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INFLUENCE OF GALACTIC COSMIC RAY FORBUSH DECREASE ON THE OZONE PROFILES

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Abstract: *Recently proposed mechanism for ozone production in the lower stratosphere, initiated by the lower energetic electrons in Regener-Pfotzer maximum, could be additionally verified in periods of sudden decreases in cosmic rays intensity, known as Forbush decreases (FD). The strongest geomagnetic storm during the 24-th solar cycle (known as the St. Patrick's day storm) is characterised by a significant Forbush decrease. Analysis of time series of different neutron monitors (NM) reveals that FD accompanying the geomagnetic storm is not recorded simultaneously in NMs spread over the world. This situation allows us to compare the local ozone profiles' responses to the different spatial-temporal variability of cosmic rays intensity. The ozone profiles have been examined within the entire March and their values before and during the Forbush decrease are compared. It was confirmed that weakening of particles flux, entering Earth's atmosphere, is followed by immediate changes in ozone profile – different in the upper and lower stratosphere. Particularly, the lower stratospheric ozone demonstrates high sensitivity to the level of cosmic radiation – decreasing significantly with its depletion.*

ВЛИЯНИЕ НА ФОРБУШ ПОНИЖЕНИЕТО В ИНТЕНЗИТЕТА НА КОСМИЧНИТЕ ЛЪЧИ ОТ МАРТ 2015 ВЪРХУ ПРОФИЛИТЕ НА АТМОСФЕРНИЯ ОЗОН

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Ключови думи: *геомагнитна буря, Форбуш понижение, озонен профил*

Резюме:. *Валидността на предложения в последните години механизъм за производство на озон в ниската стратосфера – в резултат от активирането на йонно-молекулярни реакции в максимума на Регенер-Пфотсер – може да бъде проверен в периоди на внезапно понижение на потока космични лъчи, известен като Форбуш понижения. Най-силната геомагнитна буря в протежение на 24-я слънчев цикъл, известна като бурята в деня на Св. Патрик, е съпроводена със значително Форбуш понижение. Интересно е да се отбележи, че рязък спад в постъпващата космическа радиация е регистриран от наземно-базираната мрежа от неутронни монитори, в различни моменти от развитието на бурята и нейното постепенно затихване. Това ни даде възможност да сравним измененията в профилите на озона в зависимост от локалното проявление на Форбуш понижението. Настоящото изследване потвърждава установеният преди факт, че отслабването на потока космическа радиация е съпроводено с незабавни промени в профилите на озона – различни във високата и в ниската стратосфера. В частност, плътността на озона в ниската стратосфера намалява значително с намаляването на интензитета на космическите лъчи достигащи до земната повърхност.*

Introduction

The St. Patrick's day storm in March 2015 appears after the solar explosion from the western, geo-effective region on the solar disk, which triggers a partial halo coronal mass ejection, propagating toward the Earth. The interplanetary shock wave, sweeping the Earth after that, is accompanied by a significant Forbush decrease (FD), measured by various detectors. The analysis of the onset time of FD shows that many neutron monitors counted it simultaneously. However, peculiarities have been found in some of them. As an illustration of this effect, Fig. 1 presents the temporal variability of the FD onsets in three high altitude neutron monitors – Lomnicky Stit (LMKT; R=3.84, Alt=2634 m), Emilio Segre Observatory in Israel (ESOI; R=10.75, Alt=2055 m) and Tibet (TIBT; R=14.1; H=4300 m). Note the pre-storm reduction of cosmic ray (CR) flux in LMKS and its post-storm decrease in ESOI observatory, shown in Fig. 1.

