998.

Abstract. The results of three series of rocket measurements of mesospheric electric fields carried out under different geomagnetic conditions at polar and high middle latitudes are analysed. The measurements show a clear dependence of the vertical electric fields on geomagnetic activity at polar and high middle latitudes. The vertical electric fields in the lower mesosphere increase with the increase of geomagnetic indexes K_p and $\sum K_p$. The simultaneous increase of the vertical electric field strength and ion conductivity was observed in the mesosphere during geomagnetic disturbances. This striking phenomenon was displayed most clearly during the solar proton events of October, 1989 accompanied by very strong geomagnetic storm ($K_p = 8+$). A possible mechanism of generation of the vertical electric fields in the mesosphere caused by gravitational sedimentation of charged aerosol particles is discussed. Simultaneous existence in the mesosphere of both the negative and positive multiply charged aerosol particles of different sizes is assumed for explanation of the observed V/m vertical electric fields and their behaviour under geomagnetically disturbed conditions.

Keywords. Atmospheric composition and structure (aerosols and particles) · Ionosphere (electric fields and currents) · Meteorology and atmospheric dynamics (atmospheric electricity)

1 Introduction

More than 20 rocket measurements of vertical electric fields in the middle atmosphere were carried out during the last two decades using field mill technique (Bragin *et al*., 1974; Tyutin, 1976, 1988; Zadorozhny *et al*., 1989, 1993, 1994a,b). Large vertical fields with strength exceeding ~1 V/m have been detected in the lower mesosphere during nearly all of these measurements. The experiments carried out with the help of a double probe technique have also shown these large vertical fields but only occasionally (Hale and Croskey, 1979; Hale *et al*., 1981; Maynard *et al*., 1981, 1984; Hale, 1984; Croskey *et al*., 1985, 1990). By now, some regularities concerning the electric field behaviour in the mesosphere have been clarified (Bragin *et al*., 1981; Goldberg, 1984, 1989; Goldberg and Holzworth, 1991; Zadorozhny *et al*., 1989, 1994a,b; Zadorozhny and Tyutin, 1997). However, the nature of the large vertical fields as well as the role they play in the physics and the chemistry of the middle atmosphere have not yet been clarified. Here we continue to analyse the available experimental data in order to understand the nature of the fields. The results of three series of simultaneous measurements of the mesospheric electric fields, ion density and conductivity carried out under different geomagnetic conditions at polar and high middle latitudes (Zadorozhny *et al*., 1989, 1994a) are analysed here. The first two series were carried out in the Northern Hemisphere on Heiss Island (80.6°N). The third one was taken in the Southern Hemisphere (50–60°S) in the Indian Ocean on board the research vessel. We discuss here also a possible mechanism of generation of the vertical electric fields in the mesosphere caused by gravitational sedimentation of charged aerosol particles.

2 Instruments and methods of measurements

The measurements of the vertical component of the electric field strength E_z, positive ion density n_i, and ion conductivity σ_i were carried out by means of instruments installed in the top part of the meteorological rocket M-100B. Two kinds of payload for the M-100B rocket were used. The EI-100 payload contains an electric field mill probe, a plane multigrid ion trap, and a

Correspondence to: A. M. Zadorozhny
E-mail: zadorozh@phys.nsu.ru Phone: 7-3832-397859
Fax: 7-3832-397101

*Paper Presented at the Second IAGA/ICMA (IAMAS) Workshop on Solar Activity Forcing of the Middle Atmosphere, Prague, August 1997 relaxation sensor for positive and negative electrical conductivity. The M-100KT payload contains the field mill, a spherical grid condenser for measurements of positive ion density, and a resistance wire thermometer. Three EI-100 payloads were launched successfully from Heiss Island during the experiments in winter 1983/1984. The M-100KT payloads were used for the experiments in 1989 also on Heiss Island and in the Indian Ocean.

The vertical component of the electric field strength was measured by means of the electric field mill probe (Tyutin, 1976). The electric field mill operation is based on principle of a rotational capacitor. External electric fields induce the charge on plates of the rotational capacitor. If the capacitor is loaded by a resistor, an alternating current is produced in a circuit with the frequency of rotation of the capacitor. A current amplitude is proportional to the component of the external electric field, which is perpendicular to the axis of rotation of the capacitor. Placement of the sensor in the payload was adjusted for the purpose of measuring a vertical component of the electric field strength. A more detailed description of the electric field mill with a special emphasis on a reality of rocket measurement of the atmospheric electric fields can be found in the paper by Zadorozhny *et al.* (1994a).

Conductivity measurements were made by means of a technique based on the determination of the relaxation time constant of the medium (Bragin *et al.*, 1973). In order to measure the conductivity a fixed positive or negative voltage biases a metallic sphere and then the potential of the sphere is measured while the sphere discharges due to negative or positive conductivity of the medium to its floating potential. Both positive and negative conductivities were measured in our experiments.

