Review of Examples of Solar Wind Lower Atmosphere Coupling Observed in the Electric Field (Ez) Variations at the Earth's Surface During Magnetic Storms

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ABSTRACT: Relations between the electric field in the lower atmosphere and solar wind changes are still scarcely investigated and poorly understood. Taking this into account the studies of fair-weather ground level electric field, carried out in the polar station Hornsund (Spitsbergen) and the mid-latitude station Swider (Poland) were extended by simultaneous data acquired by ground-based geomagnetic and riometer station recordings, radar ionosphere observations and satellite-based geospace measurements. Additional monitoring of meteorological and other local disturbances allowed strict selection of fair-weather days. The results obtained have allowed to confirm in individual cases the existence of coupling of the ground-level electric field with the solar wind changes. They were observed only in polar regions during magnetic substorms, driven by solar wind at its usual moderate variability. The focus of this current review is on the response of the ground-level electric field to dramatic solar wind changes after coronal mass ejections which are responsible for geomagnetic storms. At mid-latitudes such phenomenon was first observed by *Nikiforova et al.* [2005] and *Kleimenova et al.* [2008]. There is growing and considerable amount of such observational evidence in individual cases. Their understanding requires further experimental investigations and theoretical treatment, beyond the present atmospheric electricity range confined to the lower atmosphere. A preliminary attempt showed qualitatively that the mid-latitude lower atmosphere electric field, depends, among other factors, on the solar wind-driven electric current system of the ionosphere and magnetosphere.

INTRODUCTION

A response of the ground-level fair-weather electric field, Ez, the to the solar wind (SW) changes were observed earlier only in polar regions during geomagnetic substorms [e.g. *Olson*, 1971; *Bandilet et al.*, 1986; *Apsen et al.*, 1988; *Sheftel*, 1991]. The response in Ez has been extensively investigated for the polar station Hornsund (77.00°N, 15.55°E, Φ=74°) [*Michnowski et al.*, 1991b,a; *Kozyreva et al.*, 2007; *Kleimenova et al.*, 2010, 2011, 2012; *Michnowski et al.*, 2014]. Both the magnetic and electric variations are then produced by the same source, i.e. solar wind parameter changes. In the case of the substorms these changes are caused by usual variability of the solar wind and do not last very long. The solar plasma of a powerful coronal mass ejection (CME) can impact the Earth's magnetosphere as solar wind plasma bubbles of strongly changed parameters, such as the imbedded interplanetary magnetic field, IMF B, speed, V, interplanetary electric field, E_{sw}, density, N_p, and pressure, P. Such event produces large changes in the magnetosphere-ionosphere (M-I) currents, manifested in observed simultaneously magnetic disturbances. Such geomagnetic field variation from its normal behavior, called magnetic storms, last usually from one to several days. Their intensity and duration are described by the Dst index presenting the average deviation of the geomagnetic field X (H) component, reported by low latitude magnetic stations. At high latitudes, the magnetic storm appears usually as a series of subsequent substorms, observed for a very long time in polar regions. Statistical search of the dependence of Ez on high magnetic activity at mid-latitude station

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Swider (52.12°N, 21.24°E, Φ=48°), has not provided results which could be then interpreted [*Kalinowska-Widomska*, 1976]. Individual events of Ez variations related to high magnetic activity at middle and low latitudes had not been found at all for a very long time. The examples studied and reviewed below are an attempt to indicate that such events indeed represent a physical relationship.