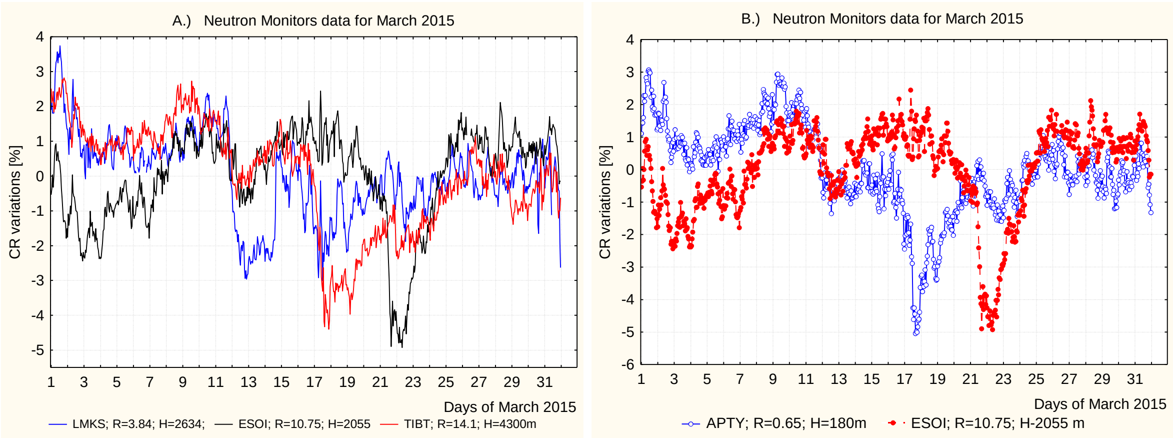

Fig. 1. Time series of cosmic radiation measured in several neutron monitors' locations

According to the resent understanding, the non-simultaneous FD events occur when a relatively weaker interplanetary magnetic cloud strikes the dusk side of the magnetosphere [1]. The heterogeneity of the interplanetary magnetic field and disturbed magnetosphere are the main reasons for the observed differences in FD onset time, depending more on the measuring station's longitude than on its latitude [2]. This situation has been exploited as a possibility to investigate the local response of ozone profile to the short lasting decrease of the cosmic ray flux reaching the surface.

Data and methods of analysis

The hourly values of neutron monitors counting rates have been derived by the freely available data at NMDB portal: http://www01.nmdb.eu and the IZMIRAN data server: http://cr0.izmiran.ru/common/links.htm. Provided data are pressure and efficiency corrected. The relative changes in cosmic radiation in % are calculated as deviations from the monthly mean values, normalised by the same mean and multiplied by 100.

Gridded data for a atmospheric ozone profile has been taken from the ERA-Interim reanalysis http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/. The deviations from the monthly mean values have been used for assessment of the short-term fluctuations in ozone's profile.

Two methods have been used as quantitative estimators of similarity in temporal variability of cosmic radiation and ozone profiles – the classical cross-correlation method and the artificial neural network one.

Results

The spatial distribution of the cosmic ray Forbush decrease (FD) in March 2015 has been constructed from observatories, participating in the world neutron monitors network, with altitude less than 500 m. above the sea level (see Fig. 2). Note the heterogeneously distributed FD being more significant in regions with stronger longitudinal magnetic gradient.

Two monitors – APTY (67.57^{0}N; 33.39^{0}E) and ESOI (33.3^{0}N; 35.8^{0}E) – have been selected for analysis of the ozone response to the reduced CR intensity. They have different geomagnetic rigidity (R) what means that particles with different energies and different origin are able to affect the ozone profiles over both observatories. At the same time the two monitors are placed near 30^{0}E longitude, which excludes the potential influence of the geomagnetic field longitudinal gradient. Moreover, the FD onset in both observatories is shifted by four days, allowing us to analyse the ozone response to the global (storm related) and local changes of the atmospheric ionization.

The daily O_3 profiles over Apatite, shown in Fig. 3, illustrate fairly well the ozone sensitivity to the variations in arriving cosmic rays. Note that the Forbush decrease commencement is followed by a reduction of ozone density in the upper stratosphere, and its pile up in the lower stratosphere – starting at March 18, 2015. The low magnetic rigidity of APTY indicates that it is freely accessible to the CR, arriving along the open geomagnetic field lines.

