# TEMPORAL AND SPATIAL VARIABILITY OF TOTAL OZONE CONTENT IN MOLDOVA: SATELLITE RETRIEVALS AND GROUND OBSERVATIONS

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## Abstract

The total ozone content (TOC) values retrieved from measurements of spectral backscattered radiation with Total Ozone Mapping Spectrometer (TOMS) instruments onboard of Nimbus-7, Meteor-3 and Earth Probe platforms and with Ozone Monitoring Instrument (OMI) onboard of Aura platform are used to evaluate temporal and spatial distribution of statistical means of TOC in Moldova from 1978 to 2008. Longitudinal and latitudinal variations of monthly, seasonally and yearly means of total ozone content across the territory of Moldova are observed. Differences between statistically mean values of TOC retrieved for two pairs of sites situated at the borders both in latitude and longitude directions are used for analysis. Ranges of differences between retrieved TOC for respective pair of sites in the North-South and for pair of sites in the West-East directions amounted to 25 DU and 10 DU (for monthly means of TOC), and to 4.8 DU and 2.2 DU (for yearly means of TOC). Monthly means of total ozone content for all sites reveal distinctive seasonal variation with maximum on the order of 378 DU in spring and minimum of the order of 289 DU in fall. The climatic norm for yearly means of TOC amounts to 335 DU. The trend of TOC over Moldova is -2% per decade.

## 1. Introduction

Ozone in atmosphere represents a natural shield against the harmful solar UV radiation which reaches the Earth's surface and exerts unfavorable influence on the human health, on the other biological life, and ecosystems. Height distribution of the atmospheric ozone and total ozone content on regional and global scales are changing as a result of chemical destroying of ozone molecules due to an increase in the ozone-depleting substances generated from natural processes and growing of anthropogenic activities. Another reason of ozone variability consists in the complex dynamical processes taking place in the atmosphere. These reasons are closely connected with each other through the complex processes, such as heat and mass transfer and chemical reactions in atmosphere. It was well established from numerous ground observations and from satellite platforms retrievals that total column ozone content at the middle latitudes (35°N-60°N) has been decreasing for several decades over 1978-2005 [1, 2]. During these decades of observations, a specific trend with ozone depletion was clearly observed. In the period from pre-1980 to 1997-2001, the total ozone content has depleted on an average by about 3% in the northern middle latitudes (35°N-60°N) [1] and averaged for the period 2002-2005 total ozone was about 3% lower than their 1964-1980 values and similar to their 1998-2001 values [2]. Value of ozone depletion also depends on season of the year. In the Northern Hemisphere ozone depletion amounted to 4% and to 2% in winter-spring and in summer-autumn, respectively [1].

In this paper, we study variation of the total ozone content (TOC) in column of atmosphere or total column ozone derived for the particular sites in Moldova by using linear interpolation of gridded multi-annual datasets from satellite observations. Gridded datasets were retrieved from TOMS measurements onboard of Nimbus-7 (N7), Meteor-3 (M3), and Earth Probe (EP) satellite platforms and from OMI measurements onboard of Aura satellite platform during the period from 1978 to 2008. TOC mean values retrieved from TOMS and OMI measurements are compared with the ground observations carried out with hand-held photometer at the solar radiation monitoring station at the Institute of Applied Physics, Chisinau (Kishinev) from 2004 to 2008. Latitudinal and longitudinal variations of monthly, seasonally, and yearly means of TOC derived by using interpolation of gridded data from satellite observations for particular sites on the territory of Moldova will be presented.

