GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L20105, doi:10.1029/2006GL027718, 2006

Rapid fluctuations of stratospheric electric field following a solar energetic particle event

M. Kokorowski,[1] J. G. Sample,[2] R. H. Holzworth,[1] E. A. Bering,[3] S. D. Bale,[2] J. B. Blake,[4] A. B. Collier,[5] A. R. W. Hughes,[5] E. Lay,[1] R. P. Lin,[2] M. P. McCarthy,[1] R. M. Millan,[6] H. Moraal,[7] T. P. O'Brien,[4] G. K. Parks,[2] M. Pulupa,[2] B. D. Reddell,[3] D. M. Smith,[8] P. H. Stoker,[7] and L. Woodger[6]

Received 31 July 2006; revised 29 August 2006; accepted 15 September 2006; published 25 October 2006.

[1] During January, 2005, there were several large X-class solar flares and associated solar energetic particle (SEP) events. Coincidentally, the MINIS balloon campaign had multiple payloads aloft in the stratosphere above Antarctica measuring dc electric fields, conductivity and x-ray flux. One-to-one increases in the electrical conductivity and decreases to near zero of both the vertical and horizontal electric field components were observed in conjunction with an increase in particle flux at SEP onset. Combined with an atmospheric electric field mapping model, these data are consistent with a shorting out of the global electric circuit and point toward substantial ionospheric convection modifications. Additionally, two subsequent, rapid changes were detected in the vertical electric field component several hours after SEP onset. These changes result in similar fluctuations in the calculated vertical current density. We will describe how rigidity cut-off dynamics may be crucial in understanding these sudden jumps in the vertical electric field. **Citation:** Kokorowski, M., et al. (2006), Rapid fluctuations of stratospheric electric field following a solar energetic particle event, *Geophys. Res. Lett.*, *33*, L20105, doi:10.1029/2006GL027718.

1. Introduction

[2] During solar energetic particle (SEP) events, large populations of protons with energies exceeding 1 GeV [*Reames*, 1999] can penetrate deep into the atmosphere and significantly perturb the natural atmospheric electrical systems [*Holzworth and Mozer*, 1979; *Holzworth et al.*, 1987]. In the period from 15–20 January, 2005 there were five X-class solar flares culminating in an X7.1 eruption on January 20th. This event caused the largest ground level enhancement (GLE) in neutrons from high-energy SEPs since 1956 evidenced by the 30 fold increase detected at the McMurdo neutron monitor [*Bieber et al.*, 2005], and a unique three-peaked increase at the neutron monitor at the South African National Antarctic Expedition (SANAE) IV commencing at 06:51 UT [*Moraal et al.*, 2005]. During this event, the MINIature Spectrometer (MINIS) balloon campaign, flown from SANAE, had one payload aloft at 70.9°S, 10.9°W geographic, at which dramatic electric field and conductivity changes were recorded.

[3] Generally, SEP electrons do not have direct access to the neutral atmosphere [*Vampola*, 1969]. Therefore, further mention of SEPs in the atmosphere relate to protons and a small numbers of heavier ions. Magnetic rigidity cutoffs restrict SEP access such that they can only reach polar regions and, depending on how energetic a particle is and how disturbed the magnetosphere is, possibly mid-latitudes as well [*McCracken*, 1962, *Share et al.*, 2002]. As SEPs penetrate into the collisional atmosphere, they ionize neutrals along the way, greatly enhancing the electrical conductivity [*Holzworth and Mozer*, 1979; *Holzworth et al.*, 1987]. Enhanced conductivity can cause communication disruptions (radio, GPS, avionics [*Jones et al.*, 2005]) and can have significant impacts on atmospheric chemistry [*Jackman et al.*, 2005; *Verronen et al.*, 2005]. Under normal fair weather circumstances, the largest vertical electric fields in the atmosphere arise from the global electric circuit (GEC) [*Wilson*, 1920]. The GEC describes the movement of charge from the earth to the ionosphere by thunderstorms and the return current in fair weather regions where there is no storm activity. In the polar regions, at the altitude of the MINIS balloons, the largest source of horizontal electric fields are ionospheric fields associated with plasma convection in the magnetosphere [*Mozer*, 1971]. These fields are mapped down from the ionosphere into the less conductive atmosphere.