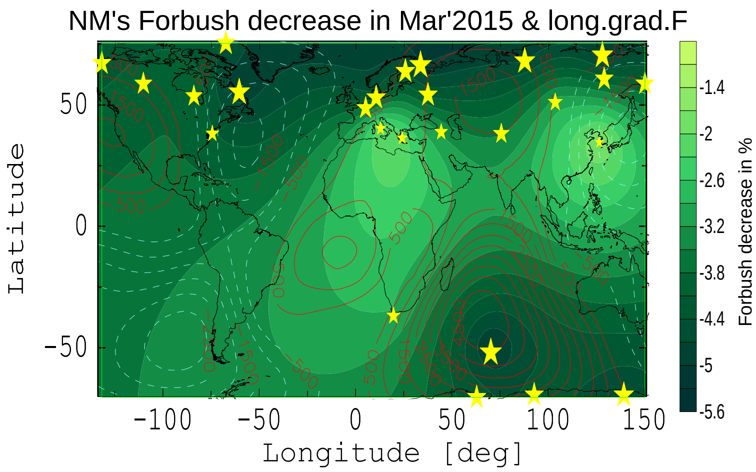

Fig. 2. Map of Forbush decrease in March 2015 as measured in the ground-based network of neutron monitors with elevation above the sea level less than 500 m (green shading) and differently sized stars. Note that larger stars denote higher cosmic ray intensity. Overdrawn is the longitudinal gradient of the geomagnetic field (contours).

When the interplanetary shock wave pass the Earth, the solar plasma propagates in polar stratosphere, activating ozone reduction – through direct dissociation or through activation of ozone destroying chemical reactions. The reduced optical thickness of the upper stratospheric ozone allows penetration of solar ultraviolet radiation deeper in the lower stratosphere, where it activates the ozone self-restoration [3]. As a result a short lasting enhancement of the lower stratospheric ozone density is detected (right panel in Fig. 3).

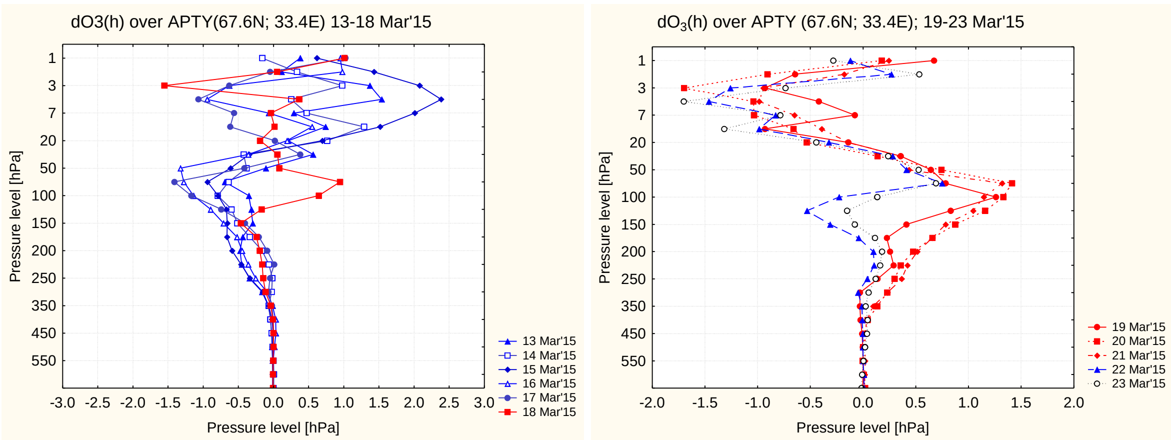

Fig. 3. Ozone profiles over Apatite before, during and after the geomagnetic storm at 17-18 March 2015.