INDIVIDUAL CASES OF Ez RESPONSE TO MAGNETIC STORMS

The response of Ez to magnetic storms in lower latitude region was first observed at Swider by *Nikiforova et al.* [2005], in the case of the main phase of a superstorm in October 2003. This storm appeared in the geomagnetic X component simultaneously over stations of the meridional chain IMAGE during local midnight hours [*Nikiforova et al.*, 2005, Fig. 2,4]. Simultaneously, a strong anomaly of the Ez behaviour in the shape of a negative deflection lasting for more than one hour was observed at Swider during fair weather time period (see Fig. 1). These anomalous changes were concurrent with the time changes in the X component and riometer absorption (R) at JYV station, which had a similar frequency structure as demonstrated by the wavelet analysis [*Nikiforova et al.*, 2005, Fig. 5]. The considered Ez anomaly at Swider not only occurred in coincidence with the jumps of R and X at JTV and nearby aurora magnetic stations but also had a similar shape of the variation of these parameters in the auroral region, with the Dst index reaching its minimum value. This distinct correspondence in the occurrence and variation character suggests that this anomaly in Ez most probably presents a response to the main phase of the magnetic storm.

The investigations by *Michnowski et al.* [2007]; *Kleimenova et al.* [2008, 2013], based on Hornsund and Swider data [*Dziembowska*, 2009], confirmed several repeatable individual responses of the Ez to the

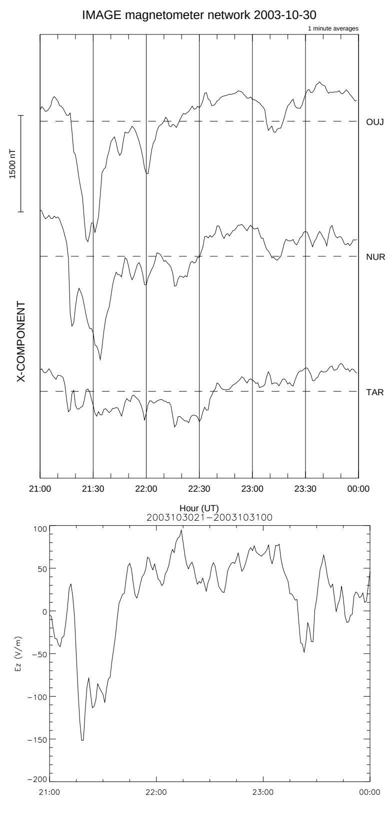

Figure 1: The response of the Ez at mid-latitude station Swider to the main phase of magnetic superstorm of October 30, 2003. Upper panel: variation of the X geomagnetic component at subauroral IMAGE stations OUI, NUR, TAR [see also *Nikiforova et al.*, 2005, Fig. 4]. Bottom panel: anomalous variations of the Ez at Swider.

magnetic storm at middle latitudes. The observation of the Ez at this time have been carried out simultaneously by two independent measurements with a field mill [*Berlinski et al.*, 2007], and a radioactive collector. As an interesting case, Fig. 2 presents the strong deviations in fair-weather Ez variations at Swider during the geomagnetic storm of 13-14 October, 2000. Simultaneously, the Dst index showed two minima of the moderate magnetic storm, during which the Interplanetary Magnetic Field (IMF) B_z had southward orientation. The strong Ez deviations from the reference average diurnal variations during quiet geomagnetic time at Swider, Ezq, are associated with the Dst minima [see also *Kleimenova et al.*, 2008, Fig. 2a]. The deviations in Ez courses at Swider took place during daytime while the largest magnetic auroral oval substorms occurred at night-time at CMO station in Alaska. No magnetic disturbances were observed at that time at the nearby magnetic station Belsk (BEL) [see *Kleimenova et al.*, 2008, Fig. 2b].

The differences between the observed Ez and the average values of Ez in magnetically quiet conditions, Ez-Ezq, indicate significant deviations, shown in the bottom of Fig. 2. In the first hours of October 13 a large increase in this difference occurred at high negative values of IMF B_z (with a short positive excursion) associated with high positive values of the solar wind interplanetary electric field E_{sw} (also with a short excursion) during a long sustained jump of solar wind dynamical pressure P. This (Ez-Ezq) negative deviation was followed by an increase in B_z to high positive values (nearly 20 nT) during the still sustained rise in P, and during a large decrease in E_{sw} ($E_{sw} = -V \cdot B_z$), which might have resulted in the deviation of (Ez-Ezq) to positive values. On the next day this deviation changed the sign indicating a large drop in the measured Ez nearly to zero values, which is unusual during fair weather. This event was associated with large E_{sw} and negative B_z. Next large negative value of (Ez-Ezq) was accompanied by a decrease in B_y to negative values during high positive E_{sw} and highly negative B_z values.