## 2. Measurement approach

Datasets with daily means of TOC retrieved from observations of the Earth's spectral backscattered radiation by using of TOMS instruments onboard of the N7, M3, and EP satellite platforms during the period from 1978 to 2005 and OMI instrument onboard of the Aura satellite platform during a period from 2004 to 2008 were joined together to create long-term time series of TOC. TOMS is a nadir looking instrument that measures albedo and derives total column ozone from the differential albedo in three pairs of spectral bands in the ultraviolet region. The EP TOMS instrument provides instantaneous field of view or the size of the "footprint" of each measurement of 39 km x 39 km at nadir. A more detailed description of TOMS instrument and about it final product can be found elsewhere [3]. The Ozone Monitoring Instrument is a Dutch-Finnish ozone monitoring instrument that is flying on NASA's Aura Mission, part of the Earth Observation System (EOS). Data are obtained from retrieving procedures of satellite images of the Earth with high spectral and highest spatial resolution with small pixel size which is of 13 km x 24 km. More detailed description of the instrument, data processing, calibration and characterization can be found elsewhere [4]. Theoretical basis of the OMI ozone product algorithm for deriving the total column ozone from spectral radiances and irradiances is based on the TOMS ver.8 algorithm applied to OMI data, and it is described in detail elsewhere [4-7]. Total column ozone values at specific sites across the territory of Moldova are derived from linear interpolation of gridded multi-year TOMS and OMI data. Interpolated TOC values to these site's coordinates are used to analyze latitudinal, $\varphi$ and longitudinal, $\lambda_o$ variation of monthly, seasonally, and yearly mean values of TOC on the territory of Moldova.

Ground-based observations of total ozone content in a column of atmosphere are regularly carried out with hand-held narrowband filter photometer MICROTOPS II ozonometer (Solar Light Co) at the solar radiation monitoring station ($\varphi$=47.00°N, $\lambda_o$=28.82°E, h=205 m a.s.l.). The station is situated in an urban environment and installed at the building roof at the Institute of Applied Physics, Chisinau, Moldova. The ground station is in operation since July 2003. TOC values were derived from the ratios of direct solar ultraviolet radiances simultaneously measured at 3 discrete wavelengths 305.5, 312.5, and 320-nm within the UV-B spectral range. Column ozone data are retrieved by using optical differential absorption technique. Detailed description of the instrument and measurement algorithm can be found elsewhere [8]. As a rule, measurements of the total ozone content are carried out during midday hours, when the small values of air mass $m$ are the case. Observations were carried out for air masses $m$ up to values $m$ = 3–3.5 (for AM and PM). MICROTOPS II ozonometer allows for making measurements of the total ozone content with an accuracy of ~2% relative to the Dobson and Brewer spectrophotometers [8-10].

## 3. Data analysis

Regular observations of the total column ozone at the ground station at the Institute of Applied Physics in Chisinau have been started by Atmospheric Research Group (ARG) since

Table 1. List of sites under examination on the territory of Moldova.

| Site | (φ, $\lambda_o$)-coordinates | |
|---|---|---|
| Briceni | 48.35°N | 27.7°E |
| Chisinau | 47.0°N | 28.82°E |
| Vulcanesti | 45.68°N | 28.4°E |
| North border (N) | 48.12°N | 28.82°E |
| South border (S) | 45.95°N | 28.82°E |
| West border (W) | 47.00°N | 28.06°E |
| East border (E) | 47.00°N | 29.61°E |

July 2003 [11]. Respective results of TOC ground observations were processed and compiled into the datasets, and hereafter referred to as ARG data. Multi-year series of TOC values acquired from TOMS measurements at the N7, M3, and EP satellite platforms and OMI measurements at the Aura satellite platform are utilized. TOMS and OMI gridded datasets data are available on-line through the NASA Goddard Space Flight Center archive in ASCII form.

Typical grid resolution (latitude x longitude) of datasets is of 1° x 1.25° - for TOMS data [12] and of 1° x 1° for OMI data [13]. Suitable column ozone values specific to pre-selected sites in Moldova are computed by using linear interpolation of gridded TOMS and OMI data. These datasets are used to assess variability of TOC across the Moldova. Analysis of TOC variability is carried out by taking into account interpolated data for two pairs of sites: situated at the borders in the North–South (N-S) and West-East (W-E) directions. Interpolated values of TOC for intermediate sites (see Table 1) will be also used. For Moldova, the distances between the north and the south borders, and the west and the east borders are ~340 km and ~260 km, respectively. In turn, this corresponds to respective angular spans of δφ ~3° for latitude and $\delta\lambda_o$ ~3.5° for longitude. Statistics of monthly $\langle X\rangle_m$, seasonally $\langle X\rangle_s$, and yearly $\langle X\rangle_Y$ means of TOC are computed by using daily means $\langle X\rangle_d$ as basic values from combined TOMS and OMI time-series and from ARG ground datasets. In spite of the short range distances between borders of Moldova, amounting to a few degrees, daily means $\langle X\rangle_d$ revealed significant variability along (φ, $\lambda_o$)-coordinates. As an example of daily TOC variability, retrieved values of $\langle X\rangle_d$ from the series of satellite observations at specific coordinates for three days are shown in Figs. 1 and 2. There were used observations from TOMS and OMI ozone datasets for set of following days: August 20, 2008 was characterized as clear cloudless day with low column ozone content $\langle X\rangle_d$= 291 DU; December 1, 1999 was characterized as a day with the extremely low value of TOC with $\langle X\rangle_d$=209 DU ever observed in the long-time series and February 17, 2008 was characterized as a clear day with high value of TOC $\langle X\rangle_d$= 426 DU. The step of interpolation of satellite data along each of (φ, $\lambda_o$)-coordinates amounts to 0.5°. It can be clearly seen that there are noticeable contrasts in TOC values retrieved from satellite observations along the latitude and longitude directions. These contrasts must be taken into account, i.e., in modeling of daily UV doses and UV Index at the sites on the territory of Moldova.