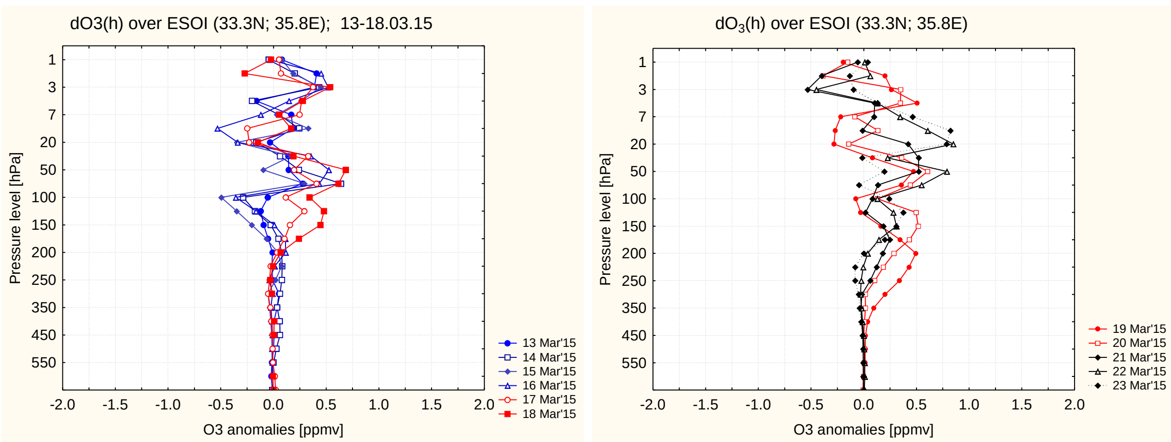

Fig. 4. Ozone profile over Emilio Segre Observatory and its variability during geomagnetic storm in 17-18 March 2015

On the other hand, the ESOI site is assessable mainly to the radiation trapped in Earth's radiation belts. This explains the smallest O_3 response over ESOI observatory to the global geomagnetic storm of March 17-18, 2015 (see Fig. 4). The weak positive anomalies in O_3 mixing ratio, between 50 and 200 hPa, starts at March 17 and continue until the onset of FD in March 21. This enhancement of the lower stratospheric O_3 is accompanied by ozone depletion at upper stratospheric levels. The latter fact is an indication of the self-restoration mechanism standing behind the positive ozone anomalies in the lower stratosphere.

The ozone response to the FD commencement in March 21-22 at Emilio Segre Observatory is shown in Fig. 5. Note the strong enhancement of O_3 density in the middle stratosphere (7-30 hPa), following the recovery of the cosmic radiation after the Forbush decrease. A short-lasting weaker peak is visible also near 100 hPa. In this case the raise of the lower stratospheric ozone density could not be attributed to the self-restoration mechanism, due to the strongest ozone enhancement in the upper stratosphere. Consequently, the only possible explanation is the activation of the ion-molecular reactions of ozone production [4].

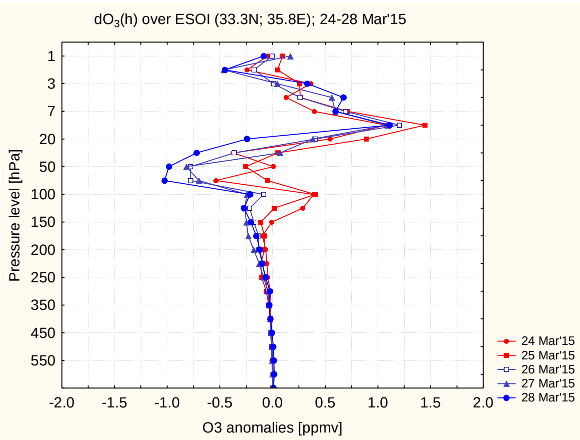

Fig. 5. Response of ozone profile over Emilio Segre Observatory to the Forbush decrease in March 21-22, 2015

