

LATITUDINAL DEPENDENCE OF THE STRATOSPHERIC OZONE AND TEMPERATURE RESPONSE TO SOLAR PARTICLES' FORCING ON 20 JANUARY 2005

Natalya Kilifarska

*National Institute of Geophysics, Geodesy and Geography – Bulgarian Academy
of Sciences*

e-mail: nkilifarska@geophys.bas.bg

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Abstract

This study examines the latitudinal-altitudinal variations of the midday O₃ and temperature response to the forcing of the enhanced flux of energetic particles, during January 2005 Solar Proton Event (SPE). We show that short-term response of the stratospheric O₃ depends strongly on the latitude and the energy of precipitating particles. At polar latitudes, where the relativistic electrons and “soft” protons are able to penetrate deeper into the atmosphere, we found a reduction of the peak ozone density in periods of enhanced particles' fluxes. Such a response is widely explained by the activation of HO_x and NO_x ozone destructive cycles. At mid-latitudes, however, the stratospheric part of the O₃ profile remains insensitive to these lower energy particles, because they affect only the thermospheric and mesospheric O₃. On the other hand, the “hard” protons, emitted during the third solar flare on 20 January, are able to propagate much deeper, affecting even the stratospheric ozone and reducing its density. As a consequence of the thinning of the ozone optical depth, the solar UV penetrates deeper into the atmosphere, activating the Slanger's mechanism for ozone production at lower levels – known also as ozone self-restoration. This could be an explanation for the obtained raise of the mid-latitude peak O₃ density in the period of atmospheric restoration after the SPE '2005.

The earlier raise of the polar ozone maximal density – i.e. between 18 and 21 January – could be related to the fact that at the moment of SPE '2005 it has been already diminished by the relativistic electrons and “soft” protons, getting ahead of the strongest proton flare. So the further ozone destruction (by particles with mixed energies) triggered the activation of its restoration several days earlier. Consequently, the latitudinal differences in the ozone response – found in ERA Interim data – could be attributed to the different energetic spectrum of solar flares, the depth of the particles' penetration into the atmosphere and the zenith angle of stratosphere illumination by the solar UV radiation. Enhancement of the lower and middle stratospheric temperature during the SPE '2005 has to be attributed to the increased ozone density and the more solar UV radiation absorbed.

Introduction

The middle atmosphere response to the influence of energetic particle (emitted by the solar proton events) is investigated by many authors [1–12], with

most of them focusing their attention on the *ozone depletion* at polar latitudes. The possibility for *ozone enhancement* has been predicted by Jackman et al., [13] using the 2D chemical-transport model of NASA Goddard Space Flight Centre. While the mechanism for ozone depletion is pretty clear (i.e. due to the activation of the ozone destructive cycles by the increased amount of NO_x and HO_x families), the mechanism of O₃ enhancement was unclear. Jackman et al., [13] attributed it to the downward transportation of the NO_x, which could transform the active chlorine and bromine families into their reservoir species, reducing in such a way the ozone destruction in the lower polar stratosphere.

This explanation is however, non applicable to the raise of the mid-latitudes total ozone density, which has been reported by Krivolutsky [2]. The latter related the ozone raise to the enhanced solar electromagnetic radiation (accompanying the corpuscular one) and corresponding acceleration of the photolysis of the molecular oxygen.

Being one of the most absorbing gases in the stratosphere, the ozone plays a key role in the thermo-dynamical regime of the stratosphere-troposphere system. For this reason the determination of factors altering its variability is of great importance. This article investigates altitude-latitude distribution of O₃ and temperature anomalies (i.e. their deviation from the climatology) before, during and after the January 2005 SPE at the longitude of Greenwich meridian. We focus our attention on the short term response of the stratospheric O₃ and temperature (T) to different spectrum of impacting particles.

Data and methods

Ozone and T profiles at the Greenwich meridian have been derived from ERA Interim reanalysis. The intensity of solar proton fluxes – measured on board the geostationary spacecrafts GOES 10 and 11 – has been used in statistical analyses to estimate the efficiency of solar particles' influence on the stratospheric O₃ and T meridional profiles. The effect of the variable solar UV radiation is estimated using data for the solar radio emission at 10.7 cm (F_{10.7}), taken from <http://spidr.ngdc.noaa.gov>. Data for cosmic ray intensity (i.e. highly energetic particles with galactic origin) are taken from the Climax neutron monitor.

Before applying any statistics, we calculate the “anomalies” of all atmospheric parameters (i.e. their deviations from the climatological means for January, calculated from the whole data records, i.e. 1979–2009 of ERA Interim reanalysis). To identify the short term response of O₃ and T to different forcing factors we have used the Partial Least Square regression technique (PLS). The PLS regression generalizes and combines features from principal components analysis and multiple regression. It is particularly useful when we search for relations between a set of dependent variables (in our case O₃ or T at all 21 levels from 925 to 1 hPa, for given latitude) and a set of independent variables (*predictors*) during a

short period of time. PLS regression analysis can be used even when the number of observations is small compared to the number of predictors. PLS searches for a set of *components* that performs a simultaneous decomposition of matrixes of dependent variables Y and predictors X. The main constraint is that these components must explain as much as possible of the *covariance* between X and Y. When a simultaneous impact of several predictors is estimated, each PLS *component* is a weighted function of the impact of different predictors. We have performed the PLS analysis for each of the forcing factors separately, but simultaneously at all levels, which ultimately gives us the maximum impact of each examined factor in the observed T and O₃ profiles.

