Proceedings of the IX Bulgarian-Serbian Astronomical Conference: Astroinformatics (IX BSACA) Sofia, Bulgaria, July 2-4, 2014,
Editors: M. K. Tsvetkov, M. S. Dimitrijević, O. Kounchev, D. Jevremović and K. Tsvetkova
Publl. Astron. Soc. "Rudjer Bošković" No 15, 2015, 149-158

THE RELATION BETWEEN SOLAR PROTON FLARES AND THE BACKGROUND CONCENTRATIONS OF NITROGEN OXIDES IN THE TROPOSPHERE

BORIS KOMITOV, MOMCHIL DECHEV and PETER DUCHLEV

Institute of Astronomy, Bulgarian Academy of Sciences
E-mail: mdechev@astro.bas.bg

Abstract. The results from the study of daily average values of the background concentrations of nitrogen oxides (NO and NO_2) in the terrestrial atmosphere are presented. The study aim was to reveal some aspects of the relation between the solar flares, as sources of solar energy protons (SEP-Solar Energetic Protons), and the nitrogen oxides formation in the Earth's atmosphere. For this aim, except the time series of the nitrogen oxides for the period Oct 15, 2004 – Sept 1, 2009, the total daily fluxes of the solar protons for the energy diapasons $E \geq 10MeV$ and $E \geq 100MeV$, registered by GOES-11 and GOES-13 satellites, were used. The obtained results suggest that the significant peaks in the time series of the nitrogen oxides should be explained with *volley* effect of NO and NO_2 formation in the middle atmosphere, which pass in the time interval from one month to about one year before the peaks registration. In view of the short period with continuous time series, to give a certain answer of the question whether and how the solar protons affect the NO and NO_2 formation it is necessary to prolong the study in future.

1. INTRODUCTION

The nitrogen oxides NO, NO_2, NO_x, and their derivatives belong to so called "small components" of the terrestrial atmosphere. Because of the toxic properties of the nitrogen oxides, their concentrations in the air are important subjects of ecologic monitoring. Energetic particles (e.g. solar protons and auroral electrons) provide the energy to drive an endothermic reaction: $NO + O_3 \longrightarrow NO_2 + O_2; NO_2 + O \longrightarrow NO + O_2; O_3 + O \longrightarrow O_2 + O_2$. The net result is *odd nitrogen*, a complex of nitrate radicals designated by the symbol NO_x. Some of the NO_x is transported downward to the troposphere, and then it is precipitated to the surface in ~ 6 weeks.

Important agents for the nitrogen oxides formation are solar activity events, such as UV and EUV radiation, solar X-ray (SXR) flares, and solar energetic particles. From a vital importance for the endothermic reactions, which produce NO and NO_2 are solar proton events, whose sources are SXR flares of class $\geq M5$ (see, e.g., Jackman and McPeters, 2011 for a review).

The subject of this study was the relation between the background concentrations of NO, NO_2 and NO_x in the Earth's atmosphere and the SPEs. The main goals were: 1) Statistical significance and rate of the influence of the solar proton flares; 2) The delay (resident time), between SPEs action and the nitrogen oxides enhancement in the Earth's atmosphere. 3) The transfer processes of nitrogen oxides between the middle atmosphere and the terrestrial surface.

2. DATA AND METHODS OF ANALYSIS

The daily average values of the background concentrations $[\mu/m^3]$ of NO, NO_2 and NO_x were registered by the complex background station of the Ministry of Environment and Water, located in the National Astronomical Observatory (NAO) – Rozhen at altitude of 1760 m above the sea. The data time series span the period from 15 October 2004 to 31 December 2012. Because of a lot of gaps in the time series in the period 15 October 2004 – 31 August 2009, the data from 1 September 2009 to the end of 2012 were used.