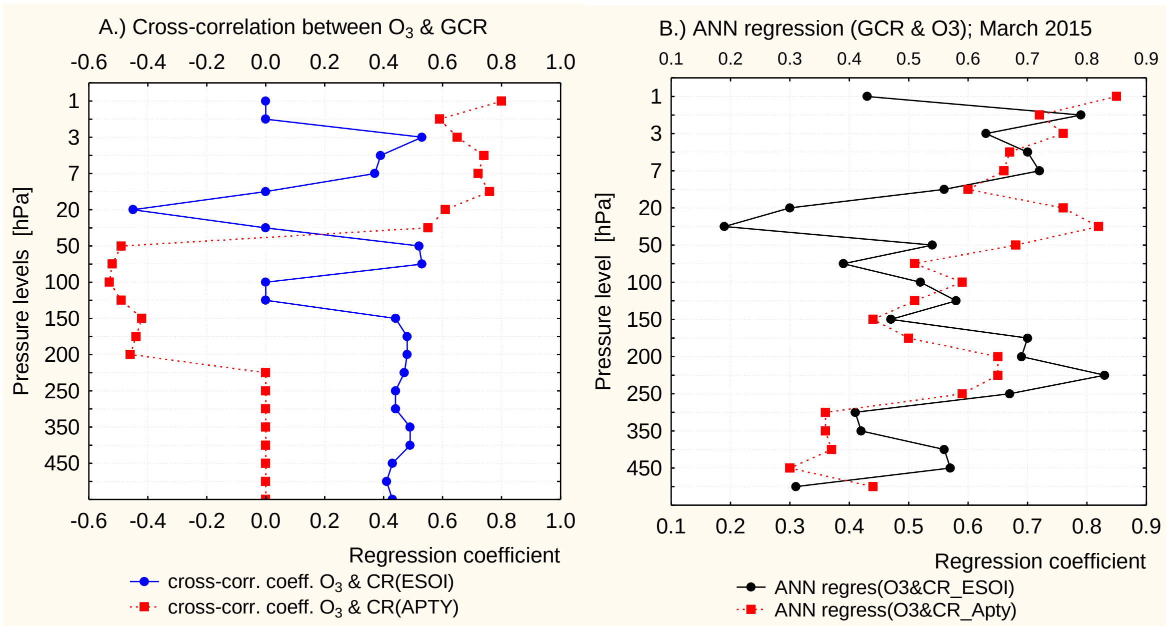

Fig. 6. (A.) Cross-correlation between galactic cosmic rays measured in Apatite (red contour) and Emilio Segre Observatory (blue contour), and corresponding ozone profiles over both sites; (B.) Similarity in temporal evolution of O_3 density and cosmic radiation measured at Apatite (black contour) and Emilio Segre Observatory (red contours) during the March 2015

Furthermore, we have assessed the rate of connection between temporal variability of incoming cosmic radiation and O_3 profiles (see Fig. 6). The left panel in the figure shows the cross-correlation coefficients between neutron monitors' records for March 2015 and temporal variations of daily ozone anomalies at each meteorological level. The figure shows a strong positive correlation of upper stratospheric ozone and cosmic radiation reaching the Apatite neutron monitor. The lower stratospheric O_3 over Apatite is moderately correlated with cosmic radiation, but with opposite sign. The strength of CR-ozone relation over Emilio Segre Observatory is weaker and more complicated. Correlation coefficients above 0.5 are found in the upper stratosphere, as well as at 50-70 hPa. Unlike the Apatite, where the tropospheric O_3 does not correlate with cosmic radiation, the temporal variations of both variables over Israel are moderately synchronised, and their correlation coefficients are between 0.4 and 0.5.

Having in mind the non-linear character of analysed data records, we have estimated the similarities in their temporal variability by the use of the artificial neural network method. The results are shown in Fig. 6 (B). A high degree of similarity has been found in the upper stratosphere over both observatories. In Apatite two more peaks of similarity are visible – at 30 and 225 hPa. In ESOI observatory the highest ever similarity between cosmic radiation and O_3 mixing ratio is found between 175- and 225 hPa. Comparison of the results derived by the two methods shows that cross-correlation technics give only a rough estimation of the possible relations between analysed variables. The neural network technic is more flexible, allowing better description of height variable relation between both variables – cosmic radiation and ozone. However, it has to be bear in mind that the anti-phase covariance is interpreted by this method as dissimilarity.