The plane and spherical grid condensers were used to measure positive ion density (Smirnykh, 1976; Kikhtenko, 1978). The outer grid of the condenser is held at rocket potential, whereas a fixed negative voltage biases the inner grid. This results in separation of positive and negative ions penetrating into the condenser with an incoming flux of air. The value of n_i is calculated from the positive ion current collected on the inner grid. The potential difference between the grids ensures registration of the ions with mobilities corresponding to masses up to about few thousands of AMU.

3 Experimental results

The first series of the measurements was taken in winter 1983/1984 at polar latitudes in the Northern Hemisphere on Heiss Island (80.6°N) (Zadorozhny *et al.*, 1989). The second one was carried out in February – March 1989 also on Heiss Island (Zadorozhny *et al.*, 1994a). The third series was taken in September – October 1989 at high middle latitudes (50–60°S) in the Southern Hemisphere in the Indian Ocean on board the research vessel (Zadorozhny *et al.*, 1994a). Positive ion density and electrical conductivity were measured simultaneously with the vertical electric field, but information on these parameters is absent in some cases. A list of the rocket flights is given Table 1. Indexes of geomagnetic activity K_p and $\sum K_p$ for the days of the rocket launches as well as maximum values of the vertical electric field strengths measured in the mesosphere during the flights are given in Table 1, too.

The results of the vertical electric field measurements above Heiss Island and the Indian Ocean are shown in Fig. 1. Figure 2 shows the temporal variations of the magnetic field at Heiss Island on the days of the rocket launches during the first series of measurements in winter 1983/1984.

The first two measurements took place at Heiss Island in the quiet geomagnetic period ($\sum K_p = 5+$ and $\sum K_p = 8+$ the days before the rocket launches and $K_p = 0$ and $K_P = 1+$ during the flights). The third rocket was launched under geomagnetically disturbed conditions ($\sum K_p = 11+$ the day before the launch and $K_p = 3+$ during the flight). The fluctuation of the magnetic field was limited to $\sim 50\gamma$ for more than 16 h before the first launch and during the measurements (see Fig. 2). Two hours before the second flight at Heiss Island the geomagnetic field disturbances with amplitudes $\sim 100\gamma$ were detected. The third flight coincided with the beginning of a magnetic substorm. During the

Table 1. List of rocket launches

Numbers	Date	Latitude	UT	K_p	ΣK_p	E_z^{max}, V/m	Payload	Measured Parameters
		Heiss Island						
1	9 December 1983	80.6°N	22:20	0	5+	−0.3	EI-100	E_z, n_i, σ_i
2	20 December 1983	80.6°N	23:05	1+	8+	−0.8	EI-100	E_z, σ_i
3	18 January 1984	80.6°N	21:05	3+	11+	−1.2	EI-100	E_z,
4	24 February 1989	80.6°N	15:05	1+	17–	+1.0	M-100KT	E_z, n_i
5	1 March 1989	80.6°N	15:05	3–	21+	−1.6	M-100KT	E_z, n_i
6	7 March 1989	80.6°N	15:05	3	25+	+1.8	M-100KT	E_z, n_i
		Indian Ocean						
7	11 September 1989	52.4°S	20:15	1–	6	−2.3	M-100KT	E_z
8	12 October 1989	57.2°S	18:30	2	16+	+4.2	M-100KT	E_z, n_i
9	21 October 1989	58.5°S	19:31	8	57	+12.2	M-100KT	E_z, n_i