The data of total daily fluxes [n/day] of the solar energetic protons (SEPs), registered by GOES-11 and GOES-13 geostationary satellites and hosted in Space Weather Center in Boulder, Colorado were also used (http://www.swpc.noaa.gov/Data/index.html#indices). The values of total daily fluxes are considered in two energetic diapasons - $E \geq 10MeV$ and $E \geq 100MeV$. For examination of the nitrogen oxides data, two methods were used: T-R periodogram analysis and cross-correlation analysis (Komitov 1986, 1997).

3. RESULTS

The comparison of the behavior of the NO, NO_2, and NO_x concentrations and the solar proton events presented in Fig. 1, 2, and 3 suggests two features of the SEPs flux behavior.

1. The SEPs flux series contain a quiet component that is characterized with low values and very slow and gradual increasing from October 2004 to September 2008, whereupon the variation tendency changes to gradual decreasing up to December 2012.

2. The SEPs flux series contain consecution of strong and weak flux peaks. The difference between strong and weak flux values vary in the range of several orders.

Fig. 1, 2, and 3 suggest three special features of the relation between the nitrogen oxides concentrations and solar proton events.

1. There is a conformity two types of events – the high values of NO, NO_2, and NO_x concentrations are measured in periods of strong proton flares.

2. The relation between two events is strong delayed by time – the nitrogen oxides concentrations are registered 7-10 months late with respect to the SEPs fluxes peaks.

3. There is second, more expressed tendency of the delaying of the nitrogen oxides in relation to SEPs fluxes – about one month.

The period of low NO, NO_2, and NO_x values between 2007 and 2009 coincides with the deep minimum of solar activity between 11-year solar cycles 23 and 24.

