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Geomagnetic storms, Forbush decreases of cosmic rays and total ozone at northern higher middle latitudes

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Abstract

Space weather affects the Earth's atmosphere in many ways and through various phenomena. Among them, geomagnetic storms and the variability of the galactic cosmic ray flux belong to the most important ones as for the lower atmosphere. Here, we summarize our previous results on the effects of strong geomagnetic storms and strong Forbush decreases of galactic cosmic rays on the total ozone at the northern higher middle latitudes, and complete them with investigations of effects of geomagnetic storms not accompanied by Forbush decreases. The effects of strong geomagnetic storms and Forbush decreases occur only in the winter part of the year, under the high solar activity and the E-phase of QBO (E-max) conditions. The effects of storms seem to be a redistribution of ozone as a consequence of storm-related changes of circulation. No event contradicts the idea that the Forbush decreases are responsible for effects of geomagnetic storms on the lower atmosphere (troposphere and lower stratosphere) including total ozone. However, under the E-max conditions in the winter part of the year, only several Forbush decreases without geomagnetic storms and only one geomagnetic storm without the Forbush decrease occurred over more than 20 years.

Keywords: Ozone; Geomagnetic storms; Forbush decreases of cosmic rays

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1. Introduction

Geomagnetic storms and Forbush decreases of the galactic cosmic ray flux belong to components of the space weather, which affect the Earth's atmosphere. Geomagnetic storms are probably the most important phenomenon among space weather phenomena. They produce large disturbances in the ionosphere, but they affect also the neutral atmosphere including the middle atmosphere and troposphere (e.g., Laštovička, 1996).

Laštovička et al. (1992) initiated our investigations of geomagnetic storm effects on the total ozone (= columnar ozone content). They found that previous results obtained by various authors on effects of geomagnetic storms on the total ozone differed substantially. They apparently did not provide a consistent pattern. More recent results of other authors (e.g., Storini, 2003; Belinskaya et al., 2001; Tassev et al., 2003) confirm this apparent inconsistence. However, our further investigations (Mlch, 1994; Mlch and Laštovička, 1995; Laštovička and Mlch, 1999) provided a consistent pattern of the geomagnetic storm effect on the total ozone at northern middle latitudes, which occurred as a significant effect only under very limited conditions, while it was negligible or at least much smaller, questionable and statistically insignificant under all other conditions. Our results revealed a significant, systematic and large effect of geomagnetic storms on the total ozone at northern higher middle latitudes around

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the latitudinal circle 50° N, but not at 40°N and 60°N, and under the following conditions:

Winter (15 November–15 March); strong storms (Ap > 60); high solar activity (R_{12} or the yearly average sunspot number larger than 100) and the east phase of the quasi-biennial oscillation (QBO)—E-max conditions.

Fig. 1 illustrates how the effect of geomagnetic storms on the total ozone in Europe (average from five Dobson stations near 50°N, 1968–1988) emerges with more and more favourable conditions. All wintertime events under the high solar activity conditions do not display an effect (bottom curve). When we select only those under the E-max conditions for storms with Ap > 40, the effect appears but its statistical significance may be questioned (middle curve). The increase of the storm limit to Ap > 60 results in a strong and statistically significant effect. There is only a very small number of such geomagnetic storms, but the effect is very similar in all individual events. Several other more recent events (not shown in Fig. 1) confirm this pattern.

