Numerical Modeling of Ozone Density in the Atmosphere after Ground Level Enhancement of Cosmic Rays on 20 January 2005

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The galactic cosmic rays create ionization in the Earth's atmosphere, especially in the stratosphere and troposphere and are the main ionization source below 35 km above sea level. The solar cosmic rays originate mostly from solar proton flares. Coronal mass ejections and shocks in the interplanetary medium also produce energetic particles. Usually solar cosmic ray particles have energy of up to several hundred MeV/nucleon, rarely up to few GeV/nucleon. The particles from primary cosmic ray radiation produce cascade processes in the Earth atmosphere. The high-energy primary particle penetrates the Earth atmosphere, collides with an atmospheric nucleus and produces new, very energetic particles. The secondary particles depose energy in the atmosphere. As a result they ionize the air, i.e. cosmic ray induced ionization occurred. The nucleonic-electromagnetic cascade in the atmosphere plays important role in physical and chemical properties of the atmosphere, precisely its ion balance. On the basis of cosmic ray cascade process simulation in the atmosphere, we estimate the ion production rate from ground level to the upper atmosphere for the solar proton flares during January 2005. Based on these ionization rates we estimate as well the ozone production rates; then we calculate also the ozone production height profiles. For this purpose CORSIKA 6.52 code with corresponding hadronic interaction models GHEISHA and QGSJET II is used for the simulations of the cascade processes in the terrestrial atmosphere.

Numerical modeling

The results from the statistical processing present a basis to seek a physical explanation for the ozone increase in the lower stratosphere. A quantitative estimation is made for this purpose concerning the possibility for creation of ozone by the solar cosmic ray flux. The calculations are made for the first 15 hours after the event which corresponds to the delay from the statistical processing. This estimation includes the following steps:

1. Differential energy spectrum determination for the proton flux in two different moments.
2. Evaluation of the ionization rate in the atmosphere at these two different moments.
3. Evaluation of the ozone production rate in the atmosphere at these two different moments.
4. Evaluation of the ozone quantity which is created in the time interval between these two different moments.

As is well known, the quantity of approximately 90% from the solar cosmic ray flux presents protons. For almost full correspondence with the statistical analysis which is made above, the same data from GOES 11 are used for the proton differential energy spectrum modeling on 20 January 2005- figure 1.

It is also well known, that this spectrum generally has the following description:

$$D(E) = k.E^{-\gamma} \qquad (1)$$

The values of k и γ at the different moments of the proton event development are different. This is true, because the proton flux in the different energy intervals which reaches the Earth at the different moments has variations.

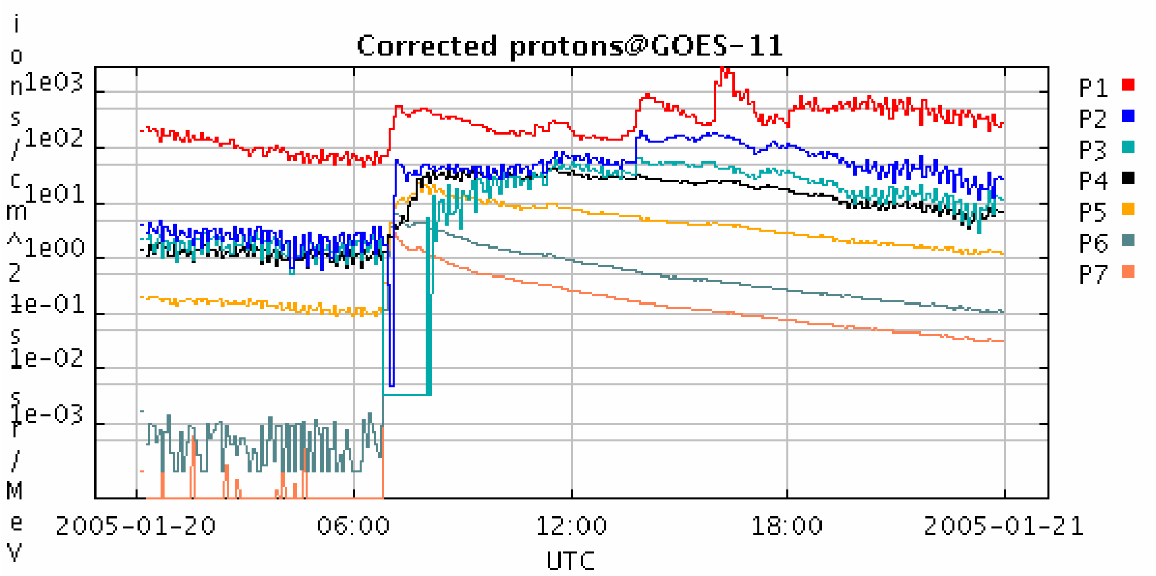
The first differential energy spectrum which we determine from experimental data, is at 08:00 UT. The time delay is 1 hour after the proton flare. We can assume that the corresponding proton flux is relatively homogenized. The evaluated expression for it is the following: $D_{08}(E) = 1{,}55.10^{6}\, E^{-2{,}32}$. The second differential energy spectrum which we determine from experimental data is at 23:00 UT. The evaluated expression for it is the following:

$D_{23}(E) = 10^{7}.E^{-3{,}43}$.These spectra are shown on Fig. 2. The primary cosmic radiation particles cause cascade processes in the terrestrial atmosphere. The high energy particles from these cosmic rays penetrate in the terrestrial atmosphere, colliding with the atmosphere nuclei and create new secondary energy particles. On this way the nuclear – electromagnetic cascades in the atmosphere appear. The secondary particles give up their energy in the atmosphere. As a result they ionize the Earth's environment. The corpuscular – electromagnetic cascades in the atmosphere are important factor in the physics and chemistry of the processes in the atmosphere and mainly in the ion balance. The cosmic ray ionization can be estimated with methods for modeling of atmospheric cascade processes and approaches of Monte-Carlo type [1, 2]. The cosmic ray ionization is calculated according (2)

$$q(h,\lambda_m) = \int_{E_0}^{\infty} D(E,\lambda_m) Y(h,E) \cdot \rho(h) dE \qquad (2)$$

where $D(E, \lambda_m)$ is the primary differential cosmic ray spectrum, λ_m is the given geomagnetic latitude, $Y(h,E)$ is the ionization yield function, ρ(*h*) is the atmospheric density (g.cm^{-3}). In the present work $q(h,\lambda_m)$ is evaluated by means of the yield function $Y(h,E)$ (3):

$$Y(x,E) = \pi\, \Delta E(x,E) \frac{1}{\Delta x} \cdot \frac{1}{E_{ion}} \cdot \Omega \qquad (3)$$



Band	Energy protons		
P1	0.8 - 4 MeV		
P2	4 - 9 MeV		
P3	9 - 15 MeV		
P4	15 - 40 MeV		
P5	40 - 80 MeV		
P6	80 - 165 MeV		
P7	165 - 500 MeV		

Fig. 1. Solar proton differential energy spectrum.

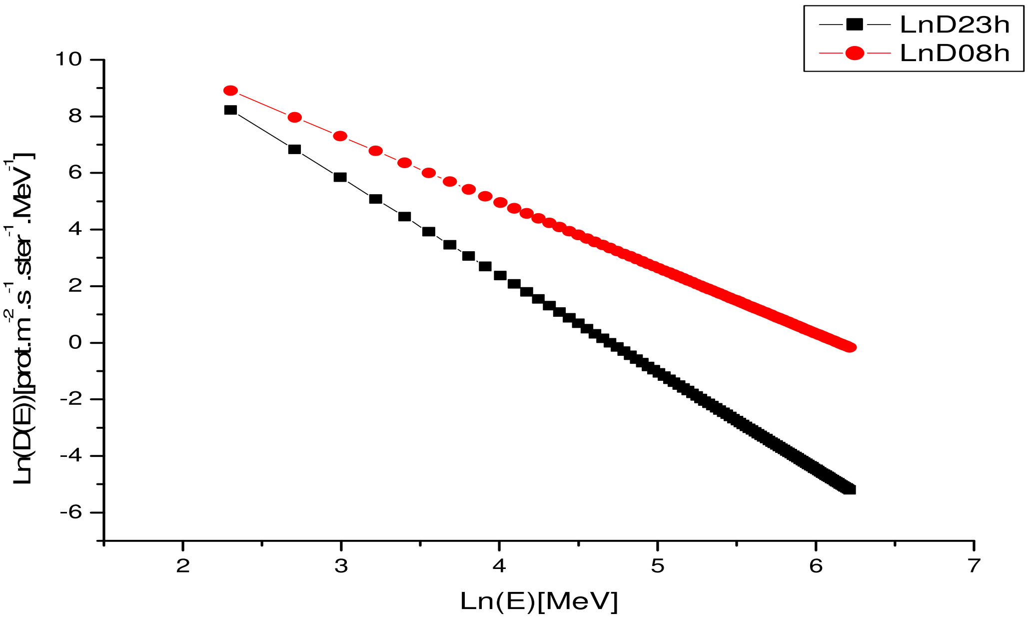


Fig. 2. Differential energy spectrum which we determine from experimental data.