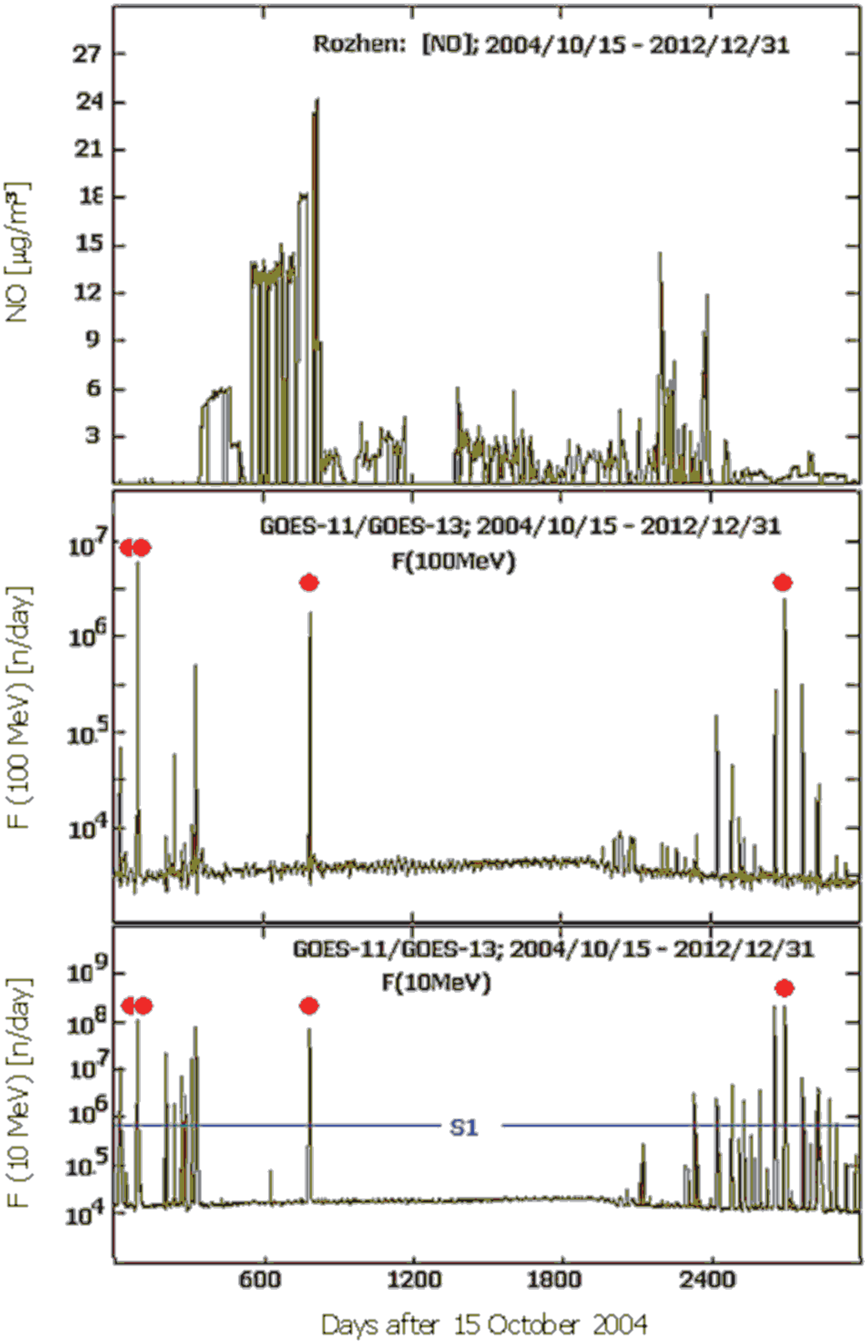

Figure 1: Daily average values of NO concentration and daily total flux (F) of the high energy protons - $F \geq 100 MeV$ (middle panels) and low energy protons - $F10 \geq MeV$ (bottom panel).