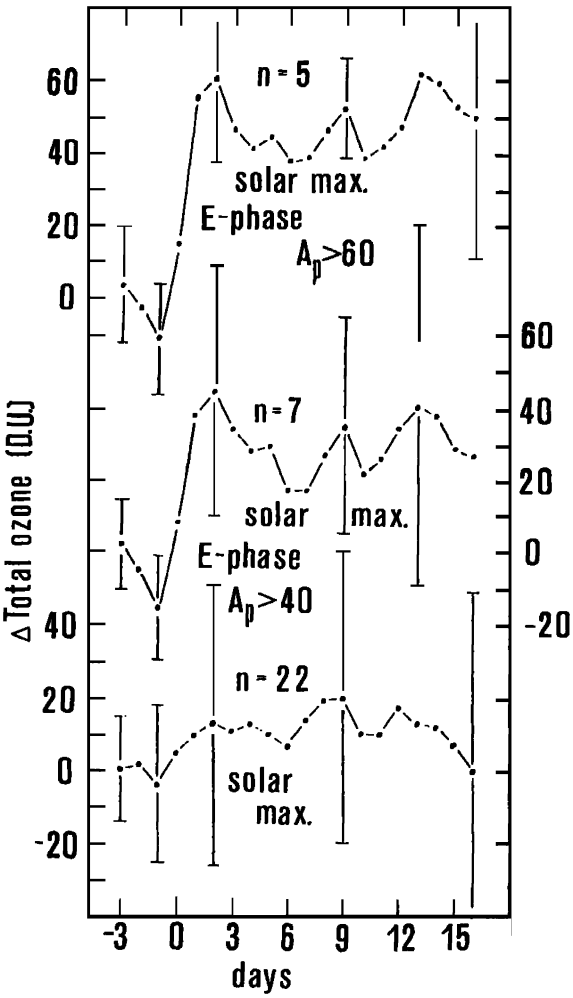

Fig. 1. Total ozone (Europe—near 50°N) deviations from average level over days −6 to 0 for major geomagnetic storms under the high solar activity conditions. All events under high solar activity (bottom curve), events under the E-phase of QBO (E-QBO; middle curve), very strong storms (Ap > 60) under the E-QBO (top curve). Vertical lines—error bars; *n*—number of events. After Laštovička et al. (1992).

Our investigations (Laštovička et al., 1992; Mlch, 1994; Mlch and Laštovička, 1995; Laštovička and Mlch, 1999) also revealed other findings:

- Just after a strong storm, we observe a significant increase of the total ozone in European–Eastern Atlantic sector due to a substantial smoothing of longitudinal variation of total ozone. Such a variation is very weak in summer and, thus, there is no effect in summer. For a similar reason there is no effect in the zonal mean total ozone. The effect is redistribution, neither ozone production, nor ozone loss.
- There are two sectors sensitive to strong geomagnetic storms both in the total ozone and in the troposphere—(1) North-eastern Atlantic + European sector, (2) Eastern Siberian + Aleutian sector.
- The total ozone response to strong geomagnetic storms seems to be caused by changes in atmospheric dynamics. Changes in the circulation pattern agree, at least qualitatively, with the changes observed in total ozone.

The energy deposition in the lower ionosphere and middle atmosphere is predominantly via the Joule heating in its uppermost part and via the energetic electron precipitation below the uppermost part. But these energetic particles are unable to penetrate down to the heights of the lower stratosphere, to the maximum of the ozone layer and below. Therefore it is necessary to look for another candidate for the agent responsible for the observed effects. The strong geomagnetic storms used to be accompanied by the Forbush decreases of galactic cosmic rays almost as a rule, therefore a hypothesis about the storm-related cosmic ray flux changes as the potential origin of geomagnetic storm effects on the troposphere, lower stratosphere and total ozone has been formulated. The Forbush decreases were found to cause changes in cloud cover, particularly in the upper-level clouds (Todd and Kniveton, 2001). Cosmic rays seem to affect clouds and climate on longer time-scales (e.g., Carslaw et al., 2002), even though there is still controversial debate about such effects (e.g, Friis-Christensen, 2000; Kristjánsson et al., 2002). The galactic cosmic ray flux changes are the basis of the "electrofreezing" and "electroscavening" theory of the geomagnetic storm effects on the troposphere (Tinsley and Heelis, 1993; Tinsley, 2000). They seem to affect the chemical composition of the stratosphere and mesosphere, particularly their minor components (e.g., Krivolutsky et al., 2002). As for the effects of the cosmic ray flux variability on the ozone layer, Krivolutsky (2003) and reference therein recently described the development of our knowledge and understanding, which is still far from being consistent and complete.

Solar protons and relativistic electrons can affect ozone. The solar proton events (SPE) can substantially reduce the ozone concentration in the mesosphere in the polar cap (e.g., Jackman et al., 1990), and very strong SPEs can measurably reduce even the total ozone (e.g., Reagan et al., 1981). However, we discuss the storm effect near 50°N, which is considerable redistribution, but not a reduction of the zonal mean total ozone. This rules out possible significant role of the SPEs in the observed effects of geomagnetic storms. Similar reasons, i.e. insufficient penetration depth for a lower stratosphere effect (relativistic electrons are important in the mesosphere and upper stratosphere, Thorne, 1980) and no observable change in the zonal mean total ozone, rule out the role of relativistic electron precipitation events, as well.

The objective of this short report is to summarize our previous results on the effects of the Forbush decreases of galactic cosmic rays on the total ozone, to complete these investigations, and to test the hypothesis on the principal role of cosmic rays in the observed effects of geomagnetic storms on the total ozone/lower stratosphere.

2. Cosmic rays and ozone

Fedulina and Laštovička (2001) found that the effects of sufficiently pronounced Forbush decreases on the total ozone at northern higher middle latitudes occurred under the same conditions as those for the occurrence of significant, systematic and large enough effects of strong geomagnetic storm effects, i.e. winter, strong effect, 50°N and the E-max conditions. They found also a similar shape and longitudinal distribution of both effects (the most pronounced effect occurred in the Euro-Atlantic sector). This is not surprising because the strong geomagnetic storms are very predominantly accompanied by Forbush decreases.

