Stratospheric ozone, solar activity and volcanism

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Abstract. The aim of this study is to investigate the long-term (multiannual) variations of the total ozone content (TOC) on the base of TOMS instrument measurements on the board of Nimbus-7 satellite for the period 1979 – 1993 AD. The total effects of the solar activity influence over stratosphere ozone has been investigated by using multiple regression analysis. The monthly radio-index $F10.7$, the cosmic rays neutron flux, the geomagnetic index Ap and the number of GOES x-ray X-class flares have been used as solar or solar-modulated parameters as predictors in the model. The global mean-monthly TOC-parameter has been used as a predictant. It has been found that the coefficient of correlation of the model between TOC and above-mentioned solar and geomagnetic factors is about 0.544. Thus the corresponding factor variance is about 37 %. The results calculated by the model have been removed from the original TOC data. It has been found out that during the first 12 years since 1979 the downward trend is predominantly caused by the solar and solar-modulated processes. However during the remaining 3 years after 1990 the slope of the negative trend has been essentially increased. This phenomenon could only be explained by some catastrophic event. Most probably such one is the Pinatubo volcano eruption in June, 1991. An evidence for the possibility that the last one is caused by trigger effect from the extremely high solar flare activity in May – June 1991, is given.

Key words: stratospheric ozone, solar activity, volcanism

Стратосферният озон, слънчевата активност и вулканизмът

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Целта на настоящото изследване е анализът на дългосрочните (многогодишни) вариации на общото съдържание на озона (ОСО), получени на базата на наблюденията с прибора TOMS от борда на спътника Nimbus-7 за периода 1979-1993 година. С помощта на многофакторен регресионен анализ е изследван сумарният ефект на влия-ние на слънчевата активност върху стратосферния озон. Като слънчеви или слънчево-обусловени фактори в регресионния модел са използвани средномесечните стойности на слънчевия радиоиндекс $F10.7$, неутронният поток от галактичните космически лъчи, геомагнитният Ар-индекс, както и месечният брой на рентгеновите слънчеви изриг-вания от клас X (по класификацията, възприета за наблюденията от спътниците GOES). Като предиктант са използвани средномесечните планетарни стойности на ОСО. Намереният коефициент на множествена корелация между ОСО и гореспоменатите слънчеви и геомагнитни фактори е 0.544. Той съответства на обща факторна дисперсия, равна на 37% от общата дисперсия. Изчислените по регресионния модел данни са извадени от оригиналните такива за ОСО и е установено, че през първите 12 години, считано от 1979 година, низхозящият тренд е бил предизвикан главно от слънчеви и слънчево-обусловени процеси. През останалите три години наблюдения, обаче, след 1990 г, наклонът на отрицателния тренд съществено се увеличава. Това явление би могло да се обясни само чрез някакво катастрофично събитие. Най-вероятно такова е било изригването на вулкана Пинатубо през юни 1991 година. Дадени са доказателства, че е възможно това изригване да е предизвикано от тригерен ефект от изключително високата слънчева еруптивна активност през май-юни 1991 година.

1 Introduction

One of the most discussed phenomenon concerning the variability of the total ozone content in the Earth atmosphere is the nature of the long-term downward trend. It has been detected after the first decade of precise satellite observations from Nimbus-7 satellite by using of TOMS (Total Ozone Mapping Spectrometer) instrument. The most widespread explanation of this phenomenon is that last one is caused by antropogenic pollution in the stratosphere because of different emissions of Cl-containing components, like the chloro-fluoro-carbons (CFCs). These emissions were considered to be the primary sources of the ozone depletion over the south polar region (the so called "ozone hole"). As another agent for the destroying of ozone is thought to be the volcanic activity.

However, the main factors for ozone balance are photochemical processes and the horizontal and vertical transport in the stratosphere. The main source of ozone molecules is the photodissociation of O_2 by the solar flux in the range of 110-180nm. On the other hand the O_3 molecules are dissociated mainly by the solar "middle" UV-range between 190-310nm (Hartley's continuum) and in significant degree by the Hartley's bands (310-360nm).