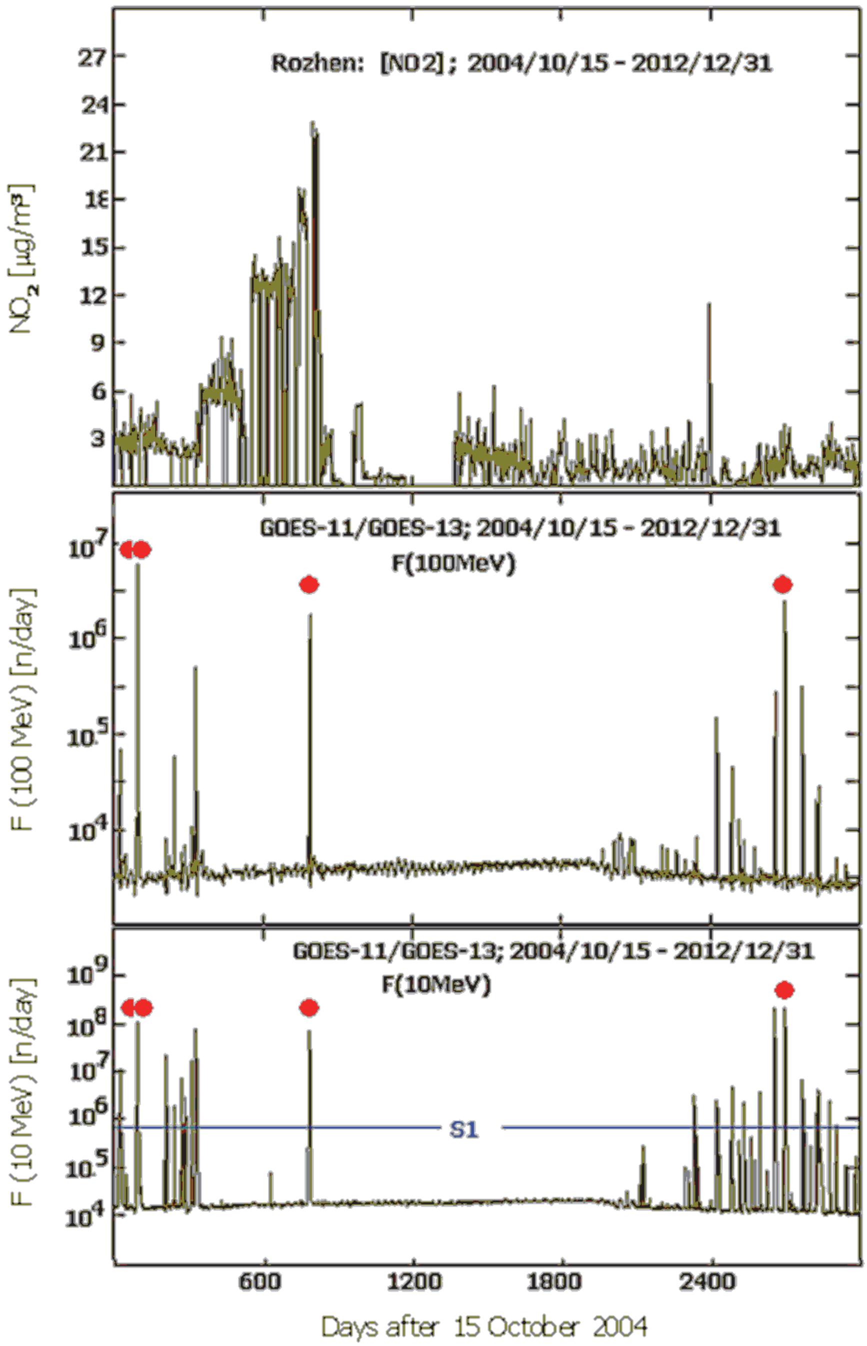

Figure 2: Daily average values of NO_2 concentration and daily total flux of the high energy protons - $F \geq 100MeV$ (middle panel) and low energy protons - $F \geq 10MeV$ (bottom panel).