[4] During the SEP event on 20 January 2005, we will show that both vertical and horizontal electric field components dropped to near zero with additional rapid changes in the vertical component several hours later. We will argue that simply increasing the local conductivity cannot account for all fluctuations measured.

2. Previous Measurements

[5] There have only been two previous successful in-situ stratospheric measurements of atmospheric electric field changes during SEP events [*Holzworth and Mozer*, 1979; *Holzworth et al.*, 1987]. The first direct correlation of SEP events and large electric field changes in the stratosphere

---

[1] Department of Earth and Space Sciences, University of Washington, Seattle, Washington, USA.

[2] Space Sciences Laboratory, University of California, Berkeley, California, USA.

[3] Department of Physics, University of Houston, Houston, Texas, USA.

[4] Aerospace Corporation, Los Angeles, California, USA.

[5] School of Physics, University of KwaZulu-Natal, Durban, South Africa.

[6] Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire, USA.

[7] School of Physics, North-West University, Potchefstroom, South Africa.

[8] Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, California, USA.

0094-8276/06/2006GL027718$05.00

was made during a large solar flare in August 1972. Geosynchronous orbiting satellite Explorer 41 recorded a four order of magnitude increase in energetic (>60 MeV) protons which slowly decayed to background levels over a five day period. Simultaneous vertical electric field measurements by a balloon at ∼30 km altitude in the northern polar cap measured a decrease in magnitude from 250 mV/m to 0 mV/m [*Holzworth and Mozer*, 1979]. This change was interpreted as a direct result of enhanced atmospheric conductivity. If the vertical current density (J) in the global electric circuit is assumed to be nearly constant and the conductivity (σ) is increased, then by Ohm's law, $J = \sigma E$, it follows that the electric field would decrease. Interestingly, the horizontal component of the electric field during that same period did not suddenly decrease as the vertical component did. It appeared as if the SEP interactions immediately affected the vertical component, but did not immediately affect the horizontal component [*Holzworth*, 1981].

[6] The next direct in-situ measurement was taken more than 10 years later in February 1984 with two important results reported [*Holzworth et al.*, 1987]. First, with both electric field and conductivity measurements made during this event, the change in vertical current density could be directly calculated with Ohm's law. In this case, the vertical current density did not remain constant but increased by a factor of two. The second important result was a measure of the spatial region of the SEP-affected electrical atmosphere. During this event, there were two balloons. The pole-ward balloon (44.6°S) measured perturbed conductivity and electric field magnitude while the more equator-ward balloon (38.7°S) did not observe any noticeable changes. In this case, the rigidity cutoff at the pole-ward balloon allowed SEPs to perturb the local electrical environment while the equator-ward balloon was at a cutoff where SEPs could not access, resulting in no noticeable changes to either the conductivity or electric field.. Although this report reinforced the validity of the idea that rigidity cut-offs play an extremely significant role in controlling SEP effects on the electrical atmosphere, it only presents a simplistic "on" or "off" view. The nature of the transition region between full SEP access and no SEP access is not explored. This leaves questions regarding transition region dynamics and how the SEPs might affect the electrical atmosphere at any given local inside the transition region unanswered.

3. Instrumentation

[7] The MINIS balloon campaign was designed with the intention of observing relativistic electron precipitation (REP), but had sufficient instrumentation to make SEP-related observations. Initial results relating to observed REP events are presented by J. G. Sample (First observations of MeV electron precipitation form multiple balloon-borne spectrometers, manuscript in preparation, 2006). The MINIS South campaign consisted of four payloads launched from SANAE IV, Antarctica, (71.7° S, 2.8° W geographic). There were two additional northern payloads launched from Ft. Churchill, Manitoba, Canada, but they did not have any electric field instrumentation and will not be discussed here. The payloads were powered with Li-Ion batteries and designed to last for an eight day flight. Data were telemetered to a ground station in Berkeley, CA via the Iridium satellite network [*Lemme et al.*, 1999]. Helium-filled balloons carried the 40 kg payloads to altitudes near 33 km. The main electric field instrumentation consisted of a set of three double Langmuir probes similar to those described by *Holzworth and Bering* [1998]. The probes were Aquadag (a carbon graphite paint) covered foam spheres, 15 cm in diameter. Using high impedance electronics, the potential difference between the probes and ground planes on the main payload frame was measured. Four horizontal probes were placed out 2 m from the payload center while two vertical probes were suspended on the balloon load line 3 m above the payload, separated from each other by 1 m. The entire payload was rotated about the vertical axis with a period of roughly 40 seconds in order to identify any non-geophysical horizontal dc offsets. Electric conductivity was determined by measuring the local relaxation time every ten minutes, following the method in *Holzworth* [1981]. Part of this method includes simultaneously shorting every probe to the main payload ground. Any dc offsets due to a floating ground can then be removed when analyzing the data. In addition to the dc electric field instruments, each balloon also carried a 3″ by 3″ NaI scintillator for detecting bremsstrahlung X-rays, a dc magnetometer and electric and magnetic VLF wave instruments.