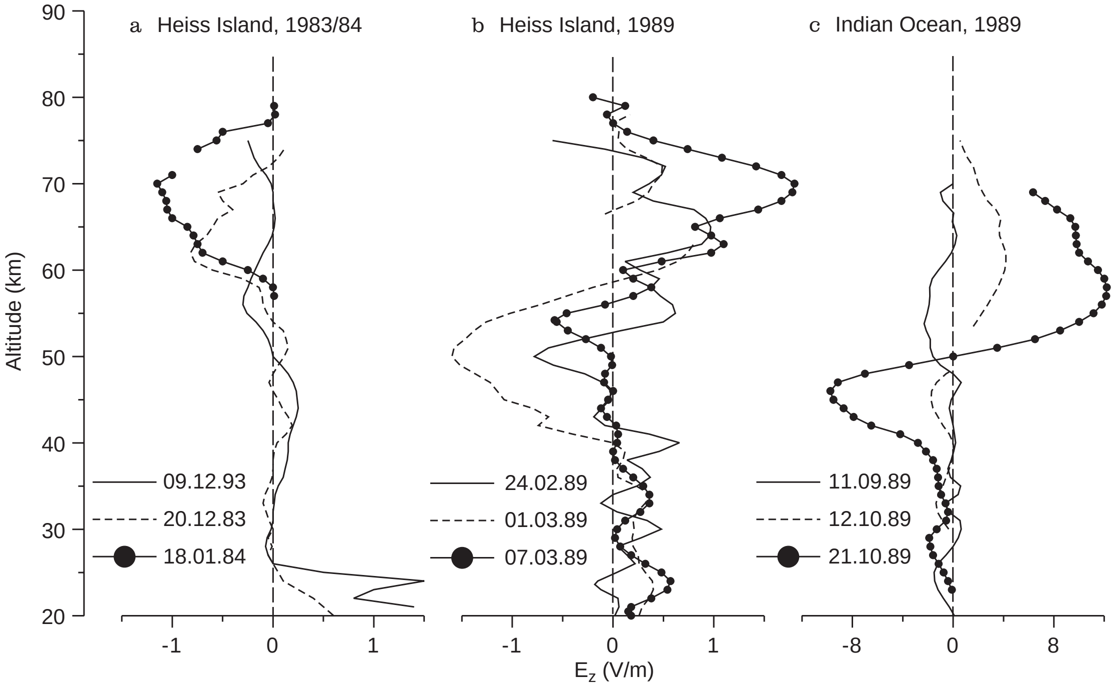

Fig. 1. The vertical electric fields measured above **a, b** Heiss Island (80.6 °N) and **c** the Indian Ocean (~50–60 °S)

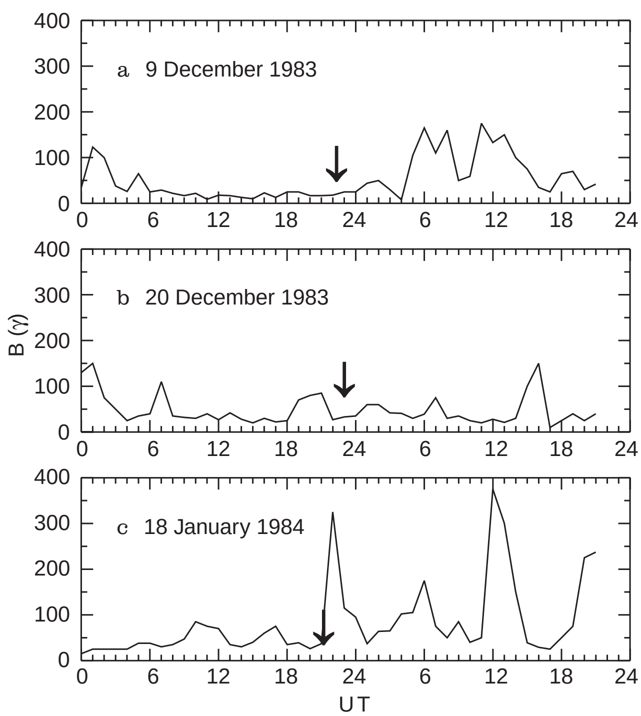

Fig. 2. Variations of the horizontal magnetic field at Heiss Island on the day of the rocket flights during the first series (Fig. 1a) of the mesospheric electric field measurements. *Arrows* indicate the time of the rocket launches

flight the magnetic field at Heiss Island abruptly increased by more than 300γ (Fig. 2).

The electric field strength in the mesosphere measured in the first flight was significantly smaller compared to those usually measured at middle latitudes (Bragin *et al.*, 1974; Tyutin, 1976, 1988; Zadorozhny, 1994a,b). The altitude profile of the electric field above ~30 km was smoother than usual (see Fig. 1a). A maximum of ~0.8 V/m appeared in the profile of the electric field strength measured in the second launch. During the third flight, the mesospheric maximum of the electric field rose to ~70 km and the electric field strength at maximum increased to ~1.2 V/m (Fig. 1a).

The results of the electric field measurements during the first series at Heiss Island show that the vertical electric fields in the polar mesosphere under a quiet geomagnetic period are significantly smaller than those at middle latitudes. These three high-latitude measurements indicate also a clear dependence of the height profile of the electric field strength on geomagnetic disturbance level: when the latter increases the mesospheric maximum of the electric field appears more distinct, it rises to higher altitudes and its strength at the maximum increases too. Simultaneous measurements at middle latitudes did not show any noticeable dependence of the electric fields on geomagnetic disturbance (Zadorozhny *et al.*, 1989).

It is of interest to notice the direct dependence of the electric field strength on conductivity derived from the measurements on December 9 and 20, 1983 on Heiss Island (see Fig. 3). At heights ~55 km, the absolute value of the electric field strength decreased when the conductivity decreased during the second flight in comparison with the first one. At ~65 km, the increase in conductivity brought about the increase in the field strength. And, although at 55 km in both launches the absolute value of the electric field strength is commensurable with precision of measurements, at 65 km the