In order to study the spatial variability of total column ozone in Moldova, we selected two pairs of sites situated just at the borders in the N-S and, respectively, W-E directions with (φ, $\lambda_o$)-coordinates presented in Table 1. Daily means of TOC $\langle X\rangle_d$ as basic values were retrieved from long-time series of TOMS and OMI observations and then linearly interpolated at coordinates of these particular sites. Adequate monthly, seasonally, and yearly means were computed on the basis of daily means $\langle X\rangle_d$. To make assessments of TOC variability across the territory of Moldova, the equation of difference Δ is introduced. It is defined as a difference between respective daily (d), monthly (m), seasonal (s), and yearly (Y) means of TOC observed at pre-selected pairs of border's sites in the N-S and W-E directions as follows (with adequate indexes): $\langle X(N)\rangle_k$ - $\langle X(S)\rangle_k$ and $\langle X(W)\rangle_k$ - $\langle X(E)\rangle_k$, and these differences are designated as $\Delta_k$(NS) and $\Delta_k$(WE), where index k= {d,m,s,Y}.

The spread of differences $\Delta_d$ between daily means of TOC $\langle X\rangle_d$ observed at respective border's sites in the N-S and W-E directions shows large variability. For OMI observations during a period of 2005-2008, the differences $\Delta_d$ showed variability ranged from – 50 DU to

50 DU for N-S and from -40 DU to 25 DU for the W-E directions. These margins of difference $\Delta_d$ may be considered as rare extreme values because of high nonuniformity of ozone layer occurring along the N-S and W-E directions for some daily TOC observations. The frequency of occurrence of differences $\Delta_d$ between daily means of TOC values retrieved at pairs of sites in these directions is shown in Fig. 3. It can be clearly seen that broad distribution function of differences Δ is most of all specific to the N-S direction**.**

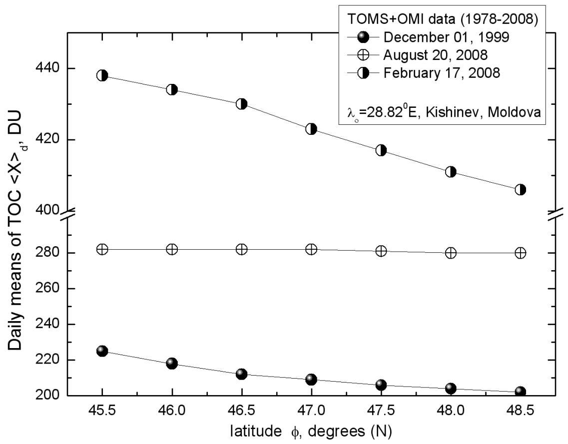


Fig. 1. Latitudinal variation of daily means TOC $\langle X\rangle_d$ retrieved from TOMS and OMI observations for set of days: 20/08/2008, $\langle X\rangle_d$=291 DU (clear day); 01/12/1999, $\langle X\rangle_d$=209 DU (extremely low TOC); 17/02/2008 $\langle X\rangle_d$=426 DU (clear day, high TOC).