Another example of magnetic storm effect on Ez variation at Swider is the case of May 23-24, 2000, illustrated in Fig. 3. There the Ez variations during this magnetic storm were compared to Ezq (average fair-weather and quiet magnetic variations) in the previous days as well as by the use of averaged long-term fair-weather Ez Swider variation (not shown). The first deviation (Ez-Ezq) indicated by positive enhancements in the bottom panel of Fig. 3 in early morning hours was associated with a jump in the dynamic pressure P and high values of solar wind electric field E_{sw} [see also *Kleimenova et al.*, 2008, Fig. 3a]. The second, more considerable deviation (a negative one) of the recorded Ez corresponded to strong H disturbances, which occurred in auroral stations (CMO and SOD) on both hemispheres as it is shown in the lower part of the right panel of [see *Kleimenova et al.*, 2008, Fig. 3b].

Another example of a remarkable decrease in Ez during a magnetic storm on 3 October 2001 is presented in Fig. 4. At the start of the magnetic activity has already been higher and continued to increase as the Dst index reached the value of –166 nT at $\sim$ 14 UT. The IMF B_z become largely negative from about 6 UT (with three negative excursions of smaller amplitudes earlier) until 16 UT. The B_y component change sign from negative to large positive amplitudes (maximum of +15 nT) shortly after 12 UT and remained such until about 17 UT. There were also a few rapid increases in the solar wind pressure throughout the day, with the largest at about 12 UT. Around 14 UT the ground-level Ez begin to decrease dramatically, until shortly before 18 UT. Its variation from 18 UT until 21 UT cannot be considered as the fair-weather conditions were absent. The measured at Swider ground-level current density, J_z also decreased between 16 and 17 UT (*Odzimek et al., in preparation*).

REMARKS ON INITIAL RESULTS

The individual events of relation of the atmospheric electric field Ez to solar wind changes found during geomagnetic storm development, have been investigated in the Ez deviations in reference to its relevant quiet magnetic course. These deflections are present as decreases of the field, or positive changes, i.e. increases. Both kinds of the response are of various amplitude, duration and shape. The large variability