4. Observations

[8] During the events of January 2005, there were four southern MINIS balloon flights, allowing the extreme event on 20 January 2005, to be completely recorded from before onset until complete relaxation several days later. We will focus this report on measurements during the single largest event on 20 January. Only one payload (Flight 2 South) was aloft for the entire duration although a second payload was launched about 14 hours after the SEP event onset.

[9] Upon the SEP onset at 6:51 UT, MINIS Flight 2 South was at 70.9° S, 10.9° W geographic and 30.9 km altitude. Over the course of the day, the balloon drifted nearly 400 km to 71.4° S and 21.5° W and reached a maximum altitude of 33.2 km. Coincident with the SEP flux increase, which can easily be seen in the GOES proton data in Figure 1, a huge conductivity increase was measured (Figure 2a). The dotted line represents an average conductivity calculated from a moving 5-point smoothing window for the time period following the SEP onset. We will use this average later to calculate the current density. The data points in Figure 2a are determined from the collection of negative ions only with error bar determination discussed below. Positive ion conductivity is not used for the following reason. During an SEP event, ozone between 50 and 80 km in altitude can become significantly depleted [*Degenstein et al.*, 2005]. The lack of ozone at high altitudes increases the UV photon flux and photo-ionization on the probes at the balloon altitude near 30 km which artificially decreases the relaxation time constant associated with the positive ion polar conductivity. During the SEP event, positive ion conductivity in the vicinity of the payload is measured to be artificially high. In order to estimate the electrical conductivity as accurately as possible, we assume that the conductivity of positive ions is equal to that of the negative ions [*Byrne et al.*, 1990]. The total electrical

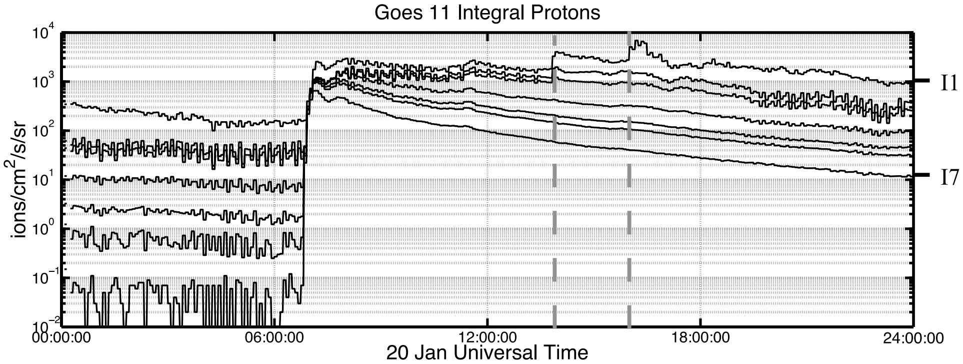

Figure 1. One-minute-averaged GOES 11 corrected integral proton channels during the January 20, 2005. All seven channels I1 through I7 are plotted for integral amounts greater than 1, 5, 10, 30, 50, 60 and 100 MeV protons respectively. The SEP arrival is evident 06:51 UT. Rapid increases in the low energy proton channels beginning at 13:48 UT and 15:58 UT coincide with the last two sharp jumps in the MINIS vertical electric field (Figure 2b). Data obtained from the NOAA/NGDC.

conductivity plotted is double the determined value from the negative ions.