Atmospheric short term response to proton forcing

January 2005 is characterized by a sequence of 3 intensive solar flares on 15, 17 and 20 January, followed by the largest *ground level event*¹ measured by neutron monitors since 1956 [14–16]. The anomalies in temperature and ozone profiles, derived from ERA Interim reanalysis, are presented in Fig. 1. The figure gives a first impression for the Northern hemisphere stratospheric response to precipitating solar energetic particles during January 2005 SPE. It is well seen that since 17th January the lower to middle stratosphere is warmer by up to 12÷16⁰ K while the O₃ mixing ratio is higher by 1÷3 ppmv (part per million by volume). These anomalies persist until the end of January, and appear again on 7 February, lasting for another week or so. Complimentary to the results of Fedulina [1], showing a well pronounced depletion in the O₃ concentration and T below 20 km, we found out that the mid-latitude stratospheric response to the January 2005 SPE, manifest itself with an increased ozone mixing ratio and temperature raise at 20÷30 km altitude. Both anomalies appear around 40÷60°N latitude and expand slowly with time toward the equator.

The reasonable question raised from Fig. 1 is whether these T and O₃ anomalies are related to the solar proton event or appear coincidently? As independent variables, used in the Partial Least Square regression analysis (PLS), have been selected: solar radio emission at 10.7 cm (F_{10.7}), integral electron flux with energies E > 2 MeV, integral soft proton flux with energies E > 1 MeV and the flux of hard protons with E > 60 MeV, as well as the galactic cosmic rays (CRs). To analyse the time evolution of the forcing factors and corresponding T and O₃ response, we have examined three periods (characterised by a different spectrum of precipitating energetic particles) i.e. 9–19 January, 17–27 January and 28 Jan–07 February.

Examination of the solar protons with energies E > 1 MeV and E > 60 MeV (shown in Fig. 2) reveals that during the second solar flare (on 17 January) the

¹A sharp increase in the ground-level count of cosmic rays by neutron monitors (at least by 5% above background) associated with solar protons of energies > 500 MeV.

“soft” protons’ intensity is much higher than that of the “hard” protons. The most powerful flare is observed on 20 January 2005, characterised by a sharp increase of the “hard” protons’ spectra. On the next day – 21 January, there is another peak in the “soft” protons’ intensity, but it is more than twice weaker than the first one.

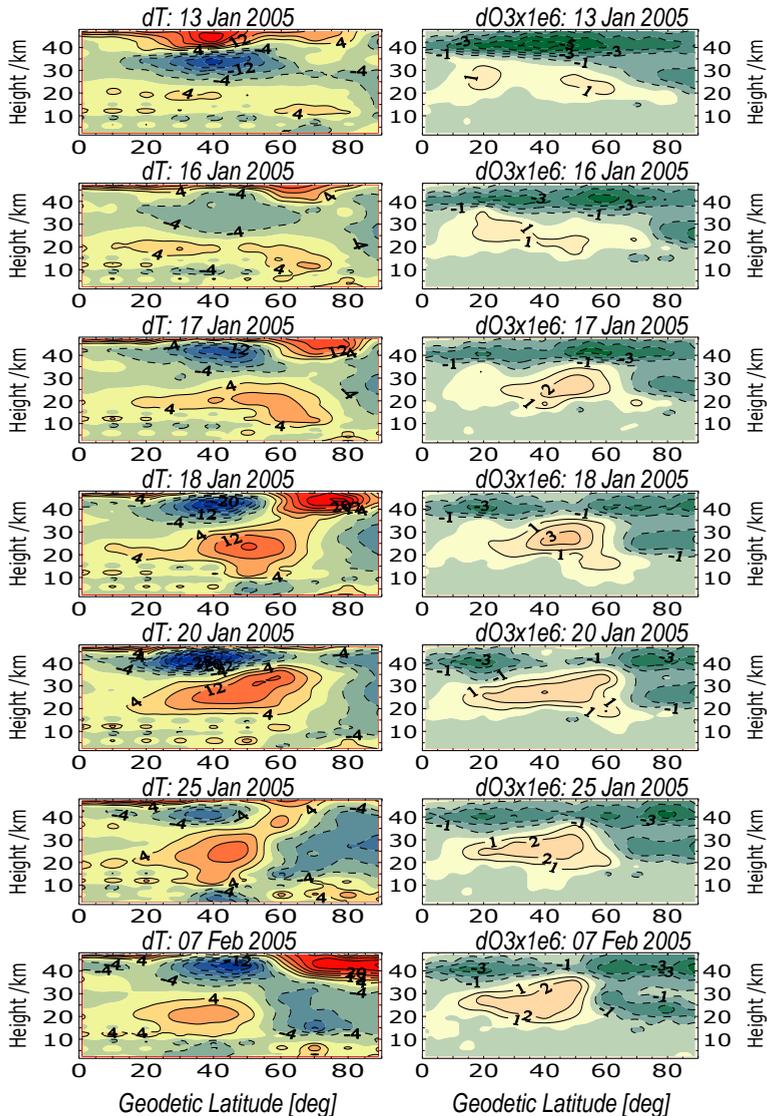


Fig. 1. Meridional cross-section of T and O_3 anomalies before, during and after January 2005 Solar Proton Events. The O_3 contour labels [ppmv] have to be multiplied by 10^{-6} . Dash contours indicate negative anomalies.