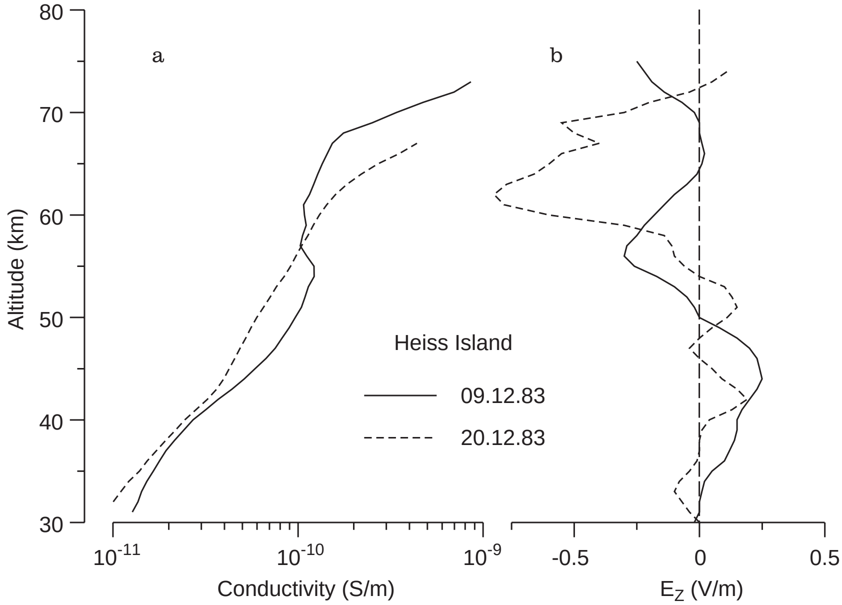

Fig. 3. The altitude profiles of **a** the total ion conductivity and **b** the vertical electric fields measured simultaneously above Heiss Island

variations of both the electric field and conductivity are considerable.

The second series of electric field measurements was made under more disturbed geomagnetic conditions. Index $\sum K_p$ ranged from 17– to 25+ for the days of the rocket launches in this series. The maximum absolute values of the electric field strength in the mesosphere, measured during the second series, are larger than those measured during the first one under quieter geomagnetic conditions (see Table 1 and Fig. 1).

In the second half of October, 1989 when we were carrying out the experiments in the Indian Ocean, a series of strong solar flares was observed, the strongest one (of 4B class) occurred on October 19, at about 13:00 UT. Other strong flares were registered on October 22 and 24, 1989. The flares were accompanied by a very large increase in fluxes of high-energy protons $(\mathrm{E} = 4.2 - 850\,\mathrm{MeV})$ and electrons $(\mathrm{E} > 2\,\mathrm{MeV})$ which were observed until the end of October (Solar-Geophysical Data, 1989). Extremely powerful solar flares in the second part of October induced a very strong geomagnetic storm with the ssc (sudden storm commencement) on October 20, 1989 at 09:17 UT, peaking with $K_p = 8+$ on October 20 near 18 UT and on October 21 near 10 UT. During the storm on October 1989 we measured the mesospheric vertical electric field strength and positive ion density (launch 9 in Table 1) (Zadorozhny *et al.*, 1992, 1994b).

The results of the electric field measurements in the Southern Hemisphere are given in Figs. 1c and 4. It can be seen, that the maximum absolute values of the vertical component of the electric field strength for these

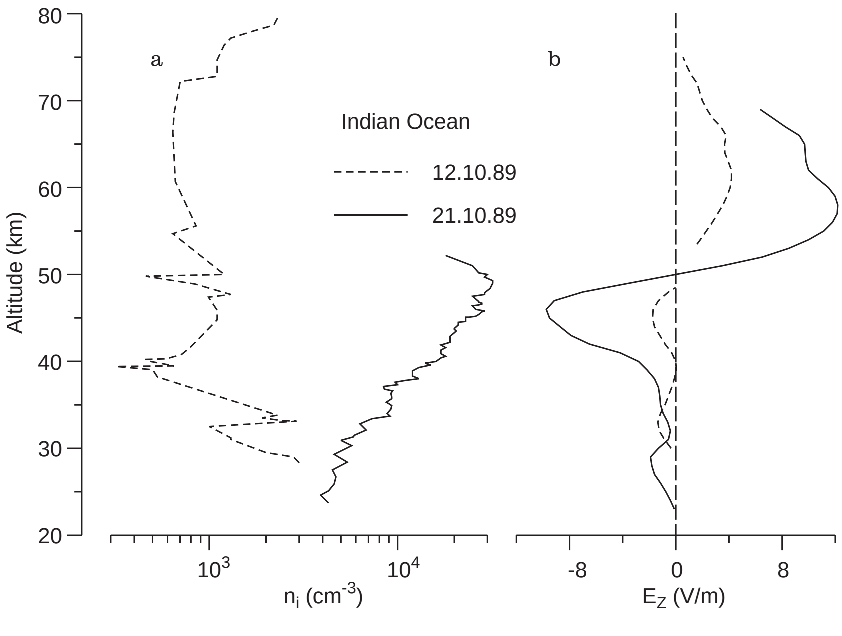

Fig. 4. The altitude profiles of **a** the positive ion density and **b** the vertical electric field strength measured in the Southern Hemisphere. The *dashed curves* show the measurements under relatively quiet geomagnetic conditions. The *solid curves* show the measurements during the strong solar proton events. The ion densities are not shown above about 52km for the rocket flight on October 21, 1989 during the SPE because the ion trap was off-scale here

launches at heights of $\sim$50-70 km are more than about 1 V/m, much greater than those measured above Heiss Island. A maximum value of 12 V/m was detected at about 58 km at 58.5°S on October 21 during the solar proton events (SPE). Fields as large as those obtained in this experiment, during the SPE accompanied by the very strong geomagnetic storm, have never been previously observed in the mesosphere.