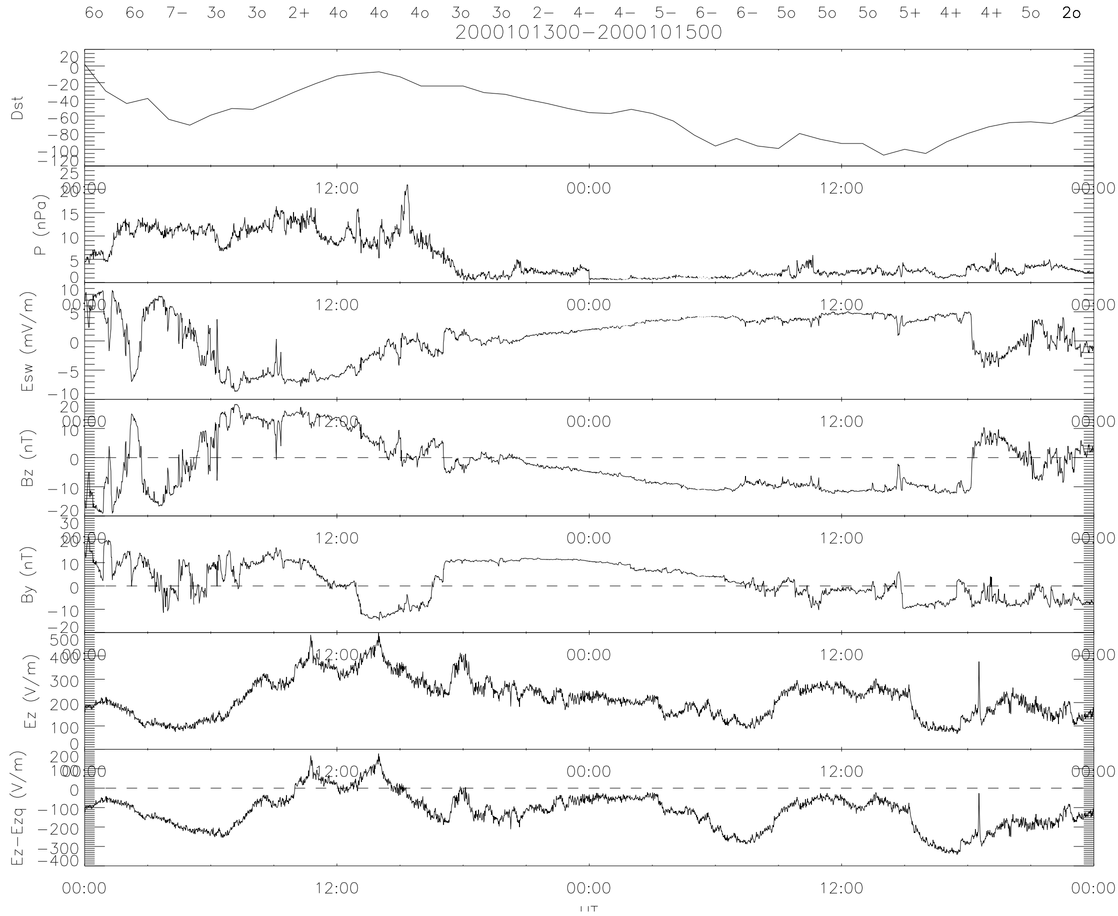

Figure 2: The characteristic response of the Ez at mid-latitude Swider station to magnetic storm of October 13-14, 2000, and selected magnetic indices and important parameters of the solar wind. Panels show variations of main parameter variation, from top: Dst-index, solar wind parameters: pressure, P, electric field E_{sw} and IMF components B_y and B_z. Values of Kp are displayed in the top line above panels. Two bottom panels show the fair-weather Ez recordings during the event and the estimated difference between the observed and corresponding averaged Ez values on magnetically quiet fair-weather days in October 2000.

of the deflections can be caused by many factors acting simultaneously in the lower atmosphere below the ionosphere and in the areas above it - in the magnetosphere with the ionosphere and the huge space between the Sun and our planet [*Michnowski*, 1998]. In such situation the search and comparison of common features in Ez response to parameter changes in SW, was a tedious task. However, for a single polar substorm, much less complicated than a geomagnetic storm, and, on the other hand, for a very large number of these simpler cases, a regular and repeatable character of the Ez response in polar regions to SW changes, was revealed. This conclusive statement was, moreover, corroborated by the determination of global ionosphere electric potential distributions delivered by semi-empirical models based on SuperDARN radars and low orbiting satellite measurements such as the Weimer model. These findings were summarized and published previously.

The present review of the Ez response cases to the powerful shock changes in the SW parameters after CME events responsible for geomagnetic storms, concerns disturbances in the global planetary system of electric currents. The present difficulties in the interpretation of the obtained results are gradually to be solved. Now they do not allow to establish sufficiently the common repeatable features in the reviewed