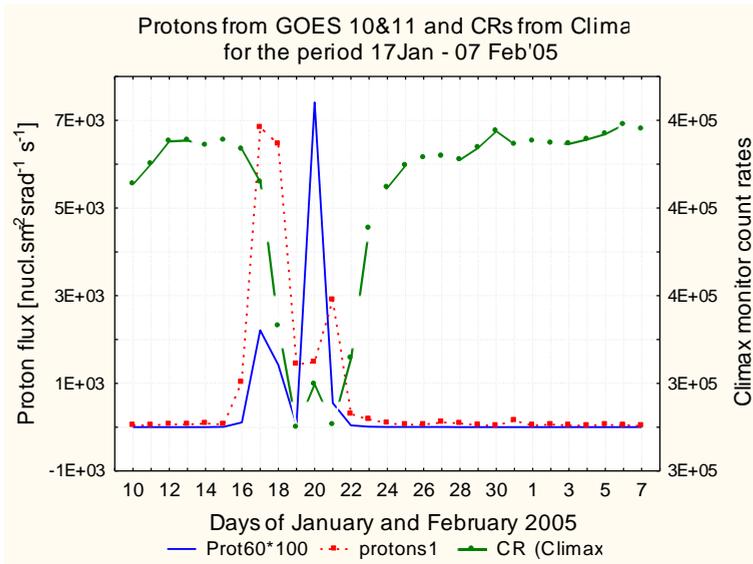


Fig. 2. Time series of protons with energy $E > 1$ MeV (*protons1*) and with $E > 60$ MeV (*prot60*) compared with the Forbush decrease of galactic cosmic rays

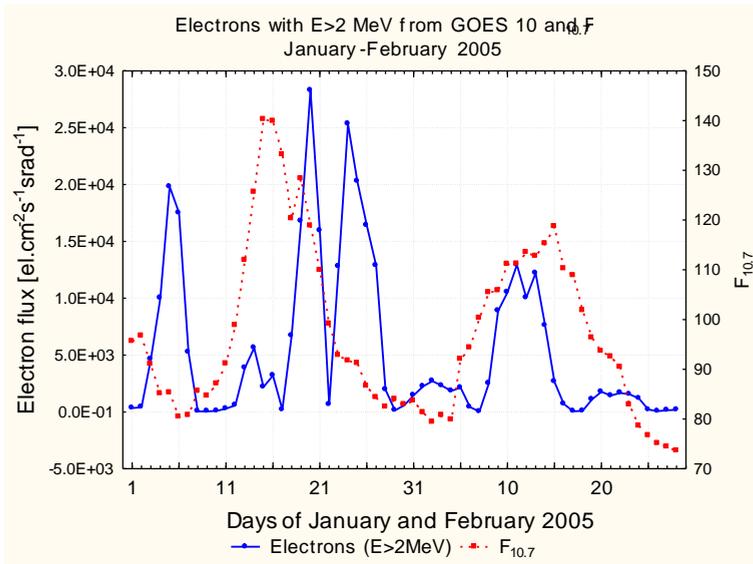


Fig. 3. Time series of the integral electron flux with energy $E > 2$ MeV, measured on board the GOES 10 satellite (continuous line with dots), and solar radio emission at 10.7 cm ($F_{10.7}$) – a proxy of solar UV radiation (dashed line with squares)

Figure 3 illustrates, in addition, the temporal variability of the *relativistic electrons*, measured on board the GOES 11 satellite. It is worth noting that their temporal variability is determined by the the high speed solar wind streams (emanated from the solar coronal holes), which enhance the population of energetic electrons (with $E > 4$ KeV) in the magnetosphere and modulate their precipitation into the lower thermosphere and mesosphere [17]. The examination of the time series of relativistic electrons with energies >2 MeV, measured on GOES 10 satellite, for the period 2000–2009, shows that their intensity is an order of magnitude higher in the period 2003–2006. This is obviously related to the fact that solar wind streams become more intensive and recurrent, when the Sun approaches the minimum of its 11 year cycle.