[10] Directly following the SEP onset, there are noticeably fewer data points and the spread in conductivity value is quite large. There are fewer data points because the onboard computer was receiving an unexpectedly large number of particle counts from the crystal scintillator (REP events generally create much lower count rates than this SEP event). The massive number of counts effectively drowned the computer and as a result, some data were lost and the scintillator spectra data during this interval are not straightforward to interpret. The large error bars on the conductivity values after SEP arrival is due to the sampling rate which was slow when compared with the unexpectedly fast relaxation times. The sample rate during the conductivity calibration cycles was 10 Hz which is sufficient for nominal conditions. However, with an unexpected 20-fold increase in conductivity, the sampling rate was no longer much greater than the relaxation time. This increases the error associated with each decaying exponential conductivity fit. The error bars in Figure 2a show the 95% confidence bounds associated with the least squares fit. Despite a large range of confidence intervals, the significant electrical conductivity increase of an order of magnitude or more, is apparent.

[11] In addition to the conductivity, the electric field at the payload also changes dramatically at the SEP onset. Figure 2b shows one-minute-averaged vertical electric field. Before the SEP event, the field is comparable to what would be expected from the fair weather global electric circuit - varying around 100 mV/m and pointing down. As the SEPs arrive, the vertical field magnitude drops to near zero. The data also become much less noisy as a result of two things. The first effect comes from the conductivity enhancement because the probes can draw more current from the air in order to make potential difference measurements. Additionally, there is an instrumental source of noise which oscillates at the payload rotation frequency and whose magnitude is proportional to the measured geophysical field. This noise source could be accounted for by an asymmetric low-work-function conductor too close to one of the probes. Interestingly, hours later, in two separate events, the electric field suddenly changes again at 14:00 UT and 15:56 UT. The jump at 15:56 UT appears to change not only the magnitude, but the direction of the electric field. The direction reversal persists for several hours as the field gradually relaxes toward nominal conditions the next day. The authors are not aware of any previously reported reversal of this nature. Although there are sources of significant noise, all identified dc offsets have been removed resulting in a typical error of up to 15 mV/m [*Holzworth and Bering*, 1998].

[12] Along with the vertical electric field, the horizontal field also changes significantly. Figure 2c shows the south pole-ward and east-ward components of the horizontal field. Like the vertical field, at SEP onset, the magnitude drops considerably. However, there are no signs of significant, rapid dc changes coincident with the secondary vertical electric field jumps. The horizontal field appears to grow back to normal as the day goes on.

5. Discussion and Conclusion

[13] From the MINIS observations, it is evident that the 20 January, 2005 SEP event had a significant impact on atmospheric electrodynamics. Here, we discuss the ways in which MINIS observations are consistent with previous measurements as well as possible mechanisms which may be responsible for any deviations. Reports on both of the previous in-situ measurements describe a sudden vertical electric field magnitude decrease and conductivity enhancement coinciding with the onset of an SEP event. The MINIS data are consistent with this basic observation (see Figure 2). What sets the MINIS data apart are the two subsequent, rapid jumps in the dc vertical field several hours afterwards and the observations of the total (not just vertical) electric field disappearing suddenly at SEP onset.

[14] In an attempt to understand the effects of the SEP event on the GEC observed by MINIS, let us compare the vertical electric field and current density with the previous measurements mentioned above. In all three cases, conductivity enhancements accompanied decreases in vertical electric field magnitude, but there are significant differences in current density. *Holzworth and Mozer* [1979] assumed a very small current density change. *Holzworth et al.* [1987] calculated a factor of two increase from 2 pA/m^2