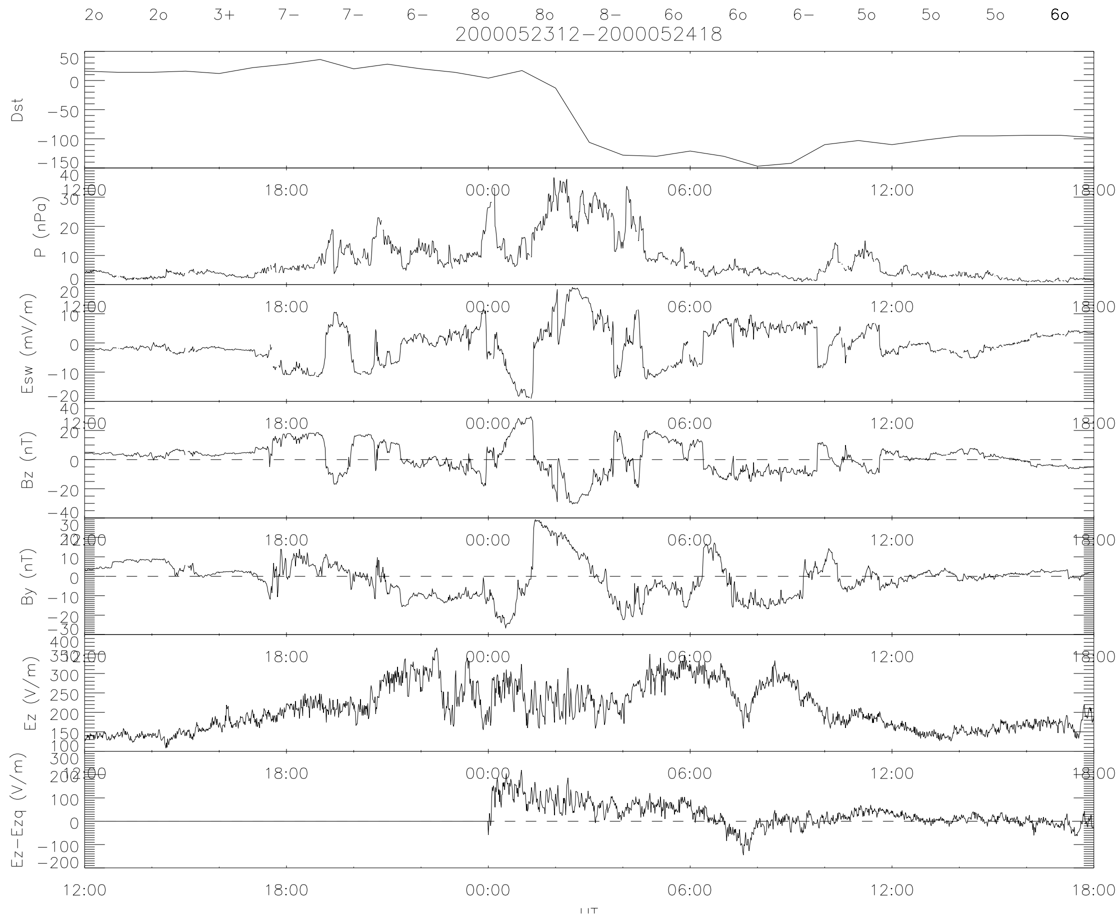

Figure 3: The response of the Ez at mid-latitude Swider station to magnetic storm of May 23-24, 2000. Description the same as in Fig. 2. Ezq values have been taken from 23 May 2000.

examples of Ez responses associated with geomagnetic storms. Nevertheless, there remains now another possibility of confirming the physical dependence of observed Ez reaction to relevant changes in SW. Using the advanced knowledge on the coupling of the ionosphere electric potential dependence and SW parameter changes, it is possible to find easier the searched relationship in the individual cases and to allow to check whether and how the measured at ground level Ez variations correspond to the time changes of the ionospheric potential above the site [e.g. *Odzimek et al.*, 2011]. The ionosphere potential distribution, statistically determined in relation to SW parameters changes by empirical and semi-empirical models, have been lately applied in numerical simulations of the relationship between the M-I electric currents and magnetic fields configuration with configurations with the SW parameters changes. The advanced general knowledge of this coupling gives a possibility to explain qualitatively and, in some circumstances, to calculate quantitatively the ionospheric potential change above the Ez at measuring site in relation to the known SW parameter change. In some individual events of response, the features of geomagnetic field in the world networks of magnetic stations and of Ez in Swider are characteristically in accordance with such explanation. Penetration of the SW electric field seems to offer other explanation of the changes in ionosphere potential in low latitudes. In both kind of the interpretation an intrinsic role play, but not in an identical way, the field-aligned currents, FACs.