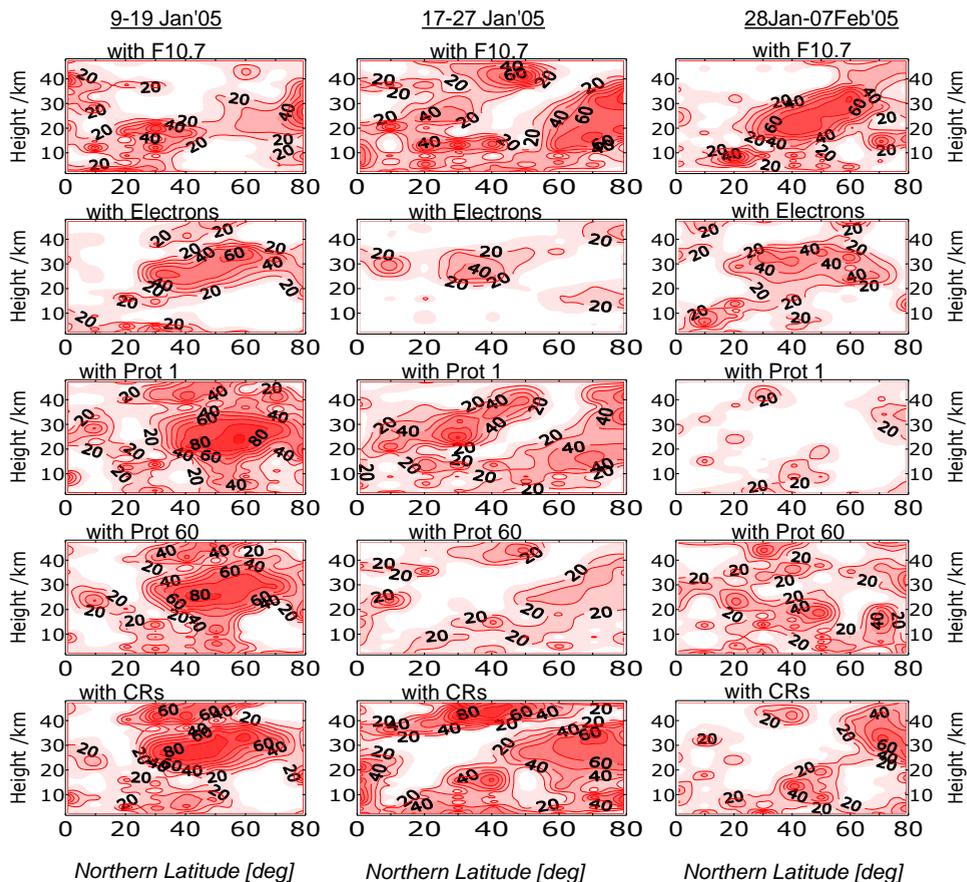


Fig. 4 (a). Percentage impact of the solar UV radiation (I^{ST} row), electrons with $E > 2$ MeV (2nd row), protons with $E > 1$ MeV (3rd row), protons with $E > 60$ MeV (4th row) and cosmic ray flux (from Climax neutron monitor) in temperature variability for the period 10 January – 7 February 2005

Within the investigated period, the first raise of the relativistic electrons' intensity has appeared between 4th and 7th January – i.e. 3 day before the first and 10 days before the second solar flare. Furthermore, there are two more picks – on 20th and 23th January – obviously related to the SPE'2005, and another raise between 10th and 14th February. In addition, the 27-day periodicity of the solar UV radiation is also showed in Fig. 3.