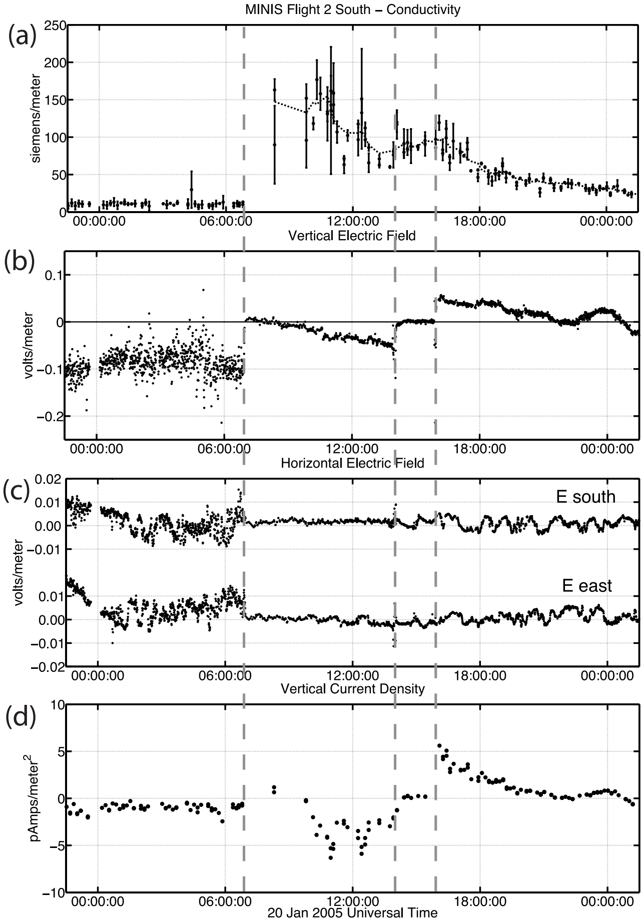

Figure 2. (a) Electrical conductivity at MINIS Flight 2 South on January 20, 2005 in pico-siemens/meter. SEP arrival is at 06:51 UT. The dotted line is a smoothed average to the data series after the SEP onset. (b) One-minute-averaged vertical electric field in volts/meter with positive pointing upward. The field initially disappears at SEP arrival and there are additional, sudden jumps at 14:00 UT and 15:56 UT. Typical error bars are 10–15 mV/m. (c) Horizontal electric field in volts/meter. The horizontal field dramatically decreases magnitude at SEP arrival, but there are no subsequent, rapid jumps. The dashed gray lines mark the SEP onset and the sudden jumps in the vertical electric field. (d) Vertical current density in pico-Amps/meter^2. The current density shifts rapidly with the electric field at 14:00 UT and 15:56 UT.

to 4.5 pA/m^2 vertically down, which lasted for only 20 minutes - on the order of the GEC relaxation time. MINIS vertical current density calculated using Ohm's law is shown in Figure 2d. For the time after the SEP event, the averaged conductivity plotted in Figure 2a was used. Not only did the current density remain altered for over 12 hours, but the magnitude and direction of the current was not constant, varying between ±5 pA/m^2. Rapid changes are seen when the vertical electric field fluctuated suddenly, which will be discussed shortly. Because the payload computer was overloaded with scintillator counts during the SEP event, the first conductivity measurement after onset is more than an hour later. It could be that the current density changes were greater directly following onset. Based on the GEC leaky capacitor model described by *Chalmers* [1967], if the total GEC current was assumed constant over this time scale, and if we also assume global thunderstorms were not changed by SEPs, then an increased conductivity in the polar regions would lead to both increased current density near the poles and decreases everywhere else. *Holzworth et al.* [1987] postulated that this did not happen for the 1984 event because its duration was not large compared with the total relaxation time of the GEC. The MINIS data show current density perturbations on time scales much longer then the maximum suggested GEC relaxation time of 40 minutes. If it can be determined that low-latitude current density decreased globally during the SEP event, then that would lend support to a model of the GEC as a constant current source. In order to account for the observed magnitude fluctuations, calculations of the total current density changes may need to include current arising from the precipitating SEPs themselves. *Reagan et al.* [1983] postulated that the proton and electron current may be sizable during large SEP events and could, in part, cause a vertical electric field reversal.