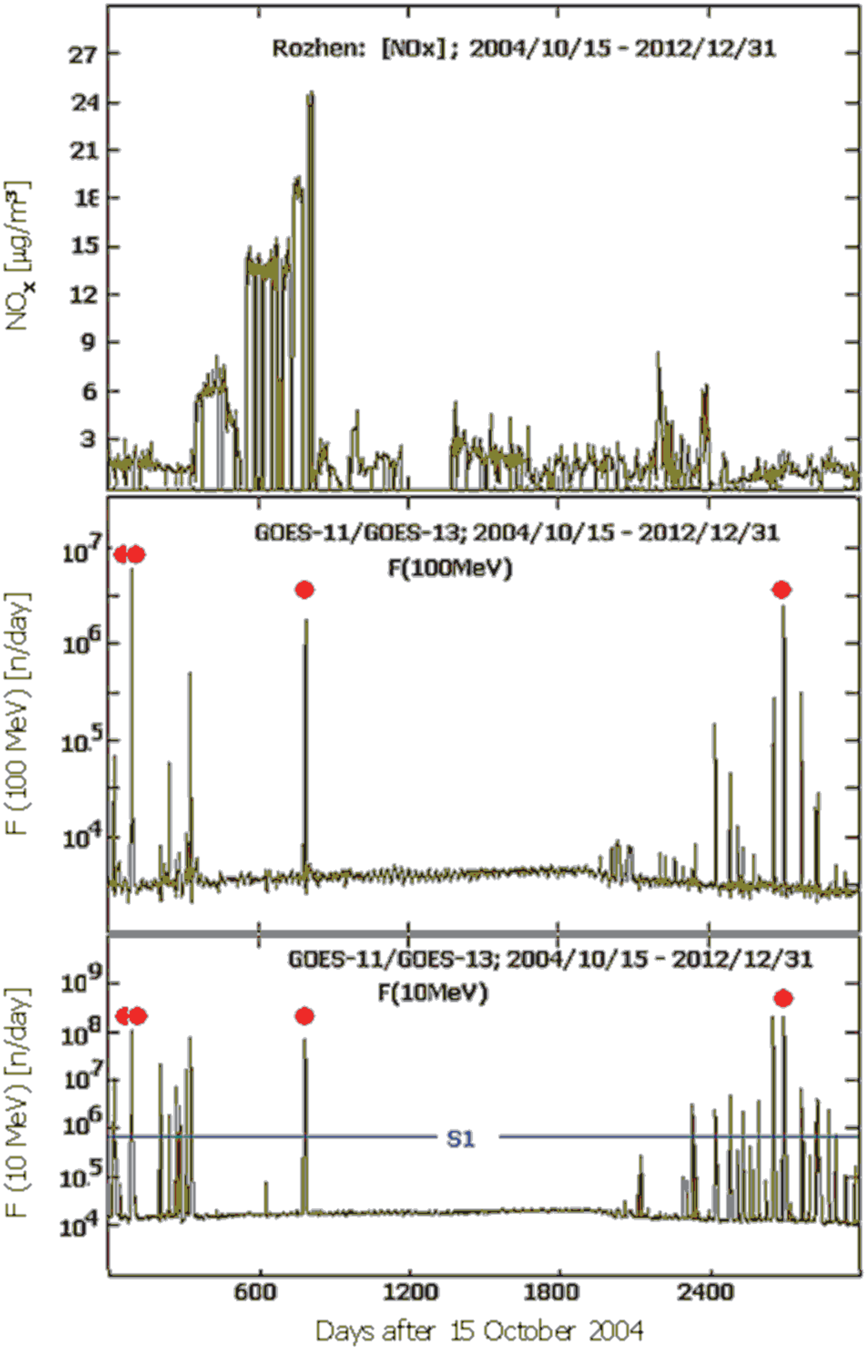

Figure 3: Daily average values of NO_x concentration and daily total flux of the high energy protons - $F \geq 100MeV$ (middle panel) and low energy protons - $F \geq 10MeV$ (bottom panel).

An important question in our analysis of the two types of data series is searching of statistically significant cyclicities in their behaviors. In the first part of data (15 October 2004 – 31 August 2009) the time series have many data gaps and only visual indications for some cyclicities could be found. In the second data part (1 September 2009 – 31 December 2012) the time series are continuous and a quantitative analysis is applicable for them, e.g. T-R periodogram and cross-correlation analysis.

The results from the T-R periodogram analysis are presented in Fig. 4 for the nitrogen oxides data and in Fig. 5 for the SEP data. These analyses of the two events outline three important features.

1. A significant variations with duration of 9-10 months (270–290 days) are outlined in the NO and NO_2 time series (Fig.4).

2. There is a strongly indicative cycle of about 540 days in the $NO-2$ time series, which is resonantly divisible by 180-day one (Fig.4).

