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# THE EFFECT OF MAJOR METEOR STREAMS ON THE TOTAL OZONE IN THE EARTH'S ATMOSPHERE

Yu. M. Gorbanev[1], I. A. Stogneeva[1], V. A. Shestopalov[1], E. F. Knyazkova[1], I. I. Kimakovskaya[1], S. R. Kimakovsky[1], A. V. Golubaev[2]

[1] The Research Institute "Astronomical Observatory" of the I.I. Mechnikov Odessa National University, Odessa, Ukraine, *skydust@ukr.net*

[2] Institute of Astronomy Kharkiv National University, Kharkiv, Ukraine, *Alexandr_sky@mail.ru*

ABSTRACT. The correlation between the total ozone and activity of major meteor streams, such as the Perseids, Geminids, Leonids and Orionids, has been found using the Total Ozone Mapping Spectrometer (TOMS) measurements of the global ozone distribution over the periods 1978 – 1993 and 1996 – 2001. The autocorrelation analysis of the total ozone time series for the period of about 20 years has confirmed the existence of regular changes in the ozone levels at the peaks of meteor shower activity. It has been established that TO decreases after the dates of peak activity of meteor streams (e.g. the Perseids) or during the whole periods of meteor shower activity (e.g. the Geminids, Orionids and Leonids). The analysis of the total ozone distribution (in the Southern and Northern Hemispheres), as well as the local distribution of ozone (over the selected surface area of several hundred square kilometres), was performed during the Leonid meteor shower in 1999. The atmospheric zones for which the ozone distribution pattern can be described as a result of interaction between the meteor shower material and the ozone layer were localised by applying the TOMS data. Such zones correspond to the regions where the highest Leonid activity has been observed. According to the radar observations (conducted in Kazan, Russian Federation), three activity maxima of the 1988 Geminid shower were reported: on the nights of $7^{th}$, $12^{th}$ and $14^{th}$ December, 1988. The TO decrease was observed on the same dates. Thus, the analysis of the TO changes during the periods of intense meteor shower's activity enables to preliminary assess the maximum overall decline in the total ozone concentration which makes about 5 DU over two weeks. From the results obtained it can be inferred that the ozone layer can be used as an indicator of the interaction between the meteoric material and the Earth's atmosphere.

**Key words**: ozone; meteor; Total Ozone Mapping Spectrometer (TOMS)

## 1. Introduction

One of the important tasks of meteor astronomy is to estimate the global influx of interplanetary dust to the Earth's atmosphere. Various techniques of observations, including visual, photographic, television and radar ones, as well as theoretical methods, have been invoked to address this challenge adequately. All methods for observations involve selectivity due to non-regularity of monitoring, the location of a ground-based observation site, weather conditions, etc. Such selectivity of observations of meteor events in the Earth's atmosphere does not enable to obtain a global pattern of the interplanetary dust influx in meteor streams; hence, satellite observations which provide detailed monitoring of the atmospheric parameters over a long period of time are of great interest with regard to the meteor astronomy tasks. This paper presents an attempt to test the hypothesis about the effect of the meteoric influx on the total ozone (TO) using the TO geophysical satellite data.

Such an effect will be more pronounced, yet short-term for large meteoroids entering the Earth's atmosphere. For instance, as reported in (Gorkavyi et al., 2013), the bolide which exploded near Chelyabinsk (Russian Federation) on $15^{th}$ February 2013 had formed a new aerosol layer above the Junge layer in the Earth's atmosphere. That new aerosol layer remained in the atmosphere for more than three months. The present study results are based on the measurements by the limb profiler of the Ozone Mapping and Profiler Suite (OMPS) installed on the recently launched

NASA-NOAA Suomi NPP spacecraft. The presence and long lifetime of the stratospheric debris related to the Chelyabinsk bolide has been confirmed by the data obtained with the Optical Spectrograph and Infra-Red Imaging System (OSIRIS) on-board the Odin satellite and reported in the studies (Rieger et al., 2013; Rieger et al., 2014).

The ozone layer monitoring has shown that the TO undergoes significant regular or non-regular changes (Oltmans et al., 1998). The results of processing of the rocket-borne TO measurements reported in (Callis et al., 1979) are indicative of the correlation between the ozone concentrations at altitudes above 26 km and the solar activity. Solar proton flares can also cause the ozone depletion in the Earth's atmosphere (Stephenson et al., 1992; Shumilov et al., 1996; Kasatkina et al., 1998; Tassev et al., 1999; Krivolutsky et al., 2001; Kuznetsov, 2002). Volcanic eruptions are another natural factor affecting the TO. In the study (Deshler et al., 1996), by the example of the Mt. Pinatubo eruption, the authors showed the existence of a correlation between the ozone levels and volcanic aerosol at altitudes below 14 km.

Having analysed the extended TO data set obtained with the Solar Backscatter Ultraviolet instrument (SBUV) on the Nimbus-7 spacecraft and SBUV/2 on-board of the National Oceanic and Atmospheric Administration weather satellites NOAA-9 and NOAA 11 over the period from January 1979 to December 1995, the authors (McCormack et al, 1997) concluded that volcanic eruptions did affect the total amount of ozone in the Earth's atmosphere. The total-column ozone measurements using a Dobson spectrophotometer during a total solar eclipse occurred on $24^{th}$ October 1995 reported in (Chakrabarty, 1997) may serve as an example of the ozone layer sensitivity to the external effects. A sharp fall in the ozone column was observed 15 minutes before the total phase followed by a sharp rise 10 minutes upon its completion. The amplitude of the effect made $5 - 11$ % of the initial TO value.