Figure 5 shows the maximum absolute value of the vertical electric field measured in the mesosphere as a function of the geomagnetic index K_p and $\sum K_p$. Here the dots refer to the measurements (see Table 1) and the lines are the tendencies based on these data. A clear dependence of the mesospheric electric fields on geomagnetic activity can be seen both at a polar region (Heiss Island) and at high middle latitudes (the Indian Ocean).

4 Discussion

The effects of geomagnetic storms on the lower ionosphere and middle atmosphere show themselves essentially through the penetration of energetic particles (Laštovička, 1996). In particular, rocket experiments by Goldberg *et al*. (1984, 1990, 1994) gave direct evidence of the influence of the energetic particles to the middle atmosphere electrodynamics. These findings show that the variations of ion pair production rate, caused by energetic particles, appear to be the main source of the observed dependence of the mesospheric electric structure on geomagnetic activity. The detected increase of the vertical electric fields with simultaneous increase of ion conductivity, caused by the enhanced ion pair production rate during the geomagnetic disturbances (Figs. 3 and 4), is particularly surprising. The extrapolation of the ion density measurements on October 21, 1989 (launch 9) up to 60–70 km (see Fig. 4), and the assumption that the ion mobility does not change significantly during the enhanced ionisation rate, lead to the conclusion that the mesospheric ion conductivity on October 21, during the SPE, was, at least by an order of magnitude, higher than under quiet conditions before the beginning of the SPE. Holzworth *et al.* (1987) detected a similar increase of the vertical component of the electric field strength in the stratosphere with a simultaneous increase of conductivity during the SPE of February 1984. In a passive medium, where the current is given by exterior sources and Ohm's law holds, an increase in conductivity must be accompanied by a decrease in electric field strength.

The measured vertical electric fields E_z and ion density n_i allow us to estimate a vertical current density j_z that flows through the mesosphere:

$$j_z = \sigma_i E_z = q_e n_i \kappa_i E_z \tag{1}$$

Here σ_i is the total ionic conductivity; κ_i is the mobility of the ions; and q_e is the unit electrical charge. According this equation, the value of j_z in the vicinity of mesospheric maximum of E_z near 60 km was equal to about $3 \cdot 10^{-11}$ A/m and about 10^{-10} A/m during the flights on December 9 and 20, 1983, correspondingly

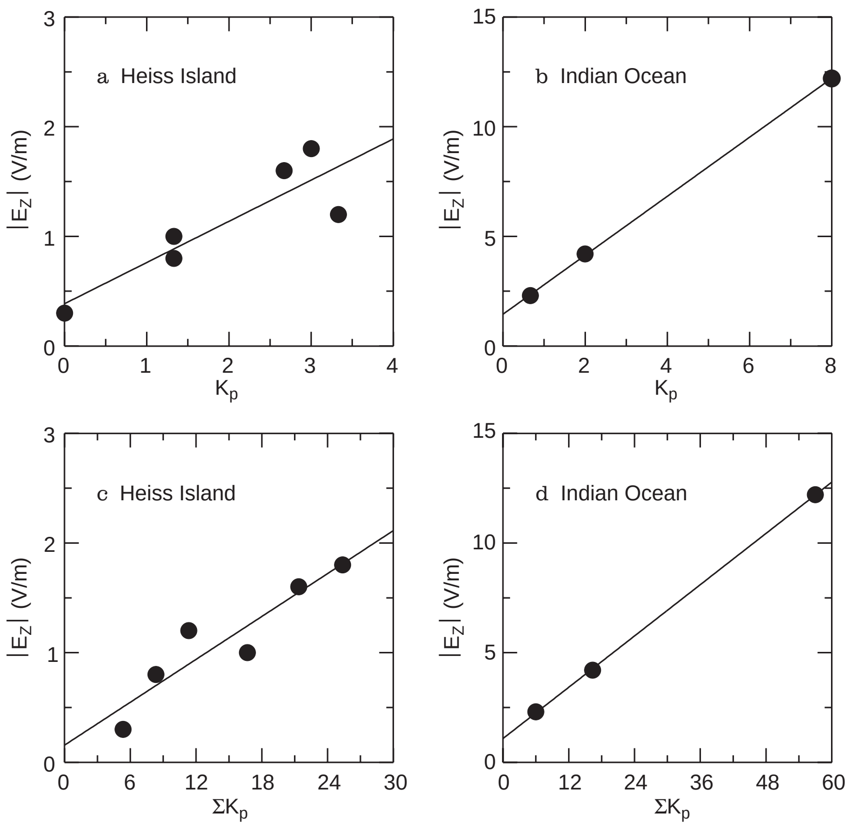

Fig. 5. The maximum absolute value of the vertical electric field measured in the mesosphere as a function of the geomagnetic index **a, b** K_p and **c, d** $\sum K_p$

(see Fig. 3). These values exceed the fair weather current density in the lower atmosphere by one order of magnitude and more. Using $\kappa_i = 1.5 \cdot 10^4\,\mathrm{cm}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}$ (Meyerott *et al.*, 1980) and the data for n_i and E_z from Fig. 4, one can obtain $j_z \approx 10^{-9}$ A/m at about 60 km under quiet conditions on October 12, 1989. This value exceeds the fair weather current density by more than two orders of magnitude. During the SPE the vertical current in the lower mesosphere was essentially enhanced due to a simultaneous increase of the ion density and the electric field strength. If the mobility of the ions did not change very much during the SPE then the enhancement of the vertical current density on October 21, 1989 was about 100 times. Holzworth *et al.* (1987) observed only a twofold increase of the vertical current density in the stratosphere at 26 km altitude during the SPE of February 1984.