The solar energetic particles (SEP) with energies $E \geq 1$ MeV, as well as the galactic cosmic rays, are able to penetrate the Earth middle atmosphere and stratosphere. Thus they could participate in the O_3 balance both by impact dissociation of O_2 and O_3. Evidence, that high energetic solar protons, whose primary source is a strong solar flare in August 04, 1972, had affected the mesosphere and stratosphere ozone abundance, are given still by Heath et al. (1977) and Maeda & Heath (1980). The effects of SEP events over the stratospheric and mesospheric ozone during the solar cycle No 23 (1996 – 2008 AD) has been studied by many authors (Kryvolutsky et al., 2008; Jackman et al., 2008; Damiani et al., 2009 etc.). In some of these analysis the role of SEP over the other important for the O_3-balance gases, like NO_x, $HOCl$, O, is also taken into account. The general conclusion from the predominant part of these studies is that SEP events lead to ozone depleting both in stratosphere and mesosphere.

The depletion of ozone layer by galactic cosmic rays (GCR) has been considered by Tassev & Tomova (2001) and Lu (2001). Especially in the second study the GCR destruction effect over chlorofluorocarbons ($ClFC$s) with escaping of Cl-atoms is consedered as an additional O_3 depletion mechanism. By the Forbush-effect the maximum of GCR-flux in Earth atmosphere occurs near to the minimums of sunspot Schwabe-Wolf's cycle, while the SEP-events are placed predominantly near to the sunspot maximums and very often also on the downward solar cycle phase.

On the other hand, the solar UV-flux reaches its maximum near to sunspot Schwabe-Wolf's cycle and consequently, the photochemical processes of prduction of O_3 by O and photo-dissociation of O_3, reaches their maximum during this time.

All this considerations point out that the overall solar activity influence on the ozonosphere is strongly nonlinear. That's why it is not correct to describe it only by one overall factor, but as an ensemble of factors, which describe the influence of the different solar processes over the ozone.

By these reasons the main subject of the study is the building of multiple regression model where few solar or solar-modulated observed parameters are used as predictors of the global TOC. The attributes of this model as well as the residuals between observed and modeling data have been analyzed. The last procedure is hold for the more precise separation between the solar and terrestrial factors on which the ozone content is dependent.

2 Data and methods

For the aims of this study we use the mean-monthly maps of TOC global distribution, which has been obtained by TOMS instrument on the board of Nimbus-7 satellite in the period January, 1979 – April, 1993. Their version 7 is published on CD. The following solar indexes are used as predictors of TOC:

- The radio index $F_{10.7}$ as a better proxy of the solar UV-flux in the range 110-180nm (for the O_2 photodissociation) and 190-310nm (the Hartley's continuum of O_3 absorption and photodissociation);

- The GCR neutron flux data by Moscow station which are used as a proxy of the GCR-flux background;

- The daily and monthly numbers of the strongest x-ray X-class solar flares (by GOES classification) as a proxy for the extreme solar flare activity and SEP (Solar Energetic Particles) events;

- The planetary Ap-index as a proxy for geomagnetic activity and the efficiency of the solar activity events over Earth magnetosphere and atmosphere;

All solar and geomagnetic data are published in the National Geophysical Data Center (USA) and could be used through its STP-server ($ftp://ftp.ngdc.noaa.gov/STP$)

The multiple regression model has been built by using 6D-STAT software package. The addition or removal of factors and terms is made on the base of Snedekor-Fischer's F-test.

3 Results and analysis

On Fig. 1 the monthly values of mean planetary ozone content in the period 1979 – 1993 are shown. The effect of seasonal variations related to polar night/day changes in the both polar regions is not removed. We test the possible significance of this circumstance by time series analysis and found that there are 6 and 30 month oscillations, but not detectable cycle by annual ($\sim$ 12 months) duration. Consequently, there are no significant effect, caused by periodic visibility/non-visibility of regions with local significant deviation like the Antarctic "ozone hole". The downward trend during the whole series is well visible. Between 1979 and 1990 it is essentially weaker in respect to after 1990. The mean coefficient of linear correlation of the trend between TOC and the time is r=-0.655 and r/σ_r=15.07 where $\sigma_r = (1 - r^2)/\sqrt{N}$ is the correlation coefficient error and N=172 is the length of time series in months

Obviously the faster TOC decrease after 1990 is most probably caused by some catastrophic event. It is accepted that the powerful eruption of Pinatubo volcano on the Philippines is the reason of this strong downward trend after 1990.