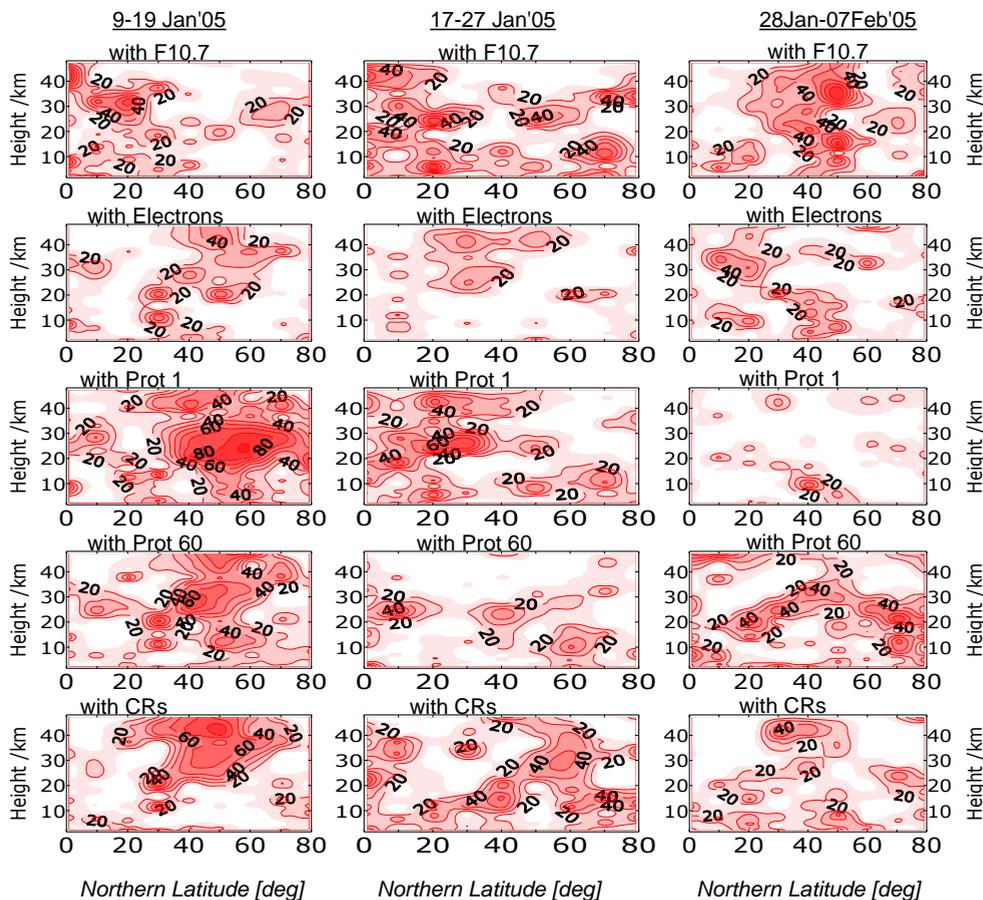


Fig. 4(b). Percentage impact of the solar UV radiation and energetic particles in ozone variability during the period 10 January – 7 February 2005

Figure 4 presents the calculated coefficient of determination R^2 multiplied by 100, which gives the percentage impact of each factor in T and O_3 variability. The analysis of Fig. 4(a) shows that middle-stratospheric warming during the *first* analysed period (refer to Fig. 1) could be attributed mainly to three of the examined factors: (i) increased density of “soft” protons, having a maximum at 17–18th

January, which describe up to 80% of T variability, (ii) the enhancement of “hard” protons and (iii) the Forbush decrease of GCR. The impact of the last two factors is about 70–80% of the T variability. The particles’ impact, however, seems to be short lasting and during the *second* and *third* time intervals is strongly weakened and dispersed (see the middle and right columns of Fig. 4(a)). In the second half of January two other factors become particularly important – i.e. the solar UV radiation and the relativistic electrons (with $E > 2$ MeV). Each of them explains up to 60% of the T variability (Fig.4(a), middle and right columns).

The ozone’s response to the analysed forcing agents is shown in Fig. 4(b). It is easily noticeable that before the solar proton event, the mid- and high latitude O_3 variability is closely related to the particles intensity – soft and hard solar protons and cosmic rays (Fig. 4(b), left column). During the main phase of the SPE’2005, as well as during the atmospheric recovery phase, the particles effect on the O_3 is substantially diluted. As should be expected, the “soft” protons impact is minimised during the recovery phase, due to the severe decrease of their flux intensity (refer to Fig. 2). The “hard” protons’ effect, however, does not disappear for the same reason, which is a hint for existing mechanism ensuring delayed O_3 response to the high speed protons. The impact of relativistic electrons remains noticeable during the recovery phase, due to subsequent spike in their intensity (refer to Fig. 3). The gradual increase of CR intensity, after the Forbush decrease (see Fig. 2), is also well traceable in O_3 variability (the right column in Fig. 4(b)). The most important at this period seems the solar UV radiation – especially at middle latitudes – possibly due to the raise of its intensity.

Analysis of ozone profiles’ response to particles’ forcing

The current section is aimed to examine the variability of the ozone’s vertical profiles and if possible to attribute some specificity in its behaviour to the energetic particles’ fluxes. Figures 5 and 6 provide a direct view on the vertical profiles of O_3 anomalies – i.e. its deviations from the O_3 climatology for January, calculated over the entire data record (1979–2009) – at all examined 21 levels. Due to the spectral difference of energetic particles’ temporal variations, we have selected three periods in their temporal variability: (i) non-SPE conditions 3–8 January, characterised by raised integral flux of *relativistic electrons* between 4th and 7th January; (ii) the main phase of SPE’2005 (18–21 January) – characterised by a sharp increase of the “hard” solar protons (on 20th January) and a spike in the flux of *relativistic electrons* (within 19–21 January); (iii) the recovery phase after the SPE’2005 (23–27 January). The variability of O_3 profiles at 60°N and 40°N latitude, at Greenwich meridian, have been examined and compared.

The top panels of Fig. 5 reveal that the enhanced flux of *relativistic electrons* is accompanied by an increased variability of the high latitude ozone profile beneath 20 km, while their effect at mid-latitudes is substantially

suppressed. The ozone’s response to the mixed forcing (i.e. “soft” and “hard” protons, and *relativistic electrons*) during the SPE’2005 is more complicated – especially at high latitudes. The bottom panels of Fig. 5 shows a sudden enhancement of the peak O₃ density at 60 °N latitude – immediately after the raise of the “soft” protons’ flux (on 17–18 January), as well as during the peak of relativistic electrons (on 20 January), followed by the second spike in “soft” protons (on 21 January). The mid-latitude O₃ is practically insensible to these lower energetic particles – with an exception of 19th January, when the ozone density at 18 km was enhanced by ~ 40 % (Fig. 5, bottom, right column).