In any attempt of the interpretation of observed ground-level Ez response to SW events, monitored in interplanetary medium, we have to deal with global electric current system in huge M-I and interplanetary

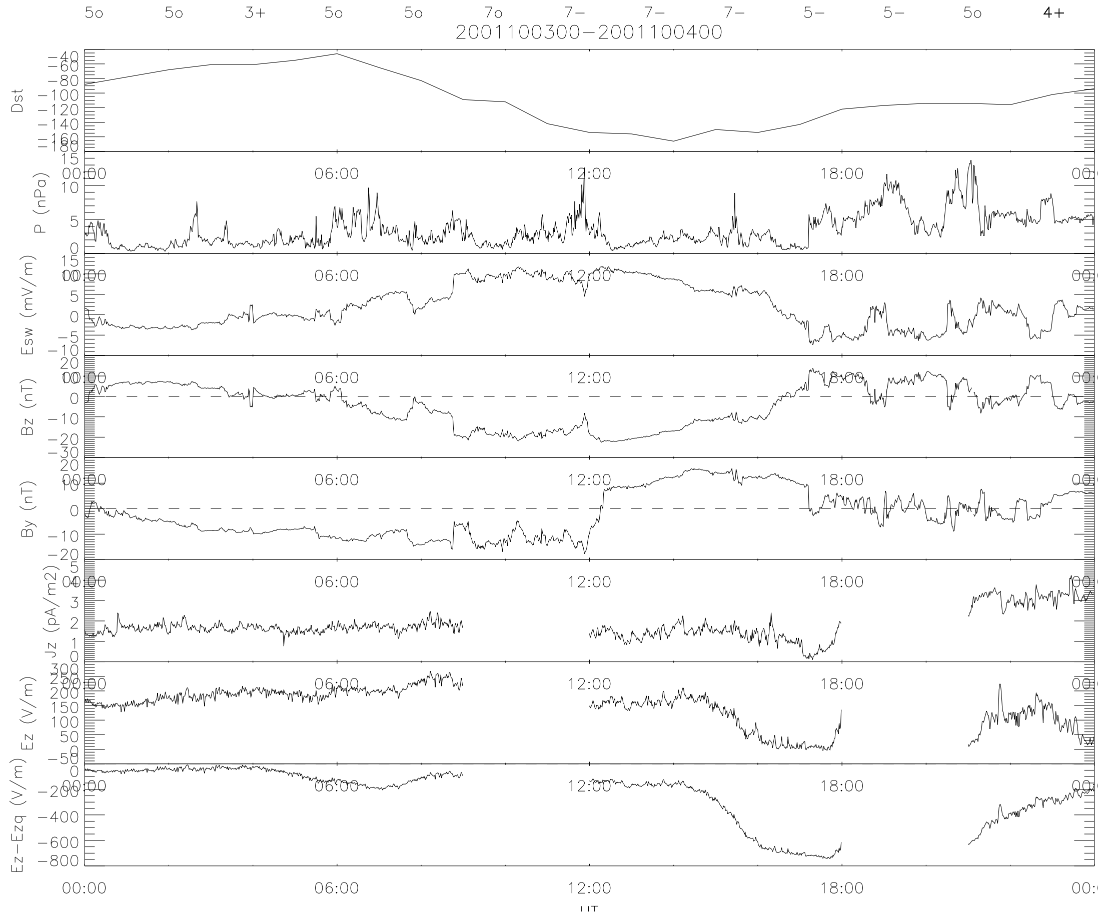

Figure 4: The response of the Ez at mid-latitude Swider station to magnetic storm of October 3, 2001. In addition to indices the solar wind parameters and Ez variations in 2, the variations of the ground-level current density Jz, are displayed in bottom panels. Only Ez and Jz variation during fair-weather have been shown.