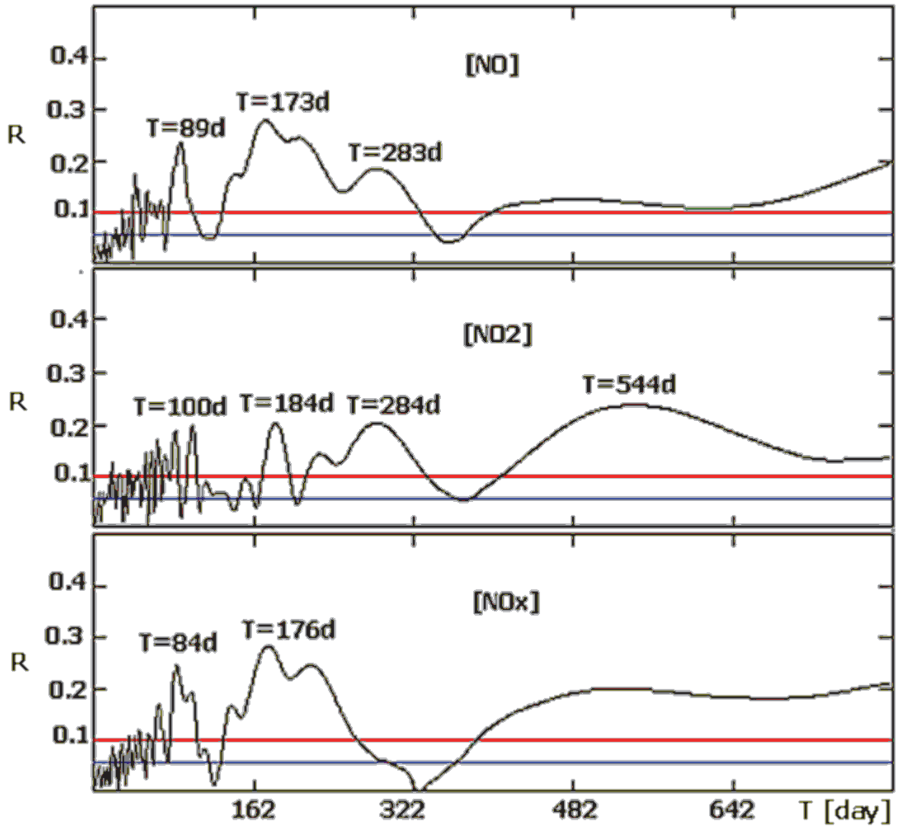

Figure 4: T-R correlagrams of the NO, NO_2, and NO_X time series for the period 1 September 2009 - 31 December 2012.

3. There is a statistically significant cycle with duration of about 180–200 days (T=182 days for F10 MeV and T=204 days for F100 MeV) in the SEP fluxes data. The origin of the quasi 180-day cycle is still uncertain (Fig.5).

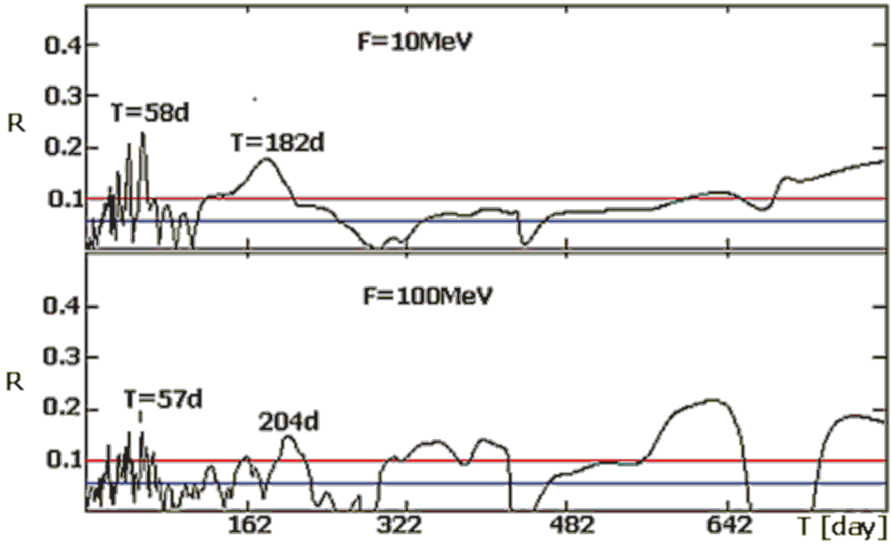

Figure 5: T-R correlagrams of the daily total fluxes time series of the low energy protons $F \geq 10MeV$ (top) and high energy protons $F \geq 100MeV$ (bottom) for the period 1 September 2009 - 31 December 2012.

The cross-correlation analysis was used to reveal some specific features refering to the phase shifting between NO, NO2, and NOx time series and those of the SEPs. The cross-correlation coefficients Rc between nitrogen oxides concentrations and SEP fluxes, presented in Fig. 6 and 7, reveals several important results:

1. There are three significant, positive peaks of Rc at a time lag (t-to) of about 260-280 days ($\sim$ 8-9 months), 305-320 days (10 months), and 430-460 days ($\sim$ 15 months).

2. There are well expressed peaks of Rc at the time lags of 9, 10, and 15 months in the time series of NO and NO_x.

3. For NO_2, a peak at a lag of about one month (30 days) is observed again. Such, but weaker peak at a lag of 28 days is observed for NO_x.