where ΔE is the energy which is included in the layer Δx of the atmosphere and Ω is the geometrical factor which is integrated over the space angle for given zenith angle. It is calculated according the oulu model which is described in [3] with application of the procedures from [4]. Consequently on the basis of the cosmic ray impact the cascade processes in the atmosphere are modeled. The ionization rate can be estimated from the Earth's surface until the upper atmosphere for given solar flare with formulas (2) and (3).

The model CORSIKA 6.52 [5] with the corresponding hadron interaction modules GHEISHA [6] and QGSJET II [7] is applied for the cascade processes modeling in the terrestrial atmosphere. The electromagnetic interactions are modeled in CORSIKA with the module EGS4 [8]. The atmosphere is divided in 103 steps from 10 g/cm^2 which secures high accuracy. The lowest cut-off energy value from 10 MeV is applied. The energy which is included in the cascades is deleted when it is very low.

The energy which is introduced by the secondary cosmic rays is obtained. The calculated ionization profiles are applicable for the whole atmosphere. All components of the atmospheric cascades are evaluated [9].

Now the vertical distribution of the ozone production rate in the atmosphere as a result from the proton flux impact must be appreciated. It can be calculated using the experimental data for estimation of the oxygen – nitrogen gas mixture radiolysis. Ozone and nitrogen oxides are generated by irradiation of oxygen - nitrogen mixture. The oxygen - nitrogen mixture can be assumed as a good description of air.