The observed behaviour of the electric fields during the geomagnetic disturbances and SPE once more points to the very strong electrical activity of the mesosphere, namely, the existence of still unknown mesospheric electric generators. One possible mechanism for these generators is a gravitational sedimentation of charged aerosols, and a correlation between aerosol content and mesospheric electric fields, revealed by Zadorozhny *et al.*, (1994a), supports this possibility. Aikin and Maynard (1990) analysed a mechanism for the generation of the vertical electric fields caused by gravitational falling through the mesosphere of meteoric and other debris charged negatively in the upper D-region of the ionosphere. The vertical electric field E_z generated by sedimenting aerosol particles with concentration N_p is defined in Aikin and Maynard's (1990) model by the expression obtained from requirement of local current balance between a downward flux of electric charge carried by the particles and a conduction current:

$$E_z = \frac{Z_p q_e N_p V_p}{\sigma_i} \tag{2}$$

Here Z_p is the number of unit charges on each particle and V_p is the fall velocity of particle. The fields calculated with the use of realistic parameters of the particles in Eq. (2) are only about 10 mV/m at the altitudes where the V/m fields are observed (Aikin and Maynard, 1990). This indicates that a more complex mechanism is required to explain the large vertical electric fields. Notice that in Aikin and Maynard's (1990) model the vertical component of electric field is reciprocal with the atmospheric conductivity, in obvious contradiction with our measurements during the SPE and geomagnetic disturbances. The main obstacle to the formation of large fields in this simple model is a high electric conductivity of the atmosphere, which is defined by diffusivity of the charged particles:

$$\sigma_i = \frac{Z_i^2 n_i q_e^2}{kT} D_i \tag{3}$$

where n_i is the concentration of ions; D_i is the diffusion coefficient; T is the atmospheric temperature; and k is Boltzmann's constant.

Cho *et al.* (1992) showed that a presence of multiply charged aerosols in the mesospheric plasma leads to a drastic decrease of an effective electron diffusivity, up to a value equal to about the diffusivity of the aerosol particles. For large enough aerosols the transition to the reduced electron diffusivity occurs sharply when somewhat more than half of the charge is tied up in aerosols. The effective ion diffusivity will obviously be decreased to about the same value under the same conditions, too.

To explain the V/m vertical electric fields observed in the mesosphere, we assume the simultaneous existence of both negative and positive multiply charged aerosol particles of different sizes. In this model, more massive charged particles falling with larger velocity initiate a charge separation. Smaller particles carried charges of other sign needed to reduce effective conductivity of the atmosphere. If both positive and negative charges carried by the particles exceed charges carried by ions and electrons, that is, if the condition of Cho *et al.* (1992) is satisfied, the effective conductivity of the atmosphere σ_{eff}, which must be used in Eq. (2), is determined by the smaller aerosol particles. For example, Eq. (3) leads to σ_{eff} equal to about 10^{-12} S/m at 60 km for the particles with a radius of 20 nm and concentration of $10^3\,\mathrm{cm}^{-3}$ if each of them carries a few unit charges. This value is less than the measured conductivity at 60 km (see Fig. 3) by about two orders of magnitude. So low effective conductivity does not contradict the existence of the V/m vertical electric fields, if we assume the parameters for the more massive particles equal to those used by Aikin and Maynard (1990).

A possible reason for the difference between the estimated effective conductivity and the measured conductivity may be understood if we look upon the mesospheric dusty plasma as consisting of negatively and positively charged aerosol particles, surrounded by clouds of positive ions or negative ions and electrons, correspondingly. Very weak electric fields that cannot destroy the interaction of the aerosol particles with ions and electrons must be used to measure the effective conductivity. The electric fields used normally in conductivity probes appear to be large enough and the probes measure the pure ion conductivity.

The proposed model makes it necessary to reconsider the earlier estimation of the vertical current density. The effective conductivity must be used in Eq. (1) for calculation of j_z. This means that the calculated values are overestimated and the real mesospheric vertical current density may be of the order of the fair weather current density in the lower atmosphere. The total electric fields will be determined significantly, in this case, both by the proposed mesospheric source and by tropospheric sources driving the global electrical circuit. The latter appears to explain the universal diurnal variation of mesospheric electric fields revealed recently by Zadorozhny and Tyutin (1997).