Discussion and conclusion

The existence of secondary souse of ozone in the lower stratosphere, activated by the atmospheric ionization produced by galactic cosmic rays, has been discovered not long ago [5]. The current research provides more evidence for sensitivity of atmospheric ozone to the amount of the arriving cosmic radiation. The examination of ozone's profiles reveals that in both analysed observatories – Apatite (67.57^{0}N; 33.39^{0}E) and Emilio Segre Observatory (33.3^{0}N; 35.8^{0}E) have been found positive anomalies in the lower stratospheric ozone, after the onset of Forbush decrease related to the geomagnetic storm on March 17-18, 2015. The mechanisms of ozone enhancement in both sites, however, are different. Thus at Apatite, which is accessible for particles arriving along the open geomagnetic field lines, the abundance in the lower stratospheric ozone density is due to the process of ozone self-restoration, after its destruction at higher levels by the lower energy solar particles, arriving with interplanetary magnetic shock [3].

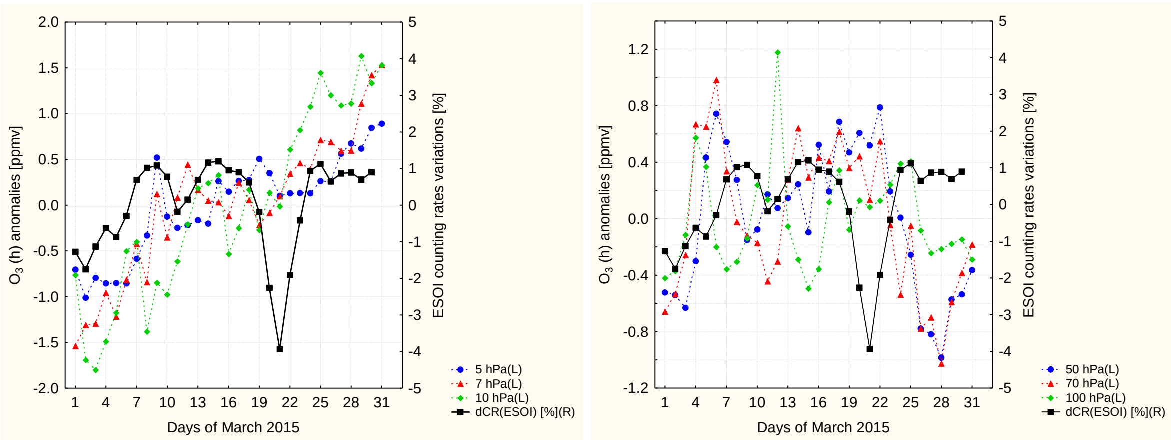

Fig. 7. Time series of O_3 at different pressure levels and cosmic radiation measured at Emilio Segre Observatory in March 2015

On the other hand, the subtropical Emilio Segre Observatory in Israel is influenced mainly by the energetic particles trapped in Earth's radiation belts. For this reason the onset of Forbush decrease in arrived cosmic radiation flux is followed by a depletion of the lower stratospheric ozone density – due to the reduced amount of available atmospheric ionisation and reduced rate of ozone production. In the period of recovery after the Forbush decrease, however, a pile up of ozone density is found – at lower and in the upper stratospheric levels. While the upper stratospheric effect (at 5-10 hPa) could be partially attributed to the transition from winter to the summer raise of ozone density (see the ozone time series shown in the left panel of Fig. 7), the enhancement in the lower stratospheric ozone should be undoubtedly assigned to the raise of the atmospheric ionisation after the Forbush decrease, and activation of additional ozone production near the Regener-Pfotzer maximum [5, 6]. In support of our conclusion, the balloon measurements over Israel, from May 2015

[7], shows that the level of the Regener-Pfotzer maximum is placed near 17 km, corresponding to the ~70 hPa, where the amplitude of ozone variability is higher (refer to the right panel of Fig.7).

In resume, the atmospheric ozone profile is very sensitive not only to the solar particles related to the geo-effective solar eruptions (broadly elucidated in scientific literature), but also to the galactic cosmic rays, and more specifically to the secondary ionisation produced by them in the lower stratosphere. The latitude dependence of the ozone response is due to the different energies of the impacting particles. The lower stratospheric O_3 at latitudes shielded by the closed geomagnetic filed lines is sensitive to the radiation trapped by geomagnetic filed in Van-Allen radiation belts. At the same time, the high latitude ozone is vulnerable to the solar plasma, hitting the Earth after solar proton events.

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