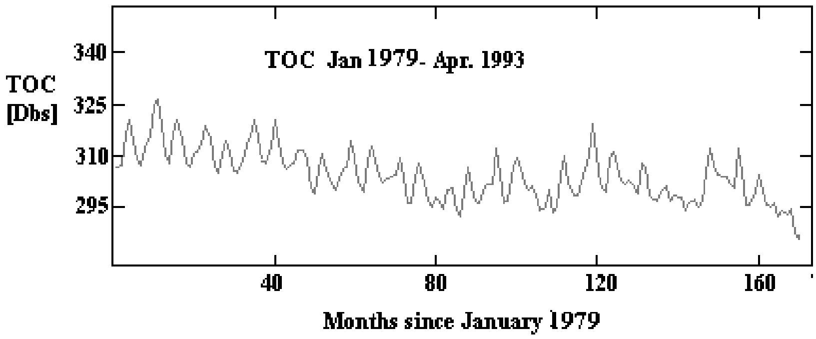

Fig. 1. The mean monthly planetary Total Ozone Content (TOC) (January, 1979 – April, 1993, AD)

We have tested this statement by assuming of an alternative explanation that may be a significant contribution could also have a powerful solar flare activity period at the end of May and the first half of June 1991.

However, for this aim it was necessary to build a regression model describing the integral influence of solar activity over TOC. After a large number of numerical experiments we found out that the best fitting between TOC and the solar and solar-modulated factors is described by the regression model

$$TOC = 298 - 0.0041R_f - 0.88F_{10.7} + 1.96N_X - 0.0011R_fN_X + 0.00056R_fF_{10.7}$$

The following signatures are used there: $F_{10.7}$ – solar radioflux at f=2800 MHz (10.7 cm) in units $10^{-21}W.m^{-2}$; R_f – the GCR-flux index by Moscow neutron monitor station; N_X – the monthly number of X-class solar flares.

The corresponding coefficient of multiple correlation is R = 0.544 and F = 1.37 where $F = s_t^2/s_0^2$ (s_t^2 is the total variance, while s_0^2 is the residual one).

It follows from the obtained value of F that the factor variance s_t^2 is $s_t^2 - s_0^2$=0.37, i.e. 37 % from the TOC total variance is caused by solar factors, which are described by the regression model. As it is shown, there is no detectable independent participation of the geomagnetic Ap- index in the TOC-changes.

The linear terms, containing $F_{10.7}$ and R_f describe the processes of O_3 dissociation due to solar UV and galactic cosmic rays respectively. There is also positive linear term of N_X, which could indicate that SEP-events could not only destruct ozone molecules by impact dissociation, but also in some degree they also could, on the other side, to stimulate the total O_3 production by generation of O atoms from O_2 impact dissociation. The interactive terms $R_fF_{10.7}$ and R_fN_X most probably describes two-or three stage processes with

O_2,O_3, NO_x, $ClFC$s, with participation of GCR and SEP particles and solar UV-radiation, which lead to generation or destruction of O_3 as a final result.

The modeled TOC values have been calculated by using of regression model. After that they has been removed from the original data. The residuals are shown on Fig.2. The downward trend is significantly smaller in the residual series compared to the original one and the linear correlation coefficient there is r=-0.44. The corresponding ratio r/σ_r is 7.15. This result shows that a significant part of the general downward trend in the whole TOC data series is caused by active processes on the Sun over the ozone layer.

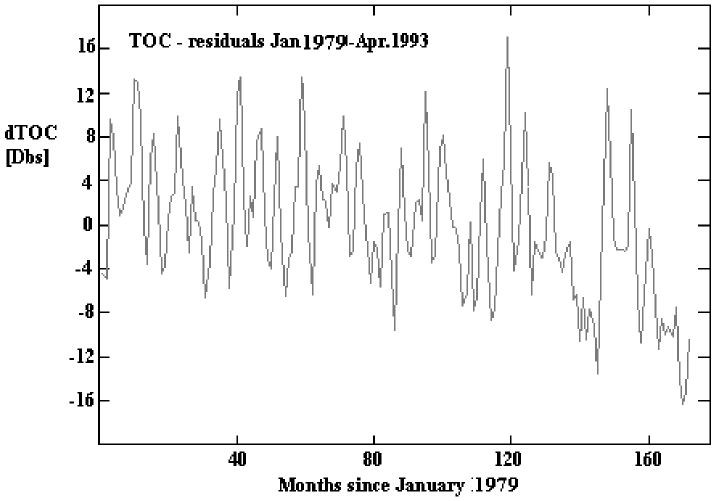

Fig. 2. The TOC residual series (January, 1979 – April, 1993 AD)

In the next step of our test we exclude the last three years from the residual TOC-series. The corresponding downward trend correlation for the period 1979-1990 AD is r=-0.17 with r/σ_r=2.15. Consequently, the downward trend before 1991 AD is caused predominantly by a complex solar impact mechanism over the ozonosphere. The coefficient r=-0.17 of the "residual" trend before 1991 AD is statistically significant with a level slightly over 95 % probability. It indicates that a small, but detectable participation of additional factors, which are not included in the regression model, should by taken into account for the full explanation of TOC decreasing tendency during the period 1979-1991 AD. These factors may be f.e. volcanic activity and "antropogenic" $ClFC$s emissions. Other solar factors or effects of interaction between different factors is not clear now, because of the lack of corresponding data.