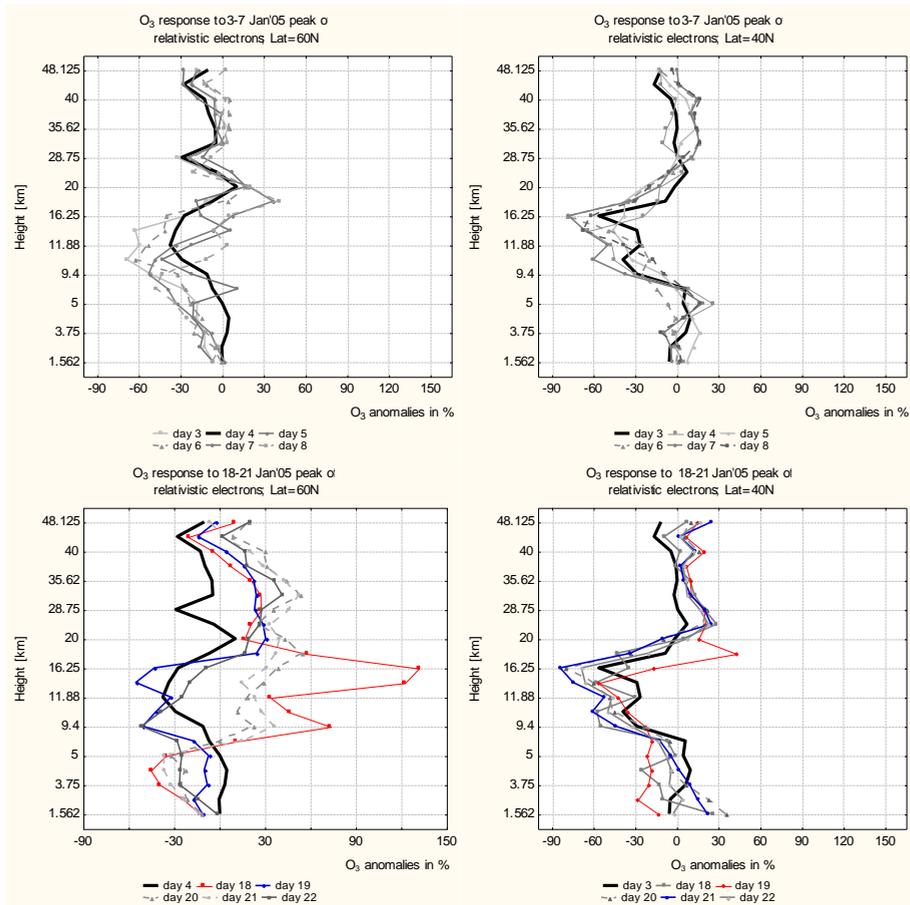


Fig. 5. Ozone profiles’ variations at 60°N (left column) and 40°N (right) column, found prior to and during the solar proton event in January 2005. Ozone profiles from 3 and 4 January (thick black lines) are chosen as undisturbed ones.

The recovery phase after the SPE'2005 is characterised by a stable depletion of the polar ozone – up to 70% compared to the January climatology (left panel of Fig. 6) – probably related to the downward transportation of NO_x family from the mesospheric levels, where they are produced. Much more surprising, during the recovery phase, is the mid-latitude O₃ behaviour. Thus, with an exception of 23rd January, all other days (i.e. 24th – 27th January) are characterised by a dramatically *increased* O₃ density – more than 150% (the right panel of Fig. 6). This ozone enhancement is hardly understandable, despite the coincidence with the 3rd sharp peak in the *relativistic electrons flux*. The lower energy of these particles does not allow them to penetrate deeper into the atmosphere, due to the geomagnetic shielding, and could not directly influence the exceptional O₃ behaviour. Fig. 3 shows, in addition, that the raise of the peak ozone density should not be attributed to the solar UV radiation, because it was in the minimum of its 27-day periodicity.

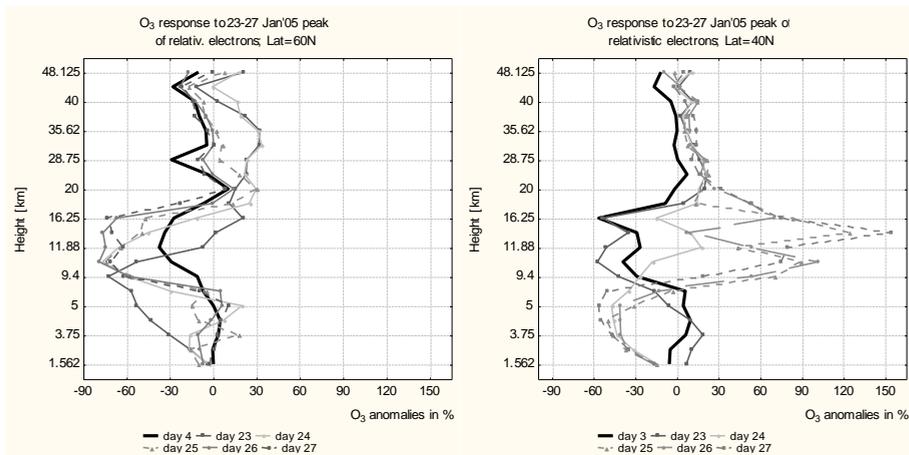


Fig. 6. Ozone profiles' variations at 60°N (left column) and 40°N (right column), found during the atmospheric recovery after the solar proton event in January 2005.