[15] There is no previous report similar to the two subsequent, rapid field changes seen in Figure 2b. These rapid jumps at 14:00 UT and 15:56 UT could, in principle, be a result of changing the input SEP spectrum to the global system. However, the high energy proton data from the POES satellites and GOES proton channels greater than 30 MeV (Figure 1) show no obvious sign of rapid flux changes (NOAA/NGDC, POES and GOES data can be obtained at http://spidr.ngdc.noaa.gov) Thus, a global SEP spectrum change is unlikely to be the cause of the rapid jumps in the MINIS vertical electric field. While global SEP flux is not rapidly changing, we investigate how local SEP flux may change at MINIS Flight 2 South. It might be that the rigidity cutoffs near the balloon suddenly shift. As SEP protons enter the magnetosphere, they undergo Størmer orbits defined by the proton's energy, incidence angle and also magnetospheric structure. With a sudden change in the magnetosphere, SEP protons may also have a rapid change in their rigidity cutoffs. *Rodger et al.* [2006] showed that rigidity cutoffs can move substantially given a change in geomagnetic activity. Based on POES data, the size of the transition region, the latitude band which all SEPs have access to on the polar side and no SEPs have access on the equatorial side, is 1500 km for the 20 January event. Sub-satellite position of locations where the POES space-craft measured large SEP flux indicate that MINIS Flight 2 South could have been inside the transition region, floating equator-ward in magnetic latitude as the day progressed. Since satellites are not always directly overhead, it is difficult to get a more accurate balloon position with respect to the incoming SEPs. A payload position inside the transition region gives us the possibility to explore electrical effects in the stratosphere as rigidity cut-offs shift location with respect to the balloon. Significant(>100 nT), sudden decreases in the northward component in ground-based IMAGE magnetometer data [*Lühr et al.*, 1998] at the same time as MINIS observes the rapid vertical electric field jumps can be seen in Figure 3. These sharp decreases indicate a large-scale shift in the geomagnetic field that could be responsible for shifts in SEP rigidity cutoffs. There are more sharp IMAGE fluctuations later on which do not

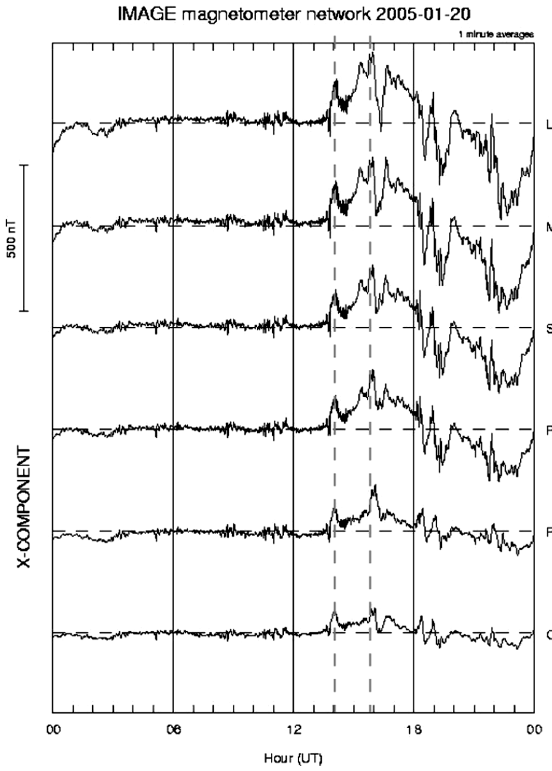

Figure 3. Northward magnetic field data from several IMAGE ground based magnetometers, headed by the Finnish Meteorological Institute, for January 20, 2005. The two dashed lines indicate the time when MINIS observed sudden jumps in the vertical electric field. MINIS Flight 2 South and the IMAGE array are separated by 40 degrees geographic longitude. Their magnetic latitude is nearly equal and opposite with Flight 2 South at 62.5 S.

show as significant a correlation with the MINIS electric field. By this time the SEP event is fading and the balloon may have floated away from the transition region.

[16] Any sudden change in local rigidity will have an affect on the local precipitating SEP spectrum. For example, the expected change measured by an observer moving equator-ward into the transition region would be to effectively remove the lower energy SEP particles from the local flux spectrum. This, in turn, will affect the local conductivity profile, electric field and current density. Consider a case where a MINIS payload was at the very equator-ward edge of the transition region, where only the highest energy SEPs have access. Since SEPs ionize more particles near their stopping altitude, there would be a localized conductivity enhancement at a specific altitude. The charge deposited into the atmosphere by the SEPs would also be localized at a specific altitude. If this conductivity enhancement and charge layer are below the balloon altitude, then an upward pointing electric field could arise which, in principle, could be responsible for the observed vertical field reversal. Rapid rigidity cutoff dynamics may be of great importance in this case and will be a focus of future work.