The increase of the vertical component of the electric field strength observed during the geomagnetic disturbances and SPE can be explained in the frame of the proposed model if the total aerosol charge increases with the ion pair production rate increase more than the ion conductivity does. In this connection, one can also notice that the observations of the V/m electric fields in the region with reduced ion conductivity (Hale *et al.*, 1981; Maynard *et al.*, 1981, 1984; Goldberg and Holzworth, 1991) does not mean that low ion conductivity is the necessary condition for supporting large electric fields. In our view, the fact of lower ion conductivity under quiet conditions reflects, first of all, the strong ion-aerosol interaction necessary for the generation of these fields.

5 Conclusion

We have analysed here the results of rocket measurements of the vertical electric fields in the mesosphere carried out under different geomagnetic conditions. The measurements show a clear dependence of the electric fields on geomagnetic activity at polar and high middle latitudes. The vertical component of the electric field strength in the lower mesosphere increases with the increase of geomagnetic indexes K_p and $\sum K_p$. The simultaneous increase of the vertical electric field strength and electrical conductivity was observed in the mesosphere during geomagnetic disturbances. This striking phenomenon was displayed most clearly during the SPE of October 1989 accompanied by a very strong geomagnetic storm ($K_p = 8+$). The extremely high value of the vertical electric field strength of about 12 V/m was detected in the mesosphere during these events when the mesospheric ion conductivity was, at least by an order of magnitude, higher than that under quiet conditions. The behaviour of the electric fields under the geomagnetically disturbed conditions points to very strong electrical activity of the mesosphere, that is, to existence of still unknown electric generators in the mesosphere.

A possible mechanism of generation of the vertical electric fields in the mesosphere caused by gravitational sedimentation of charged aerosol particles has been discussed. To explain the V/m vertical electric fields, we assumed the simultaneous existence in the mesosphere of both negative and positive multiply charged aerosol particles of different sizes. More massive charged particles falling with larger velocity initiate a charge separation. Smaller particles carried charges of other sign needed to reduce the effective conductivity of the atmosphere. The proposed model can explain the existence of the V/m vertical electric fields if both positive and negative charges carried by the aerosol particles exceed charges carried by ions and electrons. The increase of the vertical component of the electric field strength observed during the geomagnetic disturbances and SPE can be explained in the frame of the proposed model if the total aerosol charge increases with the ion pair production rate increase more than the ion conductivity does. Unfortunately, the existence of the highly charged aerosols in the mesosphere as well as the mechanisms of the particle charging are not well known at present. These appear to be the key problems that must the resolved for complete understanding of the nature of the V/m vertical electric fields observed in the mesosphere.

Acknowledgements. This work was supported under Grant 97-05-65242 of the Russian Foundation for Basic Research.

Topical Editor F. Vial thanks R.A. Goldberg for his help in evaluating this paper.

References

Aikin, A. C., and N. C. Maynard, A Van de Graaf source mechanism for middle atmospheric vertical electric fields, *J. Atmos. Terr. Phys.,* **52,** 695–705, 1990.

Bragin, Y. A., A. A. Kocheev, and O. A. Bragin, Direct measurements of the electrical conductivity and the relaxation time constant of the ionised air in the stratosphere and the mesosphere, *Kosm. Issled.* **11,** 124–129, (in Russian), 1973.

Bragin Y. A., A. A. Tyutin, A. A. Kocheev, and A. A. Tyutin, Direct measurement of the atmospheric vertical electric field intensity up to 80 km, *Kosm. Issled.* **12,** 306–308, (in Russian), 1974.

Bragin Y. A., A. A. Kocheev, V. N. Kikhtenko L. N. Smirnykh, A. A. Tyutin, O. A. Bragin, and B. F. Shamakhov, Electrical structure of the stratosphere and the mesosphere using the data of rocket investigations, in *Rasprostranenie radiovoln i fizika ionosfery,* pp. 165–183, Nauka, Novosibirsk, USSR (in Russian), 1981.

Cho, J. Y. N., T. M. Hall, and M. C. Kelley, On the role of charged aerosols in polar mesosphere summer echoes, *J. Geophys. Res.,* **97,** 875–886, 1992.

Croskey, C L., L. C. Hale, J. D. Mitchell, D. Muha, and N. C. Maynard, A diurnal study of the electrical structure of the equatorial middle atmosphere, *J. Atmos. Terr. Phys.,* **47,** 835–844, 1985.

Croskey, C. L., L. C. Hale, J.D. Mitchell, F. J. Schmidlin, and U. P. Hoppe, Electric field measurements during the MAC/EPSILON campaign, *J. Atmos. Terr. Phys.,* **52,** 1005–1065, 1990.

Goldberg R. A. Middle atmospheric electrodynamics: status and future, *J. Atmos. Terr. Phys.,* **46,** 1083–1101, 1984.

Goldberg, R. A., Electrodynamics of the high latitude mesosphere, *J. Geophys. Res.,* **94,** 14661–14672, 1989.

Goldberg, R. A., and R. H. Holzworth, Middle atmospheric electrodynamics, *Handbook for MAP,* **32,** 63–84, 1991.