Thus, the observations show that the ozone layer in the Earth's atmosphere is sensitive to the external effects. Meteor dust particles when entering and vaporising in the Earth's atmosphere also act as external factors affecting the TO. As reported in (Hedin et al., 2014), between a few tons to several hundred tons of meteoric material enters the Earth's atmosphere each day, and most of this material is ablated and vaporized in the $70 - 120$ km altitude region. The subsequent chemical conversion, re-condensation and coagulation of this evaporated material are thought to form nanometre-sized meteoric smoke particles (MSPs). It is also reported that such products of the meteoric material combustion are reckoned as a significant component of stratospheric aerosol and enhancers of the ozone depletion.

In the study (Link, 1976), the influence of the Orionid and Geminid meteor showers on the TO was concluded from the observational material of the Soviet satellite IK-3. In the meteor physics studies, the reactions between meteoric metal ions (Baggaley, 1977; Poole & Nicholson, 1975) or electrons (Poole, 1978) and ozone in the atmosphere were referred to explain the mechanisms of meteor trail luminosity. Such reactions result in decreased TO while there are also processes which may lead to the formation of meteoric ozone (Bibarsov, 1985). The impact of the sporadic meteors on the ozone layer is rather slight; it is enhanced under the effect of an intense meteor shower, and increases by many times when such phenomena as the Tunguska event occur. As reported in (Turco et al., 1981), in the early 1900s the Smithsonian Astrophysical Observatory conducted a long-term programme to estimate the variability of the solar constant. A spectrobolometer required to measure the relative solar radiation in the range of $0.35 - 1.6$ m was installed at Mount Wilson (California, USA, $34°\ N$, $118°\ W$).

Later, upon the introduction of the technique for the determination of ozone by the Chappuis-band absorption, it became possible to apply the above-mentioned measurements to calculate the ozone column concentrations during the period of the Tunguska event (about 70 % accuracy). The measurements of atmospheric transparency by the Smithsonian Astrophysical Observatory for the years 1909 to 1911 showed unusually low ozone levels in early 1909, implying a TO deficiency of 30 $\pm$15 % comparing to the seasonal mean ozone concentrations for the previous years. Based on the model calculations, the authors (Turco et al., 1982) concluded that as much as 30 million metric tons of nitric oxide (NO) might be generated in the stratosphere and mesosphere due to the Tunguska event, which resulted in the ozone reductions in the subsequent years. In another study (Park, 1978), it was also reported that the anomalous atmospheric phenomena after the Tunguska event could be attributed to the reactions of nitric oxide with atmospheric ozone. Therefore, it may be concluded from above that the effect of such a factor as the interplanetary matter influx on the ozone layer is likely to exist.

## 2. The search for the effect of annual meteor streams on the Earth's ozone layer

The main objective of this study is to test a hypothesis for the effect of major meteor streams on the Earth's ozone layer. In the study (Hughes & McBride, 1989), the resultant masses of the streams responsible for the Quadrantid, Perseid, Orionid and Geminid meteor showers were found to be $1.3{\cdot}10^{15}$, $3.1{\cdot}10^{17}$, $3.3{\cdot}10^{16}$ and $1.6{\cdot}10^{16}$ g, respectively. These results show that the Perseids are one of the most powerful meteoroid streams whose contribution to the meteor material influx into the Earth's atmosphere exceeds the contribution of other streams by $1-2$ orders of magnitude. It is the amount of meteoric material which is expected to determine the pattern of a meteoroid stream's impact on the ozone layer. Thus, the Perseid, Geminid and Leonid streams were chosen as target ones to detect a correlation between the meteor shower activity (the meteoric dust influx in time or influx rate) and the ozone content in the Earth's atmosphere.

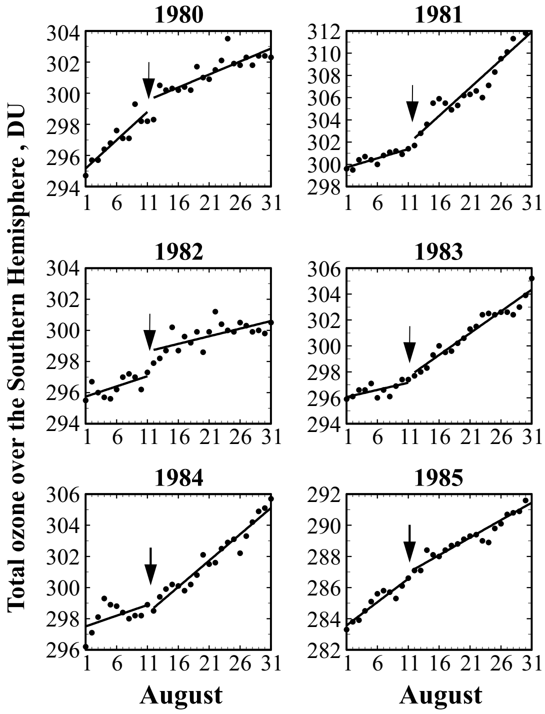


Figure 1: The total ozone over the Southern Hemisphere (SH) during the Perseid meteor shower in 1980-1985.