4. It is very interesting that there are two peaks in NO_2 time series at big lags (above one month) - the strong peak at lag of 306 days ($\sim$ 10 months) and another one at lag of 263 days ($\sim$ 9 months).

The results obtained by correlograms (Fig. 6 and 7) suggest that an essential feature of the relationship between SEPs and the nitrogen oxides formation in the atmosphere is its phase shifting in time. Hence, it exists delay time between the SEPs registering at a geostationary orbit, the endothermic reactions responsible for the nitrogen oxides formation in the middle atmosphere, and their registration in the ground-based station (e.g. in NAO – Rozhen). The presence of more than one peaks for the delay time nitrogen oxides registration could be explained with the different altitudes and geographical positions of their formation, as well as with different processes (diffusion, convection, and wind), which transfer them to the station registering equipment.

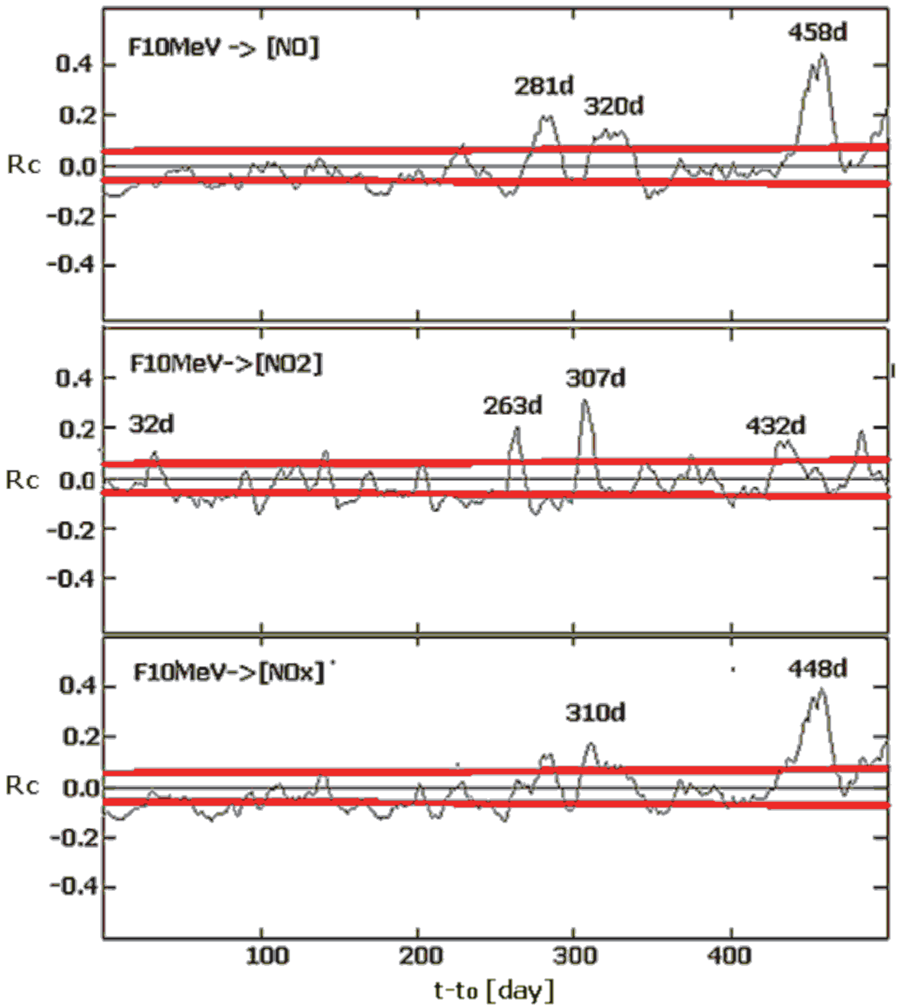

Figure 6: Cross-correlation coefficients Rc between NO, NO_2, and NO_x concentrations and low energy proton flux $F \geq 10MeV$ for the period 1 September 2009 - 31 December 2012.