[17] Before SEP onset, the horizontal fields measured by MINIS are consistent with very quiet magnetospheric convection. Due in part to the payload location near the edge of the polar region, contributions from the ionospheric dynamo, electrified clouds or other tropospheric sources have not been completely ruled out. Assuming the horizontal fields are due solely to potential differences in the ionosphere, based on work by *Park and Dejnakarintra* [1977], SEP-related increases in conductivity of would have little effect on large scale (>100 km) ionospheric horizontal electric field measurements mapped down to the stratosphere. Indeed, the horizontal electric field components did not disappear directly following SEP onset in both of the previous in-situ reports [*Holzworth and Mozer*, 1979; *Holzworth et al.*, 1987]. Regardless, MINIS observations show that the horizontal field does vanish immediately following the SEP onset. If one were to assume that the source of the horizontal electric field was magnetospheric plasma convection mapped onto the ionosphere, a vanishing horizontal electric field might imply that convection had ceased, or that the convection cells suddenly moved pole-ward relative to the balloon location. Due to an otherwise quiescent magnetosphere before and after the SEP onset, and coupled with the fact that ionospheric radars cannot easily detect fields smaller than 20 mV/m, it is difficult to find data supporting or detracting from a modified convection system. Since the horizontal field decreases occurred very rapidly (faster than an Alfven wave can traverse the magnetosphere) it is unlikely that the effect is solely caused by a global convection stoppage. However, the fact that the horizontal field stayed near zero for hours may be an important clue into magnetospheric configuration. The authors are unaware of any detailed, proposed mechanisms suggesting that SEPs actually stop magnetospheric convection from occurring. If the convection cells suddenly shifted pole-ward of the balloon, one might expect ground-based magnetometers to fluctuate suddenly at SEP arrival. However, there are no significant shifts in any of the field components in the IMAGE array at SEP onset - 06:51 UT. (See Figure 3.)

[18] In summary, the MINIS balloon campaign successfully made in-situ atmospheric electricity measurements during the extremely energetic SEP event on 20 January 2005. A vanishing of both vertical and horizontal electric field components and conductivity enhancements were observed at SEP onset as well as subsequent, rapid vertical electric field changes many hours later. These two unique features of the MINIS data set cannot be explained by simply enhancing the atmospheric conductivity. Rather, it is likely that the rapid vertical fluctuations are related to rigidity cutoff motion while the vanishing of the horizontal field may be connected to more interesting magnetosphere dynamics. Future work will focus on further explaining these unusual observations.

[19] **Acknowledgments.** We thank our South African support, which included many people from both SANAP and DEAT. We also thank the folks at CSBF for help in test launching from McMurdo in 2003 and all of the institutes who maintain the IMAGE magnetometer array. This work was supported under NSF grant OPP-0230441.

References

Bieber, J. W., et al. (2005), Largest GLE in half a century: Neutron monitor observations of January 20, 2005 event, paper presented at 29th International Cosmic Ray Conference, Sol., Helios. and Interplanet. Environ., Pune, India.

Byrne, G. J., J. R. Benbrook, E. A. Bering, and D. M. Oró (1990), Solar radiation (190–230 nm) in the stratosphere: Implications for photoelectric emissions from instrumentation at balloon altitudes, *J. Geophys. Res.*, *95*, 5557–5566.

Chalmers, J. A. (1967), *Atmospheric Electricity*, 34 pp, Elsevier, New York.

Degenstein, D. A., N. D. Lloyd, A. E. Bourassa, R. L. Gattinger, and E. J. Llewellyn (2005), Observations of mesospheric ozone depletion during the October 28, 2003 solar proton event by OSIRIS, *Geophys. Res. Lett.*, *32*, L03S11, doi:10.1029/2004GL021521.

Holzworth, R. H. (1981), High-latitude stratospheric electrical measurements in fair and foul weather under various solar conditions, *J. Atmos. Terr. Phys.*, *43*, 1115–1125.

Holzworth, R. H., and E. A. Bering (1998), Ionospheric electric fields from stratospheric balloon borne probes, in *Measurement Techniques for Space Plasmas: Fields*, *Geophys. Monogr. Ser.*, vol. 103, edited by R. Pfaff, J. E. Borovsky, and D. T. Young, pp. 79–84, AGU, Washington, D. C.

Holzworth, R. H., and F. S. Mozer (1979), Direct evidence of solar-flare modification of stratospheric electric-fields, photoelectric emissions from instrumentation at balloon altitudes, *J. Geophys. Res.*, *84*, 363–367.