According to the visual, photographic and radar observations conducted over the recent decades, the peak activity of the Perseid meteor shower falls on the night of August 12. For example, as reported in the study of (Lindblad, 1986), the visual observations of the Perseid meteor streams during $1953-1981$ indicated the following specific features of the stream activity profile: the cross-section consisted of a long-duration, rather flat component and a sharp peak of activity with duration of $1-2$ days. The shower maximum for visual meteors occurred at solar longitude $139^{\circ}.4$ (the Equinox in 1950). The Perseid shower exhibited large variations in activity from year to year. In the study of (Russel, 1986), the Perseid meteor parameters were compared for the showers of 1977, 1978, 1980, 1981 and 1983. Sixteen years of observations of the Perseid meteor shower carried out with the patrol radar in Ottawa (Canada), reported in (Simek & McIntosh, 1986), showed that a sharp flux peak occurred at solar longitude $139^{\circ}.20 \pm 0^{\circ}.026$. It was also reported from the radar observations that the shower remained rather active over several days after the peak. The shift of the Perseid maximum with time was reported in the study (Lindblad & Porubcan, 1994) based on the photographic observations in the period $1937-1985$. The peak activity of the stream was located at approximately $139^{\circ}.5-139^{\circ}.6$ in $1940-1969$ and at $138^{\circ}.9-139^{\circ}.0$ in $1970-1989$. It is likely that there are two peaks of activity for the Perseid stream. Hence, to find a correlation between the Perseid meteor stream activity and the ozone layer of the Earth's atmosphere, it is necessary to pay attention to the TO change after the night of August 12 every year.

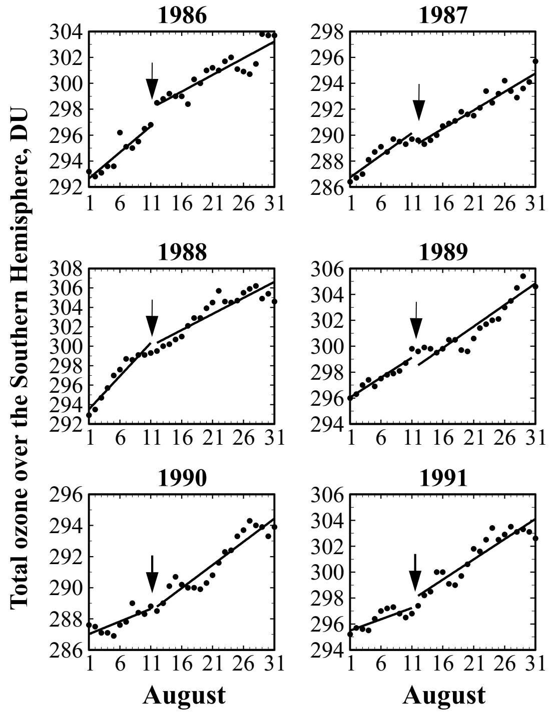


Figure 2: The total ozone over the Southern Hemisphere (SH) during the Perseid meteor shower in 1986-1991.

The measurements made by the Total Ozone Mapping Spectrometer (TOMS) (McPeters et al., 1996), which has been monitoring the Earth's atmosphere during 27 years, were used as observational material for this study. The satellite observation data are available on the web-site: *http://jwocky.gsfc.nasa.gov/*; in this study, we only used the total ozone values among all parameters measured by TOMS. A regular pattern of the total ozone behaviour was reported in our ear-

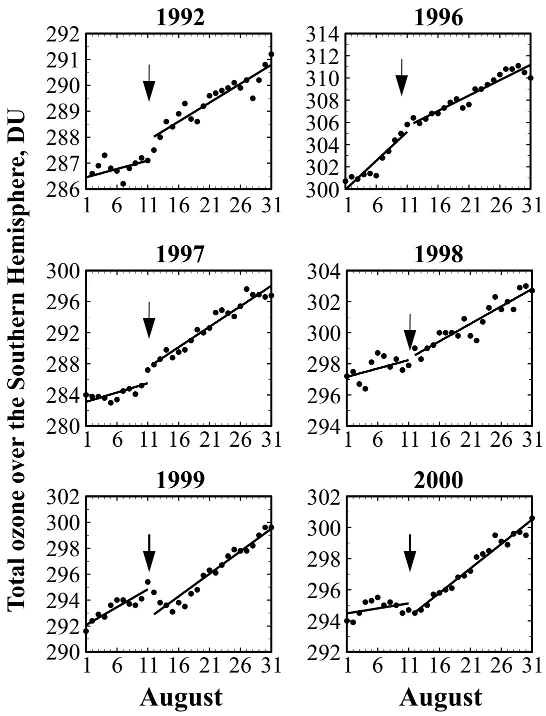


Figure 3: The total ozone over the Southern Hemisphere (SH) during the Perseid meteor shower in 1992-2000.

lier studies (Gorbanev et al., 2000; Gorbanev et al., 2001) which adopted the TOMS measurements of the global ozone distribution over the periods 1978 – 1993 and 1996 – 2001. The authors emphasise that there are specific features on the plotted total ozone seasonal variations which appear after the night of August 12 from year to year. The seasonal variations in the total ozone observed over the Southern Hemisphere (TO SH) in the month of August for a number of years are plotted in (Figs. 1 – 3). The total ozone values in the text and figures are given in commonly used Dobson Units (DU). To provide better visualization of the figures, we have approximated the total ozone curve segments before and after the activity peaks by two straight lines. The following general conclusions about specific features of the profiles in (Figs. 1-3) can be made upon the comparison of these year-to-year straight lines with each other: the straight line constructed from the data covering the period before the activity peak, in fact, merges into the straight line built for the observations after the maximum (as observed in 1985, 1989 and 1996); either a noticeable parallel shift (as in 1982 and 1999) or more or less pronounced break (as in 1980, 1981, 1983, 1997 and 2000) is recorded between the straight lines. This is one of the methods for classifying specific features of the total ozone profiles during the period of the Perseid shower activity. The autocorrelation functions (ACF) were calculated to carry out a more detailed analysis of the data. The authors of this paper suggested that an intense influx of meteoric dust to the Earth's atmosphere occurs after the Perseid shower activity peak on August 12; this dust interacts with the ozone layer thereby changing its concentration.