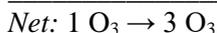
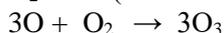
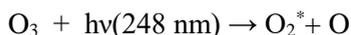
An attempt for explanations of this latitudinal variability of O₃ response to the particles' forcing, during the solar proton event in January 2005, will be given in the next section.

Mechanism of O₃ enhancement during and after January'2005 SPE

It is broadly accepted that the main effect of precipitating energetic particles in the Earth's atmosphere is the O₃ destruction, due to the activated HO_x (i.e. H, OH, HO₂) and NO_x (NO, NO₂) ozone destructive cycles [18, 19]. The satellite measurements and modeling results show that enhanced HO_x and NO_x densities can significantly impact the concentration of the mesospheric ozone.

Their influence on the stratospheric O₃, however, goes mainly through a modulation of the ozone's optical depth (i.e. the ozone column aloft a given stratospheric level).

The thinning or thickening of the O₃ optical depth increases or decreases the amount and spectral characteristics of the penetrating solar UV radiation. In normal conditions, the solar UV radiation – capable of reaching the middle stratosphere – could not dissociate molecular oxygen – O₂ [20], and consequently it could not produce ozone at these levels. However, [21] noticed that the large UV continuum, known as Hartley band (200–350 nm), is able to dissociate ozone creating vibrationally excited molecular oxygen O₂^{*}. The latter is easily dissociated by the freely penetrating at these levels longer UV radiation, creating atomic oxygen. The latter immediately reacts with the oxygen molecules, creating ozone, i.e.



In resume, dissociation of a one ozone molecule by solar UV radiation leads to the formation of three new ozone molecules. This effect is known as ozone “*self-restoration*” and has been explained for the first time by Slinger [20].

This mechanism could be activated, when occasionally the thermosphere-mesospheric O₃ is reduced, which allows more UV radiation to reach the stratosphere. The efficiency of the ozone *self-restoration* has been estimated by Kilifarska et al. [21], which created a chemical model of this effect. Using their formula (6) we have estimated the changes in the O₃ profile resulting from a uniform reduction of its optical depth (τ_3) by 30% above 35 km. Calculations have been made at two latitudes – 40° N and 60° N – using the ERA Interim data for 13 January (up to the stratopause) as non-disturbed O₃ and T profiles. The mesospheric T and O₃ concentration, as well as the whole profile of the molecular O₂ have been taken from the US standard atmosphere (1976). The concentrations of the OH radical for examined days have been taken from the MLS instrument on board the AURA satellite.

Results presented in Fig. 7 show that the reduction of the ozone optical depth aloft 35 km is really followed by an O₃ increase at lower levels. This process, however, depends on the solar zenith angle (χ) and the latitude. Thus at mid-latitudes the enhancement of the O₃ concentration is maximal near the peak of the ozone layer during sunlight hours. At sunset, however, (calculations are made for $\chi = 89^\circ$ and 105°) a distortion of the O₃ profile is found above 35 km, while the enhancement of the peak O₃ density near 25 km is strongly reduced (see the left side of Fig. 7).

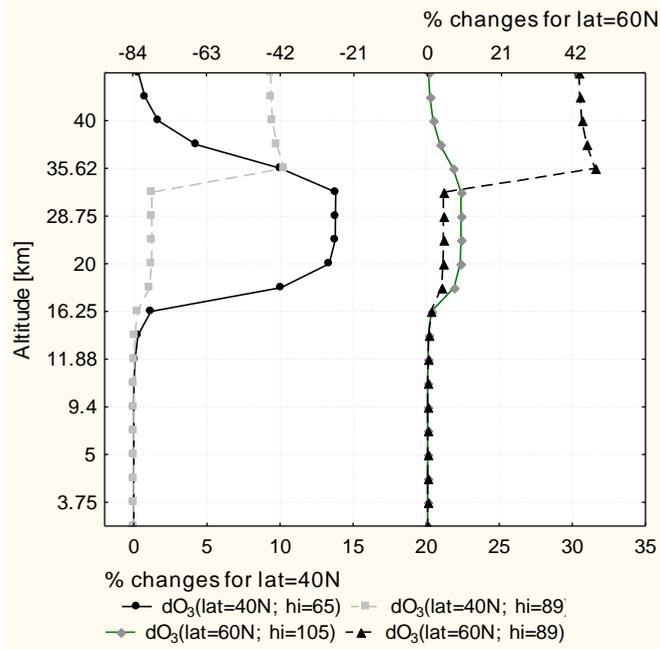


Fig. 7. Ozone response at the middle (left) and the polar latitudes (right) to a 30% reduction of its optical depth above 35 km, calculated by the [14] model. The continuous line with dots gives the O_3 profile at $40^\circ N$ calculated with a solar zenith angle $\chi = 65^\circ$, while dashed line with squares corresponds to $\chi = 89^\circ$ (left side of the figure); continuous line with diamonds corresponds to O_3 profile at $60^\circ N$ calculated for $\chi = 105^\circ$, and long dashes with triangles – corresponds to $\chi = 89^\circ$ (right part of the figure).