areas existing above the conductive ionosphere as well as in the lower atmosphere area below this common layer, i.e. the domain of the lower atmospheric electricity. At present, the examination of the relationships between the mentioned electric current systems is hampered due to the delays in the research field of lower atmosphere electricity in comparison to the M-I and lithosphere research achievements. There is also a scarcity of the data on other physical links between them, like high energetic particle fluxes or the recently found responses of M-I to rapid changes in atmospheric elements in the global atmospheric circuit, GEC. However, the presently used comparisons of the observed Ez deviations after the large changes in all SW parameters, responsible for magnetic storm, with the statistically estimated magnetically quiet fair-weather values, are confirming approximately the physical existence of the examined relationship. These initial results are in an accordance with suggestions of the development of fair-weather electricity required in the studies of global changes going on in our environment. Such suggestions were formulated, for instance, in the final conclusions of the International Workshop on Atmospheric Electricity Measurements organised by ICAE and held in Madralin in 1989 [*Michnowski*, 1991]. The response of the whole our planet to CME events may be an example of the need for further developments in atmospheric electricity not to be neglected. These should be open to the fascinating subjects of investigation on the relationships of the lower atmosphere and phenomena far away from it. Moreover, they should inspire international and cross-field collaboration as they indeed require such.

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Solar wind parameters have been obtained online from OMNI database at

`http://omniweb.gsfc.nasa.gov`

IMAGE data have been retrieved from

`http://www.ava.fmi.fi/image/jpg/jpg_form.html`

References

Apsen, A. G., K. D. Kanonidi, C. S. P., D. N. Chetaev, and V. M. Scheftel, *Magnetospheric effects in atmospheric electricity*, Publications of the SSSR Academy of Sciences, Institute of Terrestrial Magnetism, Ionosphere and Radio-wave Propagation, Nauka, Moscow, 1988.

Bandilet, O. I., H. D. Kanonidi, S. P. Chernysheva, and V. M. Sheftel, Effects of magnetospheric substorms in the atmospheric electric field, *Geomagn. Aeron.*, *26*, 159–160, 1986.

Berlinski, J., G. Pankanin, and M. Kubicki, Large scale monitoring of troposphere electric field, in *Proceedings of the 13th International Conference on Atmospheric Electricity, Beijing, China, August 13-18*, pp. 124–126, 2007.

Dziembowska, A., Eighty years of fair-weather atmospheric electricity monitoring in Poland, in *Recent developments in Atmospheric Electricity*, edited by P. Barański and M. Kubicki, vol. D-73(412) of *Publ. Inst. Geophys. Pol. Acad. Sci.*, pp. 9–14, 2009.

Kalinowska-Widomska, E., Long-term changes in magnetic and atmospheric-electric fields on the basis of the recordings of the St. Kalinowski Geophysical Observatory at Świder, Poland, in *Electrical Processes in Atmospheres, Proceedings of the 5th Internatonal Conference on Atmospheric Electricity, Garmisch-Partenkirchen (Germany), 2-7 September 1974*, edited by H. Dolezalek, R. Reiter, and H. Landsberg, pp. 736–739, Steinkopff, 1976.

Kleimenova, N., O. Kozyreva, M. Kubicki, and S. Michnowski, Variations in the near-ground electric field at high latitudes and the potential drop across the polar cap during morning polar substorms, *Geomagn. Aeron.*, *51*, 394–401, 2011.

Kleimenova, N., O. Kozyreva, M. Kubicki, A. Odzimek, and L. Malysheva, Effect of substorms in the Earth's nightside sector on variations in the surface atmospheric electric field at polar and equatorial latitudes, *Geomagn. Aeron.*, *52*, 467–473, 2012.

Kleimenova, N. G., O. V. Kozyreva, S. Michnowski, and M. Kubicki, Effect of magnetic storms in variations in the atmospheric electric field at midlatitudes, *Geomagn. Aeron.*, *48*, 622–630, 2008.