A distinctive feature of annual meteor streams is the regularity of their activity: the peaks of activity fall on specific dates within a year. However, it should be taken into consideration that the meteor stream activity is regular, but not consistent which is reflected by meteor shower rate variations from year to year. Such pattern of the meteor activity depends on specific structural features of meteor swarms and also upon how the Earth intercepts these streams. The indicated non-uniform pattern of the impact of meteor showers on the Earth's atmosphere resulted in application of the ACF technique which enabled to detect the periodicity of meteor shower activity over a long time interval (about 20 years). We have generated a correlation between a total ozone series and the same series shifted by several time steps (in days) which can be called an autocorrelation function ($R\tau$) where $\tau$ is a time shift (or time lag). An absent of any annual periodic influence of the different natural phenomena on TO, including the cosmic dust influx from meteor streams, means that the total ozone profiles would only reflect seasonal variations (which are different in the Northern and Southern Hemispheres). In fact, due to a high sensitivity of the ozone layer, TO is subject to the different-amplitude fluctuations of either human or natural origin, as well as the influence of meteoric dust. From these considerations, the ozone curve segments corresponding to the periods of activity of major meteor streams were approximated by the simplest analytic functions which is consistent with the TO seasonal variations. An ACF which does not display the fluctuation contributions was developed by the approximate values. The most important information is carried by the differences ($\Delta R\tau$) between the ACF constructed by actual and smoothed time series. The dependencies of these differences on the time lag (Fig. 4) enable to point out that specific features of the plotted $\Delta R\tau$ (usually their maxima) correspond to the dates of the peak activity of the Perseid, Leonid, Orionid and Geminid meteor showers. That is indicative of the existence of regular variations in the TO profiles during the periods of meteor shower activity over recent 22 years. Such a tendency can be observed over both the Southern and Northern Hemispheres while it manifests itself to the different extent for the different showers. Another distinctive feature resulting from the correlation analysis is that the relevant local maxima on the plotted TO differences (Fig. 4), which are accurate to within 24 hours, can be observed for the meteor showers with several peaks of activity (e.g. the Orionids and Geminids).

The search for correlations between the TO decline and meteor activity by applying the results of visual, photographic and radar observations is of a great interest. Such correlations were only obtained by the authors from the analysis of radar observations of the Perseid and Geminid activity for a number of years. The meteor radar rates for the period 1980-1985 (Simek, 1987) are presented in (Fig. 5a). The plotted activity profiles present the radar rates ($R$) for two groups of meteors, such as meteors with echo duration shorter than 1 s, which are small dust particles, and those with longer echo duration (up to 8 s), which are larger dust particles. Providing that the influence of the Perseid meteor stream on the ozone layer does exist, the difference of TO values before the shower's onset and during the peak of its activity should be correlated with the meteor rate at its peak. The difference in TO ($D_{TO}$) from July 18 to August 10 is plotted in (Fig. 5b). These dates were chosen as the onset date of intense dust influx in the Perseid stream to the Earth's atmosphere and the date preceding the shower's peak rate, respectively. The conducted analysis has shown that the highest correlation between the total ozone decline and meteor shower rate falls in this particular period. At that, the correlation coefficient is higher for the fine dust and reaches a value of 0.96.

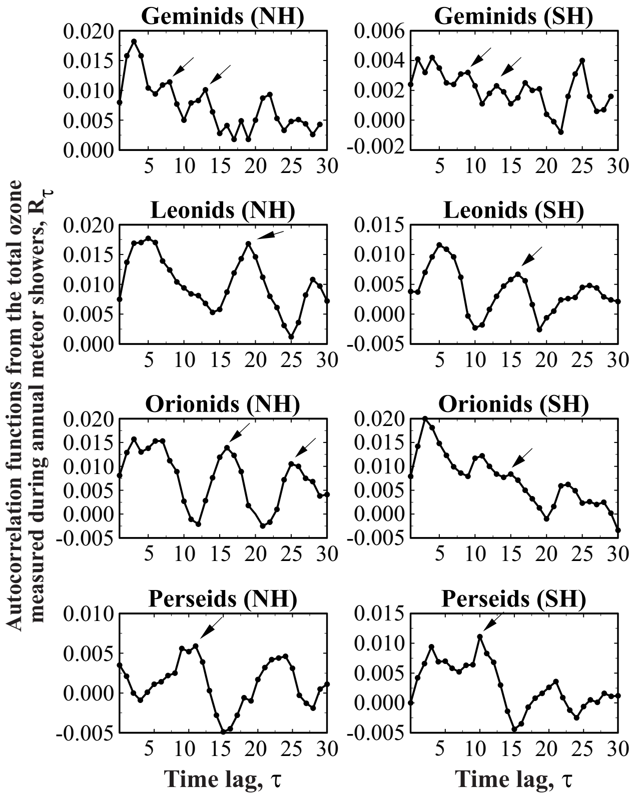


Figure 4: The autocorrelation functions from the total ozone measured during annual meteor showers.

## 3. The Geminid meteor stream pattern and total ozone

To investigate an interaction of the Geminid meteor shower with ozonosphere, the TO measurements over the Northern and Southern Hemispheres for the period of the shower activity from November 25 to December 25 in 1978 – 2001 were adopted in this study (Fig. 6a). To assess the magnitude of the TO decline, such a characteristic as the ozone deficiency ($\Delta_{TO}$) was introduced. Taking such a decrease in TO as a result of the meteor shower activity and providing that the total ozone remains at the level prior the shower's onset, we define $\Delta_{TO}$ as the difference between the actual TO and approximated level of ozone obtained from the seasonal profile segments not affected by the shower's activity (Fig. 6b).