4 Discussion

The main subject of our interest is to provide a more detailed analysis for the reason of the sharper decreasing of TOC in the second half of 1991 (the 150th month on X-axis in Fig.1 and 2) and after that. Out of doubt it is caused by Pinatubo volcanic eruption activity (Luzon Island, Philippines) during the first half of June 1991. As it is well known, the Pinatubo eruption on June 15 is the second one by magnitude during the 20th century. It is estimated in magnitude 6, according to the VEI-index. This main eruption has been preceded by series of other tectonic events – a big earthquake (magnitude M =7.7) on Luzon in July 15, 1990 , a series of earthquakes in March, 1991, in the near-volcanic region. The first significant strong eruption occurs in April 2, 1991. A monotonic increasing of volcanic activity has begun in period of May 15-28. It was followd by a magmatic eruption on June 3. On June 7 the first explosion has occurred. The main phase of activity begin on June 12 and continued up to June 15, 1991 when a series of five very strong explosions took place. They generate eruptive ash columns in the atmosphere, and their height is in the range of 19-34 km over the Earth surface.

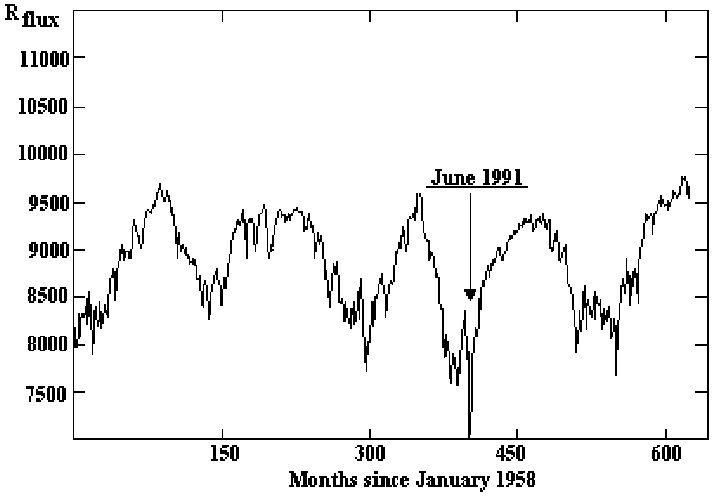

Fig. 3. The deep GCR-flux minimum in June 1991 AD in Moscow neutron monitor data series

The large quantities of active gases and aerosols during the Pinatubo eruption in 1991, which have been injected in the stratosphere during this catastrophic event, seems enough to explain the faster depleting of ozone layer in the recent part of Nimbus-7 data. However there are some interesting details, which made the circumstances near to this event much more interesting.

As it is shown on Fig.3, the period May – July 1991 AD is very interesting in aspect of GCR-flux dynamics. It is characterized by a strong minimum in June 1991, which is the deepest one during the whole more than 40-year period of regular observations in the Moscow neutron monitoring station. It is caused by a series of 3 "Forbush-decreases" on June 4, 11 and 30, respectively. One other such event occured on May 28. There is also another very large "Forbush decrease" on March 24. The GCR-flux has been fallen by 23.5 % on this date. As it is well known, the "Forbush-decreases" are caused by large coronal mass ejections (CMEs). These events are connected with the active regions in the solar atmosphere and the generated there processes. Many of them are strong solar flares. There are two x-ray X-class flares on March 23, one on March 25, 28 and 30, and one on April 20 and May 18. A very spectacular series of 7 X-class flares begin on May 29 and continued up to June 16. The corresponding dates are May 29, June 2, 5, 7, 10, 12 and 16.