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

Jackman, C. H., M. T. DeLand, G. J. Labow, E. L. Fleming, D. K. Weisenstein, M. K. W. Ko, M. Sinnhuber, and J. M. Russell (2005), Neutral atmospheric influences of the solar proton events in October–November 2003, *J. Geophys. Res.*, *110*, A09S27, doi:10.1029/2004JA010888.

Jones, J. B. L., et al. (2005), Space weather and commercial airlines, *Adv. Space Res.*, *36*, 2258–2267.

Lemme, P. W., et al. (1999), Iridium ((R))—Aeronautical satellite communications, *IEEE Aerosp. Electron. Syst. Mag.*, *14*, 11–16.

Lühr, H., et al. (1998), Westward moving dynamic substorm features observed with the IMAGE magnetometer network and other ground-based instruments, *Ann. Geophys.*, *16*, 425–440.

McCracken, K. G. (1962), The cosmic-ray flare effect: 3. Deductions regarding the interplanetary magnetic field, *J. Geophys. Res.*, *67*, 447–458.

Moraal, H., et al. (2005), The ground level enhancements of 20 January 2005 and 28 October 2003, paper presented at 29th International Cosmic Ray Conference, Sol., Helios. and Interplanet. Environ., Pune, India.

Mozer, F. S. (1971), Balloon measurement of vertical and horizontal atmospheric electric fields, *Pure Appl. Geophys.*, *84*, 32–45.

Park, C. G., and M. Dejnakarintra (1977), The effects of magnetospheric convection on atmospheric electric fields in the polar cap, in *Electrical Processes in Atmospheres*, edited by H. Dolezalek and R. Reiter, pp. 536–543, Steinkopff, Darmstadt, Germany.

Reagan, J. B., R. E. Meyerott, J. E. Evans, W. L. Imhof, and R. G. Joiner (1983), The effects of energetic particle precipitation on the atmospheric electric circuit, *J. Geophys. Res.*, *88*, 3869–3878.

Reames, D. V. (1999), Particle acceleration at the Sun and in the heliosphere, *Space Sci. Rev.*, *90*, 413–491.

Rodger, C. J., M. A. Clilverd, P. T. Verronen, T. Ulich, M. J. Jarvis, and E. Turunen (2006), Dynamic geomagnetic rigidity cutoff variations during a solar proton event, *J. Geophys. Res.*, *111*, A04222, doi:10.1029/2005JA011395.

Share, G. H., et al. (2002), RHESSI observation of atmospheric gamma rays from impact of solar energetic particles on 21 April 2002, *Sol. Phys.*, *210*, 357–372.

Vampola, V. M. (1969), Energetic electrons at latitudes above the outer-zone cutoff, *J. Geophys. Res.*, *74*, 1254–1269.

Verronen, P. T., A. Seppälä, M. A. Clilverd, C. J. Rodger, E. Kyrölä, C.-F. Enell, T. Ulich, and E. Turunen (2005), Diurnal variation of ozone depletion during the October–November 2003 solar proton events, *J. Geophys. Res.*, *110*, A09S32, doi:10.1029/2004JA010932.

Wilson, C. T. R. (1920), Investigations on lightning discharges and on the electric field of thunderstorms, *Philos. Trans. R. Soc. London, Ser. A*, *221*, 73–115.

S. D. Bale, R. P. Lin, G. K. Parks, M. Pulupa, and J. G. Sample, Space Sciences Lab, University of California, Berkeley, CA 94720, USA.

E. A. Bering and B. D. Reddell, Department of Physics, University of Houston, Houston, TX 77204-5005, USA.

J. B. Blake and T. P. O'Brien, Aerospace Corporation, 2350 E. El Segundo Blvd., Los Angeles, CA 90245-4691, USA.

A. B. Collier and A. R. W. Hughes, Physics Department, University of Kwa-Zulu Natal, Durban Centre, Durban, 4041 South Africa.

R. H. Holzworth, M. Kokorowski, E. Lay, and M. P. McCarthy, Department of Earth and Space Sciences, University of Washington, Seattle, WA 98915, USA. (mkoko@u.washington.edu)

R. M. Millan and L. Woodger, Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755, USA.

H. Moraal and P. H. Stoker, School of Physics, North-West University, Private Bag X6001, Potchefstroom, 2520 South Africa.

D. M. Smith, SCIPP, University of California, Santa Cruz, CA 95064, USA.