The logical next step is to search for the effects of the sufficiently strong Forbush decreases not accompanied by geomagnetic storms. This was done by Laštovička et al. (2003). They selected all events from the period of 1982 to 2002, which satisfied the conditions of the galactic cosmic ray flux depression of at least 3% at the Lomnický Štít Observatory in Slovakia, Dst near 0 and quasi-stable, no overlap with other cosmic ray events in the interval of days -8–$+14$, and at maximum one data gap. They found altogether 15 such events. Only four events occurred in winter, and only two of them under the E-max conditions.

Summertime events did not yield any significant effects of Forbush decreases, whereas wintertime events did, even though they were weaker. The strongest cosmic ray event of July 2001 with the galactic cosmic ray flux decrease by 15% did not reveal any systematic observable effect. On the other hand, a much weaker (6% decrease) event of January 2002 (winter, E-max conditions) provided an evident effect in the Euro-Atlantic sector near 50°N; the peak increase reached almost 100 DU and it was statistically significant at the 3σ level (Laštovička et al., 2003).

Thus the number of sufficiently pronounced Forbush decreases not accompanied by geomagnetic storms is small, but all individual events fit the above pattern of the occurrence of effects of geomagnetic storms.

The step necessary to complete the examination of the relationship between the effects of geomagnetic storms and Forbush decreases on the total ozone is to look at the effects of strong geomagnetic storms not accompanied by Forbush decreases. Such events are even more rare than those of Forbush decreases without geomagnetic storms.

We selected all strong geomagnetic storms (Dst < -200 nT) over the period 1982–2002 from Table 2 of Kudela and Brenkus (2004) accompanied by only marginal decrease or no change of the galactic cosmic ray flux at Lomnický Štít. Altogether seven such events were found. In some cases, these events were geomagnetic storms without Forbush decreases. For other events, measurements at Oulu (northern Finland) displayed the Forbush decrease, which was compensated for by a change of the vertical cutoff rigidity at Lomnický Štít.

Four events occurred in the non-winter part of the year, storms of March 30, 2001, June 1991, May 1998 and August 2000. They did not display any consistent, systematic effect of geomagnetic storms along latitudinal circles of 50°N and 60°N, as expected.

Three other events of Novembers 1982, 1989 and 2001 occurred in the winter part of the year, but in its very early phase. All three events fulfill the condition of high solar activity. The first event was observed under the W-phase of the QBO conditions, while the second and the third one fulfilled the E-max condition. No systematic, consistent effect was observed in November 1982 and at 60°N for the other two events, as expected. The event of November 1989 was accompanied only by a "mini-Forbush" at Oulu and, therefore, only oscillations of quasi-random character were observed at 50°N. This was storm without the Forbush decrease, and also without an effect similar to that caused by strong geomagnetic storms in winter under the E-max conditions. Thus the event of November 1989 supports the idea of the Forbush decrease origin of the observed effects of strong geomagnetic storms on the total ozone.

However, the total ozone changes consistent with the above reported effect of strong geomagnetic storms were observed for the event of November 2001 at 50°N, as illustrated by Fig. 2. We can clearly see a storm-related enhancement of total ozone in the Euro-Atlantic sector, between about 50° W and 40° E, which is typical for the effects of strong geomagnetic storms under the E-max conditions in winter. Thus in the first glance this event seems to indicate that there may be geomagnetic storm effect in ozone not related to Forbush decreases. However, the Oulu observatory revealed a relatively strong Forbush decrease by about 9%. This means that the Forbush decrease at Lomnický Štít was compensated for and masked by the effect of the change of the vertical cutoff rigidity during this geomagnetic storm, and the observed effect remains consistent with the idea of the Forbush decrease origin of the geomagnetic storm effects on ozone.

When we turn back to the strong geomagnetic storm criterion $\mathrm{Ap}>60$ and inspect only midwinter (January, February), we find in the period 1979–2002 only one storm observed under the E-max conditions and not accompanied by the Forbush decrease at Lomnický Štít, the storm of February 2–3, 1992. Fig. 3 shows the total ozone response to this storm at 50°N. We observe an increase of the total ozone in the North Atlantic-European sector by some 30 DU, even though shifted a bit eastward. This is more than a half of the 40–60 DU increase observed for storms with $\mathrm{Ap}>60$ in winter, E-max, in Fig. 1. But the high-latitude stations Thule and Deep River displayed an evident Forbush decrease by about 9% during this event. Thus again the observed effect may be attributed to the associated Forbush decrease.