Goldberg, R. A. C. H. Jackman, J. R. Barcus, and F. Sorass, Nighttime auroral energy deposition in the middle atmosphere, *J. Geophys. Res.,* **89,** 5581–5596, 1984.

Goldberg, R. A., C. L. Croskey, L. C. Hale, J. D. Mitchell, and J. R. Barcus, Electrodynamic response of the middle atmosphere to auroral pulsations, *J. Atmos. Terr. Phys.,* **52,** 1067–1104, 1990.

Goldberg, R. A., D. N. Baker, F. A. Herrero, S. P. McCarthy, P.A. Twigg, C. L. Croskey, and L. C. Hale, Energy deposition and middle atmosphere electrodynamic response to a highly relativistic electron precipitation event, *J. Geophys. Res.,* **99,** 21071–21081, 1994.

Hale L. C., Middle atmosphere electrical structure, dynamics and coupling, *Adv. Space Res.,* **4,** 175–186, 1984.

Hale, L. C., C. L. Croskey, An auroral effect on the fair weather electric field, *Nature,* **278,** 239–241, 1979.

Hale, L. C., C. L. Croskey, and J. D. Mitchell, Measurements of middle-atmosphere electric fields and associated electrical conductivities, *Geophys. Res. Lett.,* **8,** 927–930, 1981.

Holzworth, R. H., K. W. Norville, and P. R. Williamson, Solar flare perturbations in stratospheric current systems, *Geophys. Res. Lett.,* **14,** 852–855, 1987.

Kikhtenko, V. N., In-situ researches of electric properties of the atmosphere with the spherical wire-net condensers, *Kosm. Issled.,* **16,** 626–629, (in Russian) 1978.

Laštovička, J., Effects of geomagnetic storms in the lower ionosphere, middle atmosphere and troposphere, *J. Atmos. Terr. Phys.,* **58,** 831–843, 1996.

Maynard, N. C., C. L. Croskey, J. D. Mitchell, and L. C. Hale, Measurement of volt/meter vertical electric fields in the middle atmosphere, *Geophys. Res. Lett.*, **8,** 923–926, 1981.

Maynard, N. C., L. C. Hale, J. D. Mitchell, F. J. Schmidlin, R. A. Goldberg, J. R. Barcus, F. Soraas, and C. L. Croskey, Electrical structure in the high-latitude middle atmosphere, *J. Atmos. Terr. Phys.,* **46,** 807–817, 1984.

Meyerott R. E., J. B. Reagan, and R. G. Joiner, The mobility and concentration of ions and ionic conductivity in the lower stratosphere, *J. Geophys. Res.,* **85,** 1273–1278, 1980.

Smirnykh L. N., Rocket measurements of positive ion concentration below 90 km, *Kosmicheskie Isseledovaniya*, **14,** 151–152, (in Russian), 1976.

Solar-Geophysical Data. Prompt Reports. November 1989, NOAA/NGDC, Boulder 543, Part I, 1989.

Tyutin, A. A., Mesospheric maximum of the electric field strength, *Kosm. Issled.,* **14,** 143–144, (in Russian), 1976.

Tyutin, A. A., *The vertical electric field component in the mesosphere and stratosphere. Method and results of measurements* (in Russian), 123 pp., Ph.D. Thesis, Novosibirsk State University, Novosibirsk, Russia, 1988.

Zadorozhny, A. M. and A. A. Tyutin. Universal diurnal variation of mesospheric electric fields, *Adv. Space Res.* **20,** 2177–2180, 1997.

Zadorozhny, A. M., G. A. Tuchkov, and A. A. Tyutin. In situ measurements of electric field strength and nitric oxide distribution in the middle atmosphere during MAP/MAC period, *Collection of Works of the International Workshop of Noctilucent Clouds (Tallinn, Estonian SSR, U.S.S.R., 27–31 July 1988)*. Valgus, Tallinn, 19–25, 1989.

Zadorozhny, A. M., G. A. Tuchkov, V. N. Kikhtenko, J. Laštovička, J. Boška, and A. Novák, Nitric oxide and lower ionosphere quantities during solar particle events of October 1989 after rocket and ground–based measurements, *J. Atmos. Terr. Phys.,* **54,** 183–192, 1992.

Zadorozhny, A. M., A. A. Tyutin, G. Witt, N. Wilhelm, U. Wälchli, J. Y. N. Cho, and W. E. Swartz, Electric field measurements in the vicinity of noctilucent clouds and PMSE, *Geophys. Res. Lett*. **20,** 2299–2302, 1993.

Zadorozhny, A. M., A. A. Tyutin, O. A. Bragin, and V. N. Kikhtenko, Recent measurements of middle atmospheric electric fields and related parameters, *J. Atoms. Terr. Phys.,* **56,** 321–335, 1994a.

Zadorozhny, A. M., V. N. Kikhtenko, G. A. Kokin, G. A. Tuchkov, A. A. Tyutin, A. F. Chizhov, and O. V. Shtirkov, Middle atmosphere response to the solar proton events of October 1989 using the results of rocket measurements, *J. Geophys. Res.,* **99,** 21059–21069, 1994b.