The structural features of the Geminid shower detected from the 1988 $\Delta_{TO}$ profiles have been confirmed by independent radar observations carried out in Kazan, Russian Federation (Karpov et al., 1998). The observation data processing has shown that the shower peaked three times during the period of its activity, in particular on the nights of $7^{th}$, $12^{th}$ and $14^{th}$ December, 1988; it was likely due to the multiply-branched structure of the meteor swarm. The maximum rates of the Geminid meteor shower plotted in (Fig. 6b) are indicated by upward arrows. Three peaks were detected from the 1988 $\Delta_{TO}$ profiles falling on the nights of $6^{th}$, $11^{th}$ and $13^{th}$ of December. It should be noted that the peaks of activity over the Northern Hemisphere were observed on December 6 and 11 while those over the Southern Hemisphere were observed on December 6 and 13. The dates of $\Delta_{TO}$ maxima are shifted relative to the dates of the meteor peak rates by a magnitude of one day. This fact can be explained by the asymmetry of the Geminid meteor influx curve, i.e. the Earth intercepts larger amount of meteoric particles before the shower's peak rather than after it (Belkovich et al., 1987).

As can be seen from $\Delta_{TO}$, the TO decline is observed over both the Northern and Southern Hemispheres. Thus, it is reasonable to suggest that it accounts for the position of the Geminid radiant which is near the celestial equator and is being shifted (the daily shift is $\Delta\alpha = +1^{\circ}.1$; $\Delta\delta = -0^{\circ}.1$), so that meteoric particles get into the Southern Hemisphere. The Geminid individual radiant positions selected from a number of catalogues of photographic, radar and television monitoring data (Lindblad & Steel, 1993; Lindblad & Porubcan, 1994) were used to test this hypothesis. The selected sample of individual radiants was divided

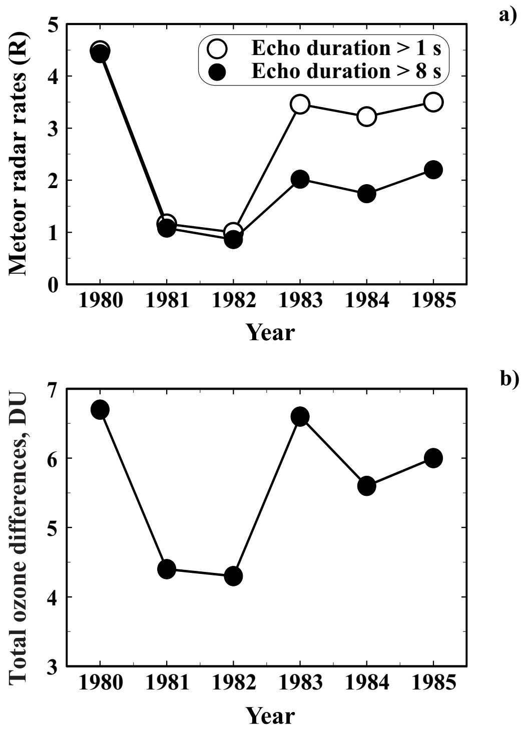


Figure 5: The correlation between the Perseid radar rates (R) and total ozone differences for the Northern Hemisphere ($D_{TO}$ NH) for the period from July 18 to August 10 over 1980–1985.

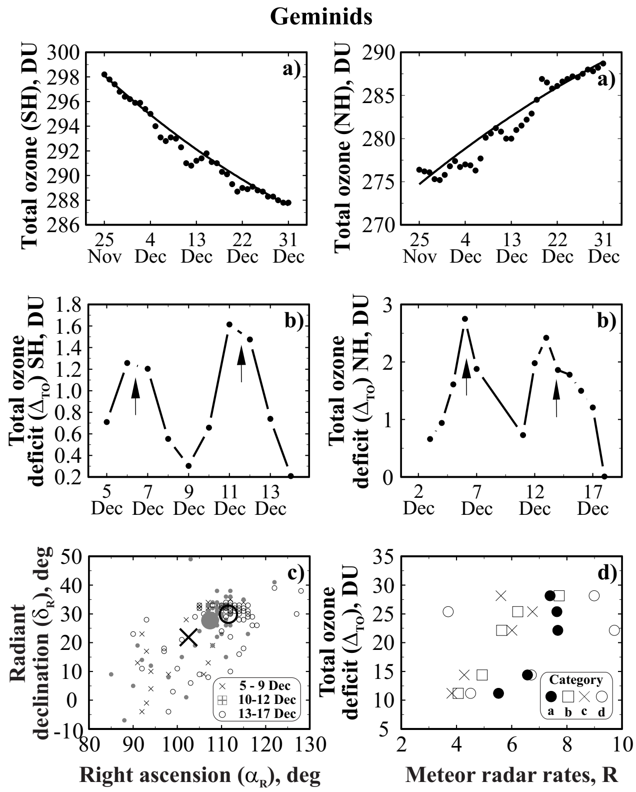


Figure 6: The Geminid meteor shower and total ozone over the Southern (SH) and Northern (NH) Hemispheres: a) the total ozone in November-December, 1988, during the Geminid meteor shower activity; b) the total ozone deficiency ($\Delta_{TO}$); c) the Geminid meteor radiant positions in December; d) the correlation between the 1988 Geminid radar rates (R) and $\Delta_{TO}$.