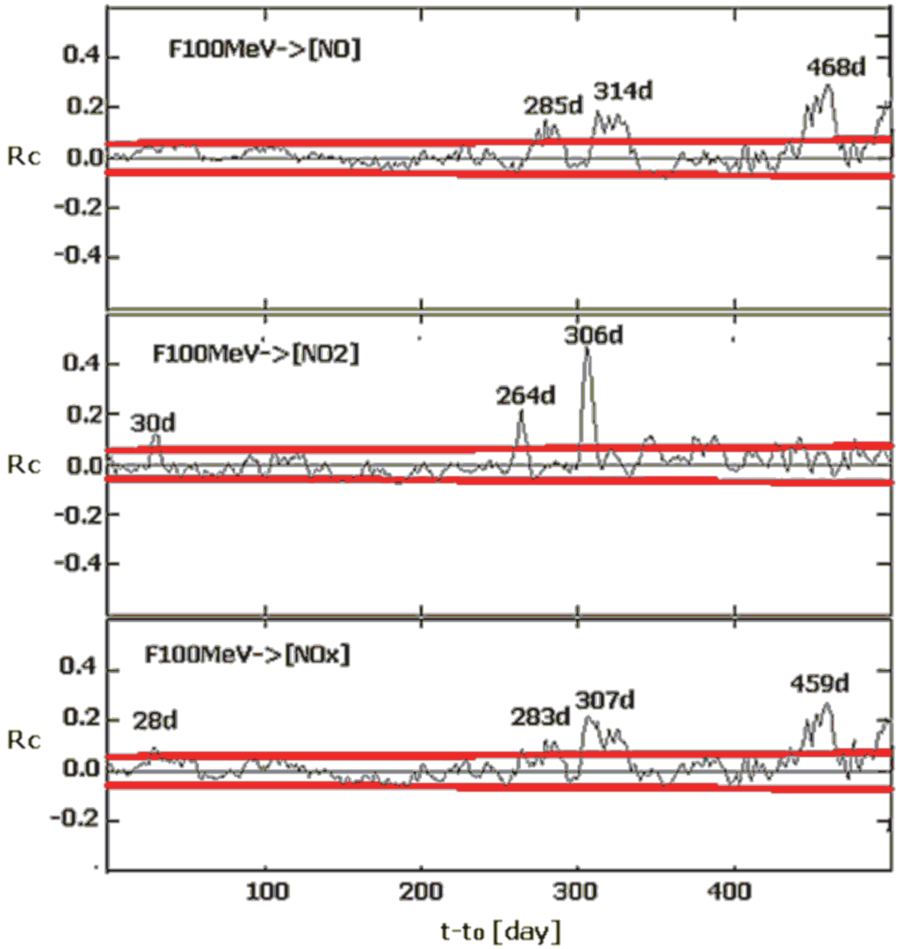

Figure 7: Cross-correlation coefficients Rc between NO, NO_2, and NO_x concentrations and high energy proton flux $F \geq 100 MeV$ for the period 1 September 2009 - 31 December 2012.

4. SUMMARY

The obtained results suggest that the significant peaks in the time series of the nitric oxides should be explained with *volley* effect of the NO and NO_2 formation in the middle atmosphere. The formation process pass in the time interval from one month to about one year before the NO and NO_2 peaks registration in the ground-based station, in dependence on their formation altitude, formation geographical position, and the type of the transfer atmospheric processes.

The time series of the nitric oxides span only part of the solar cycle 24 – its increasing phase. Therefore, to give a more certain answer of the question how the solar proton flares affect the NO and NO_2 formation, it is necessary to prolong the study during next several years, up to the end of the present 24th solar cycle (2018-2019).

The prolongation of these studies could be the base for developing of prognostic models and forecasting of the enhanced NO and NO_2 concentrations in the troposphere.

Acknowledgments

This work is supported by a grant **No. 8785/16.01.2013** of the Enterprise for management of the activities by environment protection, Ministry of Environment and Water, Bulgaria

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