Kleimenova, N. G., O. V. Kozyreva, M. Kubicki, and S. Michnowski, Morning polar substorms and variations in the atmospheric electric field, *Geomagn. Aeron.*, *50*, 48–57, 2010.

Kleimenova, N. G., O. V. Kozyreva, S. Michnowski, and M. Kubicki, Influence of geomagnetic disturbances on atmospheric elctric field (ez) variations at high and middle latitudes, *J. Atmos. Sol.-Terr. Phys.*, *99*, 117–122, 2013.

Kozyreva, O. V., N. N. Nikiforova, N. O. Kleimenova, S. Michnowski, and M. Kubicki, Electric air-earth vertical current pulsations at Hornsund during polar substorms: Case study, in *Proceedings of the 13th International Conference on Atmospheric Electricity, Beijing, China, August 13-18*, pp. 29–33, 2007.

Michnowski, S., Concluding remarks of the Madralin Workshop, in *Proceedings of the International Workshop on Global Atmospheric Electricity Measurements*, edited by S. Michnowski and L. H. Ruhnke, vol. D-35(238) of *Publ. Inst. Geophys. Pol. Acad. Sci.*, pp. 249–256, 1991.

Michnowski, S., Solar wind influences on atmospheric electricity variables in polar regions, *J. Geophys. Res.*, *103*, 13,939–13,948, 1998.

Michnowski, S., N. N. Nikiforova, and N. G. Kleimenova, The response of the ground-level electric field at Hornsund to magnetospheric-ionospheric events, in *Proceedings of the 10th International Conference on Atmospheric Electricity, Osaka, Japan, 19-24 June*, 1991a.

Michnowski, S., A. Szymanski, and N. N. Nikiforova, On simultaneous observations of geomagnetic and atmospheric electric field changes in Arctic station Hornsund, Spitsbergen, in *Proceedings of the International Workshop on Global Atmospheric Electricity Measurements*, edited by S. Michnowski and L. H. Ruhnke, vol. D-35(238) of *Publ. Inst. Geophys. Pol. Acad. Sci.*, pp. 83–96, 1991b.

Michnowski, S., M. Kubicki, N. Kleimenova, N. Nikiforova, O. Kozyreva, and S. Israelsson, The polar ground-level electric field and current variations in relation to solar wind changes, in *Proceedings of the 13th International Conference on Atmospheric Electricity, Beijing, China, August 13-18*, 2007, 4 pp.

Michnowski, S., M. Kubicki, A. Odzimek, N. Kleimenova, O. Kozyreva, N. Nikiforova, Z. Klos, and S. Israelsson, The polar ground-level electric field and current variations in relation to solar wind changes, 2014, in preparation.

Nikiforova, N. N., N. G. Kleimenova, O. V. Kozyreva, M. Kubicki, and S. Michnowski, Unusual variations in the atmospheric electric field during the main phase of the strong magnetic storm of October 30, 2003, at Świder Polish midlatitude observatory, *Geomagn. Aeron.*, *45*, 140–144, 2005.

Odzimek, A., M. Kubicki, M. Lester, and A. Grocott, Relation between the SuperDARN ionospheric potential and ground electric field at polar station Hornsund, in *Proceedings of the 14th International Conference on Atmospheric Electricity, Rio de Janeiro, Brazil, August 8-12*, 2011, 4 pp.

Olson, D., The evidence for auroral effects on atmospheric electricity, *Pure and Applied Geophysics*, *84*, 118–138, 1971.

Sheftel, V. M., Effects of magnetosphere-ionosphere generators and solar flares on the atmospheric electricity of high latitudes, in *Proceedings of the International Workshop on Global Atmospheric Electricity Measurements*, edited by S. Michnowski and L. H. Ruhnke, vol. D-35(238) of *Publ. Inst. Geophys. Pol. Acad. Sci.*, pp. 23–33, 1991.