into three groups by the dates of their intersections with the Earth, including the periods of December $5-9$, December $10-12$ and December $13-17$. A mean radiant for each of the three periods was determined within each group. Having plotted the data for three groups and calculated mean radiant positions for each of the groups, we found that the first group radiant was closer to the celestial equator than the others (Fig. 6c). This is likely why the peaks on the $\Delta_{TO}$ curves are observed on December 6 over both the Northern and Southern Hemispheres, i.e. meteoric particles get into both hemispheres. The second group radiant was shifted towards the north from the celestial equator; hence, there is a clear-cut peak on the $\Delta_{TO}$ curves for the Northern Hemisphere on December 11 while this peak is less pronounced on the ozone deficiency curve for the Southern Hemisphere. And, finally, the third group radiant position is the most distant from the celestial equator, so that the peak on December 13 can only be observed on the $\Delta_{TO}$ curves for the Northern Hemisphere. The effect of the Geminid shower activity on TO is also confirmed by a high correlation between the overall TO decline for the whole period of the shower activity and the Geminid integral radar rates ($R$) obtained by Czech astronomers (Pecina, 1999). The radar observations of the Geminids in the period 1958 – 1997 were presented in four echo duration categories, namely: a) 0.4 s $\leq T <$ 1.0 s; b) 1.0 s $\leq T \leq$ 8 s; c) $T \geq$ 1 s; and d) $T >$ 8.0 s. It was found from these data (Fig. 6d) that the highest correlation ($k = 0.96$) was observed for the b-category fine particles; hence, it can be concluded that the total ozone is the most affected by fine dust particles.

## 4. Possible display of the 1999 Leonid meteor shower activity in the ozone layer

The result obtained for the Leonid meteor storm can be reckoned as one of possible confirmations of the ozone layer role as an indicator of meteor activity. According to the visual observations reported in (Arlt et al., 1999), the 1999 Leonid meteor shower activity reached 3700 ±100 meteors per hour at the peak of the storm. Depending on the observation techniques and position of a ground-based observer, the meteor rate varied from a hundred to 15,000 meteors per hour (Price & Blum, 1998). Such an increase in the stream activity is likely due to the passage of its parent Comet 55P/Tempel-Tuttle. The TO profiles corresponding to the period of the 1999 Leonid meteor stream activity are presented in (Fig. 7).

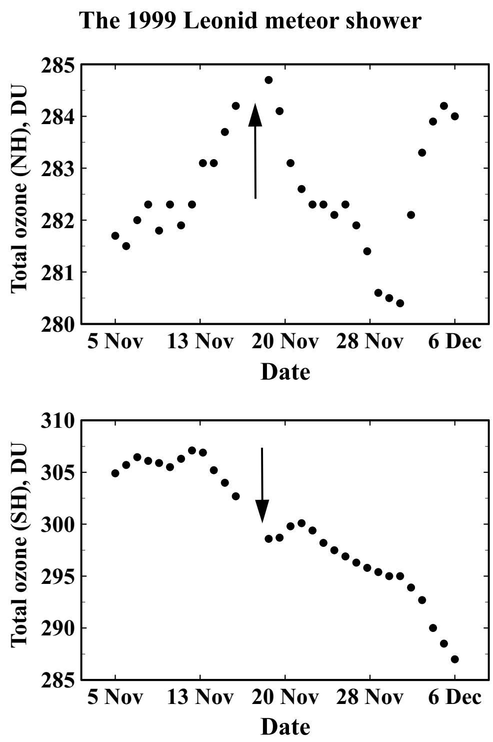


Figure 7: The total ozone over the Southern (SH) and Northern (NH) Hemispheres during the 1999 Leonid meteor shower.

A decrease in TO over the Northern Hemisphere can be observed just after November 18 which is the date of the meteor shower maximum. At this period of the year a seasonal increase in TO can be observed over the Northern Hemisphere while a decrease in TO can be observed over the Southern Hemisphere. The meteor stream activity interferes with the TO seasonal upward trend for the Northern Hemisphere and results in the TO decline after the date of the stream's peak with further re-establishment of the seasonal downward trend within approximately 10 days, which is illustrated in (Fig. 7). The influence of the meteor stream on the total ozone over the Southern Hemisphere is less significant. This is due to the fact that the maximum meteoric material influx during the Leonid shower activity occurred over the Northern Hemisphere of the Earth. Such intense meteor activity should have affected not only the total ozone, but also individual regions of the ozone layer.

A relatively lower activity of meteor showers (with meteor rate up to 100 meteors per hour) results in the TO variations, but does not affect individual regions of the ozone layer. Let us introduce the concept of the local ozone (LO) which is the ozone concentration measured through the atmospheric column over a surface area of a $1^\circ.25$ of longitude and $1^\circ$ of latitude grid cell. The satellite observation data sets have such a grid-spacing covering the entire globe, and the local ozone distribution is measured by TOMS over each of these areas. The LO change during a meteor storm occurs in the regions where the maximum amount of dust material is carried into the atmosphere, i.e. where the mean orbit of the meteor swarm intersects the Earth's orbit. To localise such regions, we used both preliminary ephemerides of the meteor shower activity and actual observation data, such as: the major peak of the 1999 Leonid shower on 18.11.1999 at $02^h03^m$ UT (Molau, 1999); at $02^h02^m \pm 02^m$ UT (Arlt et al., 1999; Rendtel et al., 2000); $01^h55^m \pm 04^m$ UT (Brown et al., 2002); the secondary peaks on 18.11.1999 at $01^h25^m$, $01^h43^m$, $01^h50^m$, $02^h33^m$, $03^h17^m$ and $03^h29^m$ UT (Arlt et al., 1999); the radian positions at $\alpha = 153^\circ.65 \pm 0^\circ.1$, $\delta = 21^\circ.80 \pm 0^\circ.0$ (Molau, 1999); $\alpha = 153^\circ.6 \pm 0^\circ.1$, $\delta = 21^\circ.9 \pm 0^\circ.1$ (Rendtel et al., 2000); $\alpha = 153^\circ.1 \pm 0^\circ.1$, $\delta = 21^\circ.5 \pm 0^\circ.2$ (Brown et al., 2002).