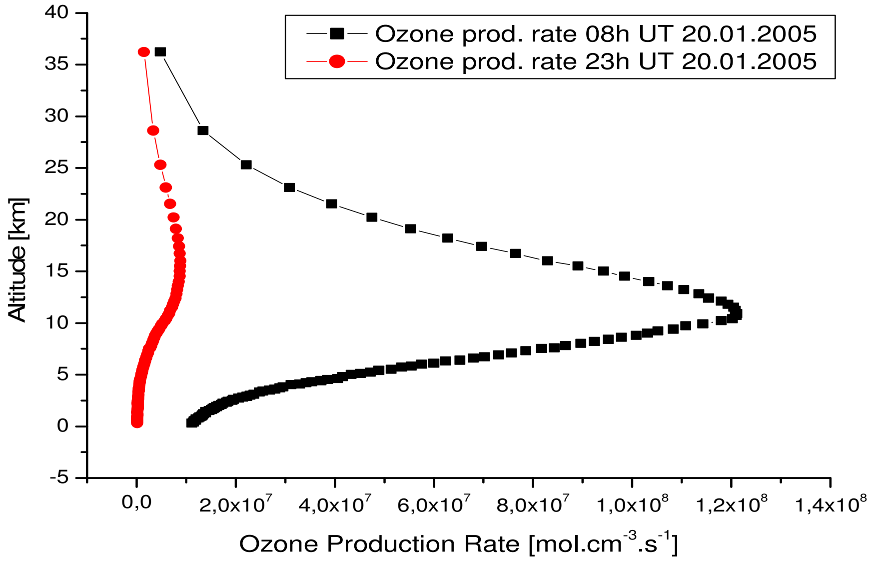


Figure.3

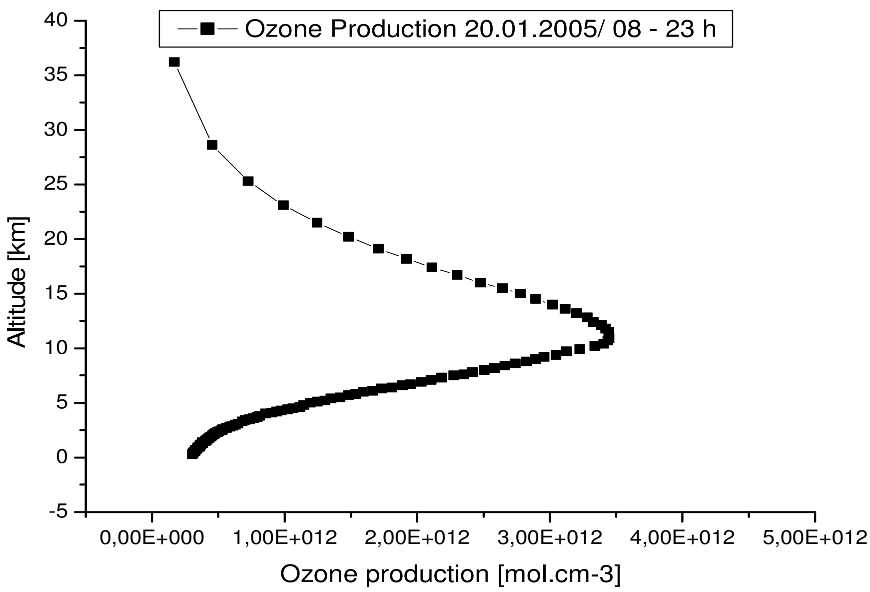


Fig. 4. Ozone production N_{O_3} *for 15 hours.*

Ozone, nitrogen oxides and nitrogen acid are also created by irradiation of humid air. Ozone becomes the basic product when the dose power is relatively high, I= $3,2.10^{10}$ Gr/s. The nitrogen oxide can be neglected, because G – the production number of nitrogen molecules by 100 eV is under 1. Because of that $G(O_3)$=10,3 mol/100 eV [10] is assumed for the air at pressure 530 hpas. For our purposes in first approximation the calculation of the vertical ozone production rate distribution by solar cosmic rays (SCR) in the atmosphere is made with the equation from [11]:

$$\frac{dN_{O_3}}{dt} = G(O_3)\frac{dE_{SCR}}{dt} \qquad (4)$$

where $\frac{dE_{SCR}}{dt}$ is the SCR energy flux which is given up in the atmosphere by the cascade processes and $G(O_3)$ is the production number of ozone molecules by 100 eV. The relationship between the SCR energy flux and the ionization rate created by it can be expressed by the equation:

$$\frac{dE_{SCR}}{dt} = \frac{dn}{dt}\times Q = \left(q(h,\lambda) - \alpha n^2 - \beta Nn\right)\times Q \qquad (5)$$

where $q(h,\lambda)$ is the ion pair production rate which is obtained with the model CORSIKA and formula (2), α and β are the recombination and attachment coefficients, respectively; Q=35 eV is the energy which is necessary for formation of 1 electron-ion pair.

With calculation of the ion pair production rate in the first case, for 08:00 UT, we obtain also the ozone production rate at this moment. After that we calculate the ion pair production rate for 23:00 UT and we obtain from it the ozone production rate at 23:00 UT. Fig. 3. We evaluate the mean ozone production rate between these two moments. We multiply with the whole interval value and we obtain the ozone production N_{O_3} for these 15 hours. This ozone production profile is shown on Fig.4. First, the maximal value on the ozone production profile is $N_{O_3} = 3{,}44868E+12$ [mol.cm^{-3}]. Second, this maximum is situated at height 10.9 km. The results are very interesting.

Conclusion

The maximal and also the other SCR ozone production values are in the order of the ozone production by UV. This result shows undoubtedly, that the statistically established ozone increase in the lower part of the stratosphere at 30 and 18 km can be caused by the cascade processes, which are induced by SCR. It must be noted, that a comparison is made between the ozone mixture ratio profile and the ozone density profile. The maximum of the ozone mixture ratio profile is situated in the height interval 30 – 37 km. The maximum of the ozone concentration is at 20 – 25 km.

In spite of the maximum displacements in both profiles, the higher values of the calculated ozone production can not be neglected. On this way, that SCR contribution in the ozone production after SPE must be taken into account also in future investigations. Furthermore, the maximum of the calculated height distribution of the ozone density is situated at altitude 10.9 km. This is the medium height of the atmospheric tropopause. Here we can make correspondence with one well known phenomenon in meteorology. This the intrusion process of stratospheric ozone in the troposphere. We can suppose with great probability, that a relationship exists between this intrusion process and the near Earth surface ozone density increase after Solar Protons Events. But this is a problem for future investigations.

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