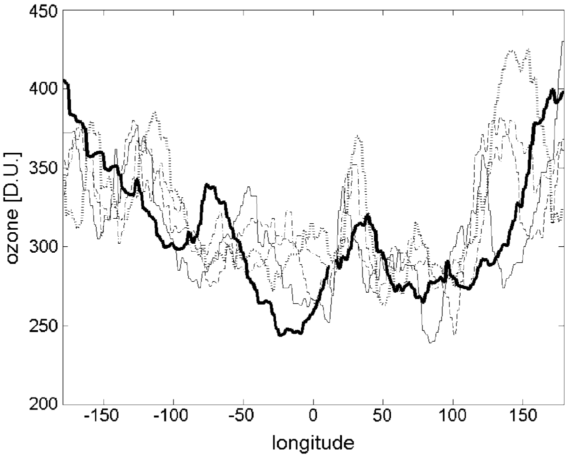

Fig. 2. TOMS total ozone (DU) along the latitudinal circle 50°N, the storm of November 24, 2001 (Dst = −213 nT). Bold curve—pre-storm level (average from days −6 to −1); thin continuous curve—day 0 (storm maximum day), thin dashed curve—day +1, thin dash-dot curve—day +2, bold dotted curve—day +3.

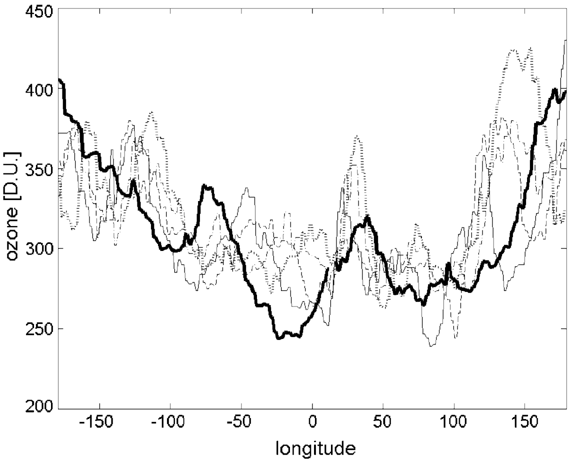

Fig. 3. TOMS total ozone (DU) along the latitudinal circle 50°N, the storm of February 2–3, 1992 (Ap = 56 and 92, respectively). Bold curve—pre-storm level (average from days −8 to −1); thin continuous curve—storm days (average from February 2 and 3); thin dashed curve—average from February 4 and 5; thin dash-dot curve—average from February 6 and 7. On February 8 and 9, another strong storm accompanied by the Forbush decrease occurred.

3. Concluding remarks

The main results of our investigations of the effects of geomagnetic storms and Forbush decreases on the total ozone may be summarized as follows:

(a) Sufficiently strong and statistically significant effects of geomagnetic storms and the Forbush decreases of the galactic cosmic ray flux appear to occur in the total ozone at the northern higher middle latitudes only for strong events ($\mathrm{Ap}>60$ for storms), in winter, and under the E-max conditions. They occur around 50°N, but not around 40°N and 60°N. The effect appears to be basically re-distribution of ozone (in the North Atlantic-European sector it means an increase of the total ozone), neither its loss, nor its production.

(b) The Forbush decreases seem to play a very important, likely rather decisive role in the effects of geomagnetic storms on total ozone.

The conclusion (b) is preliminary as it is based on a very small number of events, because the strong Forbush decreases without geomagnetic storms and, particularly, the strong geomagnetic storms without Forbush decreases (only one event, that of November 1989) occur very rarely. On the other hand, we analysed all such events and none of individual events was in the contradiction with conclusion (b).

Todd and Kniveton (2001) found a decrease in cloud cover, particularly in the upper level clouds, which was associated with the Forbush decreases. It might be caused by Tinsley's electrofreezing and electroscavening mechanisms (cloud microphysics) (Tinsley and Heelis, 1993; Tinsley, 2000). As a consequence of that, the dynamics can be changed, which might result in the total ozone redistribution. Major midwinter stratospheric warmings do not play a role, because they do not occur under the E-max conditions. Mlch and Laštovička (1995) found for all studied strong geomagnetic storms under the E-max conditions that the observed increase of the total ozone in the European sector can be attributed more or less to the same circulation pattern transporting ozone-rich air from higher latitudes located to the northwest of Europe (Iceland–Greenland region). Changes of circulation for a couple of storms under other conditions supported the observed behaviour of ozone, as well, i.e. they supported no systematic effect (Mlch and Laštovička, 1995). The question as to why and how geomagnetic storms can cause changes of the lower stratospheric and tropospheric circulation remains an open and controversial topic. We are not going to discuss this problem, which is out of the scope of this paper.

Future investigations should address the changes of ozone profile during strong geomagnetic storms and Forbush decreases. Ozonesondes cannot be used for such studies due to low frequency of soundings, no more than 2–3 times per week. Therefore we can use only the ozone profiles from the last 1–2 decades from satellite soundings by POAM (particularly POAM III), HALOE and SAGE II, if the profiles are available at higher latitudes in the required times.

Acknowledgements

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