In January the mid-day value of the solar zenith angle at $60^\circ N$ latitude is 89° and the calculated changes in the O_3 profile are found out above 35 km, reaching the values of 42÷44% increase of ozone density. Unlike the mid-latitudes, the model predicts a slight enhancement of the middle stratospheric ozone density for higher zenith angles, i.e. $\chi > 90^\circ$ (presented are calculations for $\chi = 105^\circ$; see the right side of Fig. 7). It is worth noting that the ozone *self-restoration* effect depends strongly on the lowest boundary of the mesospheric O_3 depletion. The effect is stronger, when the negative O_3 anomalies reach the upper stratosphere [21]. The results shown in Fig. 7 are a rough estimation of the *self-restoration* effect, because only the O_3 absorption at 250 nm is taken into account. More realistic results can be derived when the entire Harley and Schuman-Runge bands are included in the calculations.

The model's estimations shown in Fig. 7 could help us to understand the irregular response of O_3 profile at polar and mid-latitudes, due to the energetic particles' impact. For example, the puzzling enhancement of the polar peak O_3

density during the SPE'2005 (bottom, left panel in Fig. 5) could be attributed to the reduced O₃ optical depth, preconditioned by the increased flux of *relativistic electrons* since the beginning of January 2005 (refer to Fig. 3). The raise of “soft” protons in 17–18th January makes the polar O₃ column even thinner. At these circumstances, the higher zenith angle of the solar UV radiation illuminating the middle stratosphere, activates the self-restoration mechanism near the peak of the O₃ layer (refer to the right grey O₃ profile in Fig. 7).

At mid-latitudes, the ozone *self-restoration* is activated after the SPE'2005. This behaviour could be attributed to the less sensitivity of the mid-latitude stratospheric O₃ to the lower energetic protons and electrons, penetrating the upper atmosphere before and during the SPE'2005. However, the “hard” protons striking the atmosphere on 20th January, reduces the O₃ density deeper into the stratosphere (see the right, bottom panel of Fig. 5). In accordance with the model's simulations [21], the O₃ reduction at stratospheric levels serves as a trigger for activation of the *self-restoration* mechanism.

Conclusions

Thorough analysis of the atmospheric response to energetic particles' forcing (during Solar Proton Event SPE'2005 on 20 January 2005), shows that the stratospheric O₃ is very sensitive to the energy spectrum of penetrating energetic particles, as well as on the latitude. The evaluation and modeling of the cosmic ray interaction with the substance of the stratosphere is done by means of full Monte Carlo simulations and appropriate hadron and atmospheric models [22–25].

Evidence for an enhanced maximal O₃ density at polar latitudes and a decreased one at mid-latitudes is shown during the strongest, and with “hard” particles' spectrum, solar flare. During the recovery phase has been found the opposite response – i.e. raised mid-latitude and reduced polar ozone density.

These irregularities have been attributed do the modulation of ozone's optical depth, due to the activation of the HO_x and NO_x ozone destructive cycles at thermospheric and mesospheric levels. Thus thinning of the O₃ optical depth activates the Slanger's mechanism for ozone formation at lower atmospheric levels – an effect known also as O₃ *self-restoration*. We demonstrate that efficiency of ozone's *self-restoration* depends on the zenith angle of stratospheric illumination by the solar UV radiation – especially important at high latitudes.

The observed warming of mid-latitude stratosphere, during the SPE'2005, has been attributed to the ozone enhancement and the more solar UV radiation absorbed. The influence of high energy particles on the stratosphere continues further down to the troposphere and results in various meteorological and climatic effects [26].

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ШИРОЧИННА ЗАВИСИМОСТ НА ВАРИАЦИИТЕ В СТРАТОСФЕРНИЯ ОЗОН И ТЕМПЕРАТУРА ПО ВРЕМЕ НА СЛЪНЧЕВОТО ПРОТОННО СЪБИТИЕ ОТ 20 ЯНУАРИ 2005

Н. Килифарска

Резюме

Статията представя анализ на измененията, наблюдавани във вертикалните профили на озона и температурата на Гринуичкия меридиан, по време на протонното събитие от януари 2005 г. Изследвана е зависимостта от енергетичния спектър на частиците, измерени на геостационарния спътник GOES 11. Показано е, че озонният профил реагира по различен начин на средни и на полярни ширини. Представеното обяснение на тези особености е базирано на измененията в оптичната плътност на озона, вследствие на увеличената продукция на озоноразрушаващите HO_x и NO_x семейства. Така намаляването на оптичната плътност на озона улеснява проникването на слънчевия ултравиолет и активира производството на озон в стратосферата по механизма на Слангер (известен още като самовъзстановяване на озона). Преставени са моделни разчети на произведения по този механизъм озон. Отбелязано е, че чувствителността на стратосферния озон към измененията в оптичната му плътност зависи, както от енергетичния спектър на частиците, така и от дълбочината на проникването им в атмосферата (контролирана от геомагнитното поле). Процесът на самовъзстановяването на озона зависи още от зенитния ъгъл на огряване на стратосферата от слънчевия ултравиолет. Ръстът на температура в средната стратосфера по време на протонното събитие е обяснен с увеличената озонна плътност и по-голямото количество адсорбирана ултравиолетова радиация.