The mean orbit of the meteor stream traces an arc in the Earth's atmosphere due to the Earth's rotation and its orbital motion. The dusty cloud responsible for the major peak of the 1999 Leonid meteor storm entered the Earth's atmosphere on November 18 at about $02^h00^m$ UT at altitudes of $95 - 123$ km (Brown et al., 2002). It is feasible to localise the surface site where the storm radiant position was at the zenith at this instant of time. The geographic coordinates of this point are $\phi = +22^\circ$, $\lambda = 66^\circ$ of east longitude, which coincides with the calculations made by other authors (McNaught & Asher, 1999). Let us assume that the meteoric material influx into this region of the Earth's atmosphere will be the largest at the shower's activity peak. After the meteor event, i.e. the combustion of interplanetary dust particles, the micron-sized products of disintegration in the atmosphere descend from altitudes of $95 - 120$ km to those of 40 km and below.

In astronomy, the activity of a meteor shower is defined as Zenithal Hourly Rate (ZHR), i.e. the number of meteors recorded within an hour. As reported in (Arlt et al., 1999), the Leonid storm was observed with a peak equivalent ZHR of $80 - 100$ for 6 hours. Thus, (Fig. 8) presents the LO maps for different regions of the Earth's atmosphere which cover the area with coordinates $\phi = 66^\circ \pm 60^\circ$ , $\lambda = +22^\circ \pm 22^\circ$ where the radiant position of the meteor shower was shifting along the latitude $\phi = +22^\circ$ for 6 hours. Slanting lines with no LO data in (Fig. 8) are related to hardware specific features of data reception by a satellite.

The LO decreased due to fluctuations, but did not

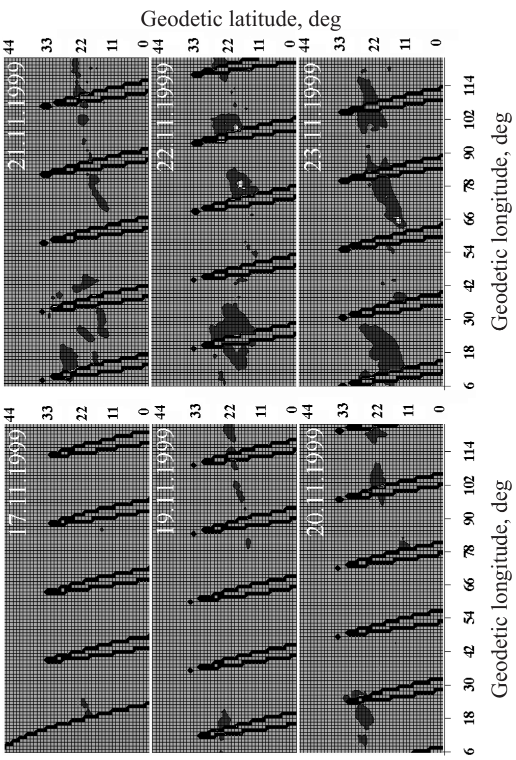


Figure 8: The 1999 Leonid meteor shower display in the Earth's atmosphere. The local ozone isoline maps for different dates during the period of the shower activity.

fall below the level of 253 DU till the peak activity on November 14 – 16; hence, the LO isocurves for the other selected six dates were plotted on the maps in the range from 200 to 250 DU. The lower level is determined by the minimum LO values in this region. Distinctive decreases in LO can be tracked along the latitude $\phi = +22°$ which correlates with the latitude of the surface sites where the radiant position is at the zenith during the whole period of the stream activity. It should be noted that these LO drops appear after the Leonid meteor shower activity on November 18, i.e. the date of the peak activity. The increased area and depth of these local formations in the ozone layer after 20.11.1999 can be described as the process of slow deposition of products of combustion and fragmentation of meteoric particles upon their entering the Earth's atmosphere and interacting with the atmospheric ozone.

In the author's opinion, the results presented in this article enable to assert that the ozone layer in the Earth's atmosphere can be an indicator of the activity of meteor showers, in particular, annual major meteor streams, such as the Perseid, Geminid, Leonid and Orionid ones. The kinematic and structural features of meteor swarms can be obtained from the responses of the ozone layer. It is suggested that further studies of the ozone concentration just in the meteor region of the Earth's atmosphere, as well as its responses on the meteor shower activity, should be carried out in the future.

## 5. Kinetics of Interaction between Meteoric Matter and Ozone Layer

In order to understand the mechanism of the correlation revealed between the activity of meteor showers and variations in the ozone concentrations, let us first get down to observations. Recent studies of the upper atmosphere composition have shown the existence of a secondary ozone layer at an altitude of about 80 – 90 km. For instance, radio observations performed with the BLM radar in 1992 – 2000 proved the existence of a secondary ozone layer at atmospheric altitudes of 85 – 90 km along with the known stratospheric ozone shield at heights up to 40 km (Cevolani & Pupillo, 2003). The authors have associated the observed variations in the mesospheric ozone concentrations with the activity of meteor showers as a result of interaction of the ablated dust particles with ozone. Meteoric ablation is the source of the metal atoms – $Na$, $Fe$, $Mg$, etc. – which occur in the mesosphere at altitudes between 80 and 105 km. At altitudes below 85 km these metals are converted mainly to hydroxides and carbonates through reactions involving $O_3$, $O_2$, $CO_2$ and $H_2O$ (Plane et al., 2014). The study (Dunker et al., 2013) investigated a possible connection between the Geminid meteor shower and mesospheric sodium layer. The results of the observations have shown that the sodium column density during the Geminid meteor shower is lower than the winter average value at the same latitude. Based on the observations conducted on $13^{th}$ and $19^{th}$ December, 2010, the authors have come to the conclusion that the daily meteoric Na flux is about 121 kg while the total daily meteoric mass flux into the Earth's atmosphere is about 20 t.