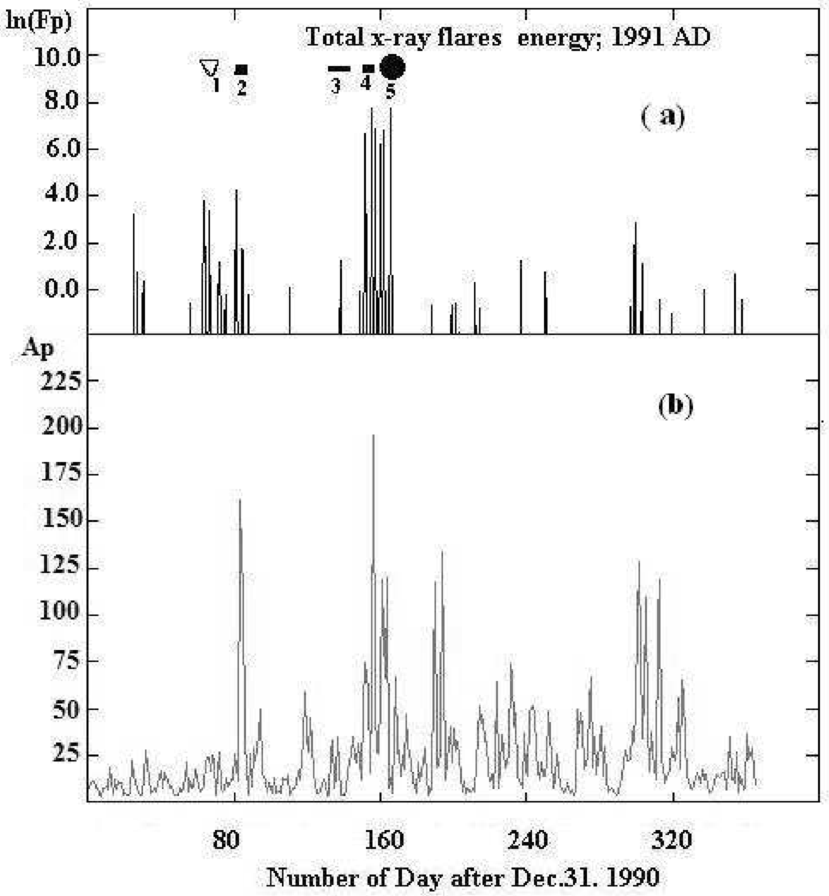

Fig. 4. Top: The daily solar flare x-flux energy, calculated on the base of X-class flares during 1991 AD. The main Pinatubo activity events are signed too; Bottom: The mean daily planetary Ap -index during the same period

The calculated total energy of the X-class flares during 1991 AD is shown on the top panel of Fig.4. The main periods of high flare activity are during March and June. Both they are very well corresponding to the main events of Pinatubo eruption activity, which are marked on Fig.4 too. They are as follows: "1" – the seismic activity in March 1991; "2" – the first magmatic eruption on April 2, 1991; "3" – the period of increasing activity during the second half of May; "4" – the first explosion on June 7; "5" – the series of large explosions on June 12-15. The both periods of solar flare activity are also geoeffective (the bottom panel of Fig.4). Two ground level enhancement (GLE) events has been registered on June 11 and 15.

The most spectacular coincidences concern the periods direct before the first strong eruption on April 2, as well as the solar and volcanic events between June 7 and 15. They indicate for a possible "solar – geomagnetic" trigger process of the Pinatubo eruption in June, 1991, AD.

There are many evidences up to this moment for relationship between the solar and tectonic activity processes. This is more certainly established for the earthquake activity (Chijevskij, 1934, 1973; Schove, 1955; Serafimova, 2005; Rogozhin & Shestopalov, 2007 etc). The solar activity due to the solar wind, SEP or GCR-particles and via the magnetosphere and geomagnetism is considered as a trigger mechanism for many earthquakes, but not for all. In this light it seems very reasonable, that solar-geomagnetic activity processes could play a trigger role for some of volcanic eruptions, but also not for all. Indeed, one of such cases is the Pinatubo eruption in 1991 AD. Unlike the last one no significant coincidences between the other large volcanic eruption (El Chichon, 1982) during the studied period and the solar flare activity has been detected.

The flare trigger-effect over some tectonic events (including volcanic eruptions) is one of the possible physical channels for indirect solar activity influence on the ozonesphere and climate.

Finally it could be not excluded, that the faster ozone depletion since June 1991 is caused by more complex reasons then just the "pure" volcanic explosion effect, including also interaction effects by two or more factors. For example the SEP events in the Earth atmosphere could cause an increased dissociation of $ClFC$s, sulfuric, nitric or other gaseous compounds which have already existed in the atmosphere before that moment or are injected there during the volcanic explosion.

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