Therefore, physical and chemical parameters of the atmosphere, including the ozone concentrations, at meteor altitudes are expected to correlate with the meteoric mass delivered. For instance, meteor radar observations at the Sodankylä Geophysical Observatory (SGO - $67°22'N$; $26°38'E$, Finland) reported by (Kozlovsky et al., 2016) have indicated that the mesospheric temperature at an average altitude of 91 km is systematically underestimated by 20 – 50 K during the Geminid meteor shower (with the peak activity on the $13^{th}$ of December). According to the SGO meteor radar observations and data obtained with the Earth Observing System (EOS) Microwave Limb Sounder (MLS) onboard the NASA Aura satellite during the Geminid meteor shower in 2008 – 2014 the peak night meteor rate accounted for $15,000 - 20,000$ meteors $d^{-1}$. A similar temperature effect has been found for the Quadrantids whereas there is no such effect for the other investigated meteor showers. The latter is likely to be associated with the chemical and physical properties of meteoric particles of the given meteor showers.

It should be noted that it would be more effective to search for a correlation between the mesospheric ozone concentration variations and such a meteor shower activity characteristic as the flux density of meteoroids within a given mass range rather than the Zenithal Hourly Rate (ZHR). According to the results reported by (Molau, 2016), the flux density at the peak of the Lyrid meteor shower activity (see Fig. 1 in the paper referred above) is about $4{\cdot}10^{-3}$ meteoroids $km^{-2}h^{-1}$ (which is four times higher than the flux density of the sporadic background). The activity profile of the Lyrids obtained from the IMO Network video observations in $2012 - 2015$ was rather smooth without year-to-year variations while the Quadrantid meteor shower showed interannual variations in the flux density (see Fig. 2 in the paper referred above) which accounted for $10^{-2}$ to $5{\cdot}10^{-2}$ meteoroids $km^{-2}h^{-1}$ (according to the reported data the indicated flux density is 10 to 50 times higher than that one of the sporadic background). The authors have also reported that the meteor shower sporadic activity is likely to correlate with the lunar phase ($\pm 15$ % relative to the average sporadic meteoroid flux density). This could explain the secondary peaks on the correlation curves presented in this paper (see Fig. 4). According to the optical observations carried out in 2011 (Molau & Barentsen, 2014) the meteoroid flux density of another meteor shower, namely the Draconids, was $(118 \pm 10){\cdot}10^{-3}$ $km^{-2}h^{-1}$. However, it should be taken into account that the afore-mentioned flux density value was reported for the meteors with a limiting magnitude of $+6.5^m$. The flux density for the fainter meteor showers may be orders of magnitude higher (there is a well-known power-law which defines that the dust trail density increases with decreasing mass of dust particles). The calculations based on the observational data obtained by other authors (Trigo-Rodriguez et al., 2013) have shown that the meteoroid flux density over six hours of the Draconid meteor shower averaged to $65.8{\cdot}10^{-3}$ particles $km^{-2}h^{-1}$. The total meteoric mass delivered to the Earth's atmosphere at altitudes up to 85 km in 2011 (on the $8^{th}$ of October) was 950 $\pm$150 kg. As reported in the paper (Ye et al., 2014), an intense outburst of the Draconid meteor shower was recorded by the Canadian Meteor Orbit Radar (CMOR) on $8^{th}$ October, 2012. The peak activity level was equivalent to a ZHR max of 9000 $\pm$1000 meteors $h^{-1}$ (the peak flux density of the meteoroids heavier than $10^{-7}$ kg was about 2.4 $\pm$0.3 $km^{-2}h^{-1}$) whereas the ZHR reported by visual observers was just about 200 meteors $h^{-1}$. According to the analysis carried out by the International Meteor Organisation (IMO) the peak ZHR was 324 $\pm$66 meteors $h^{-1}$.

It was not our aim to thoroughly examine the kinetics of interaction between meteoric matter and ozone layer as it will be the subject of our further research. However, the afore-mentioned published papers of other scientists enable to gain a rather comprehensive understanding about how meteoric matter affects the atmospheric ozone concentrations.

## 6. Conclusion

The correlation between the total ozone and activity of major meteor streams, such as the Perseids, Geminids, Leonids and Orionids, has been found using the Total Ozone Mapping Spectrometer (TOMS) measurements of the global ozone distribution over the periods $1978 - 1993$ and $1996 - 2001$. The autocorrelation analysis of the total ozone time series for the period of about 20 years has confirmed the existence of regular changes in the ozone levels at the peaks of meteor shower activity. It has been established that TO decreases after the dates of peak activity of meteor streams (e.g. the Perseids) or during the whole periods of meteor shower activity (e.g. the Geminids, Orionids and Leonids). The analysis of the total ozone distribution (in the Southern and Northern Hemispheres), as well as the local distribution of ozone (over the selected surface area of several hundred square kilometres), was performed during the Leonid meteor shower in 1999. The atmospheric zones for which the ozone distribution pattern can be described as a result of interaction between the meteor shower material and the ozone layer were localised by applying the TOMS data. Such zones correspond to the regions where the highest Leonid activity has been observed. According to the radar observations (conducted in Kazan, Russian Federation), three activity maxima of the 1988 Geminid shower were reported: on the nights of $7^{th}$, $12^{th}$ and $14^{th}$ December, 1988. The TO decrease was observed on the same dates. Thus, the analysis of the TO changes during the periods of intense meteor shower's activity enables to preliminary assess the maximum overall decline in the total ozone concentration which makes about 5 DU over two weeks. From the results obtained it can be inferred that the ozone layer can be used as an indicator of the interaction between the meteoric material and the Earth's atmosphere.

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