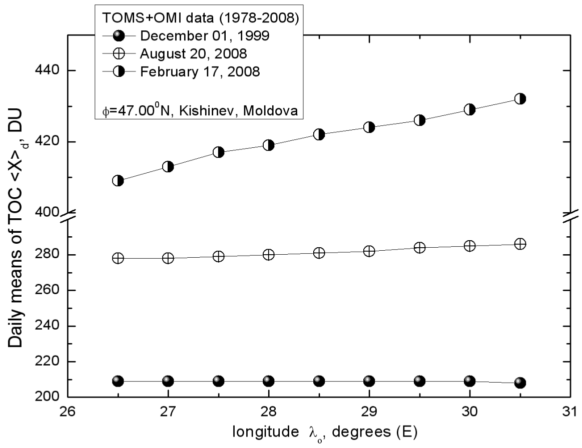


Fig. 2. Longitudinal variation of daily means TOC $\langle X\rangle_d$ retrieved from TOMS and OMI observations for set of days: 20/08/2008, $\langle X\rangle_d$=291 DU (clear day); 01/12/1999, $\langle X\rangle_d$=209 DU (extremely low TOC); 17/02/2008 $\langle X\rangle_d$=426 DU (clear day, high TOC).

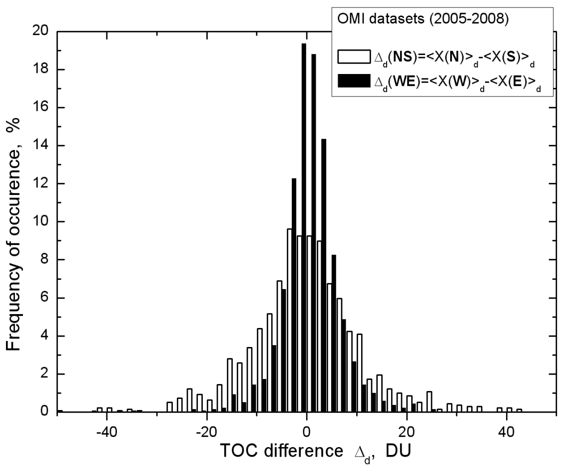


Fig. 3. Frequency of occurrence (in %) of differences $\Delta_d$ (in DU) between daily means of TOC, $\langle X\rangle_d$ retrieved from OMI datasets for each of two pairs of border sites in the N-S and W-E directions (see Table 1). Period of observations: 2005-2008.

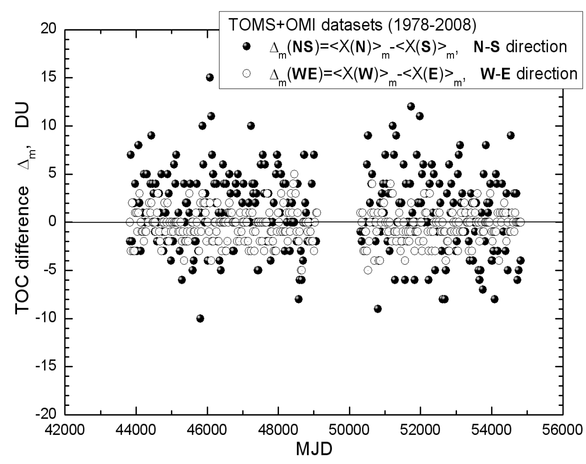


Fig. 4. Latitudinal and longitudinal variability of difference $\Delta_m$ (in DU) between monthly means of TOC, $\langle X\rangle_m$ retrieved from TOMS and OMI datasets for each of two pairs of border sites in the N-S and W-E directions, $\Delta_m$(NS) and $\Delta_m$(WE) (see Table 1). Period of observations: 1978-2008.

Latitudinal and longitudinal variability of difference $\Delta_m$ between monthly means of TOC, $\langle X\rangle_m$ retrieved from combined TOMS and OMI datasets for two pairs of sites in the

N-S and W-E directions is shown in Fig. 4. Data sets were joined together from TOMS observations from 1978 to 2004 and OMI observations from 2005 to 2008 to generate extended series of observations. Differences $\Delta_m$ for these directions are noted as follows: $\Delta_m$(NS) and $\Delta_m$(WE). It can be clearly seen that value of spread of differences $\Delta_m$ in the N-S direction is larger than in the W-E direction for synchronous observations; these values obey the inequality $|\Delta_m(NS)|<15$ DU and $|\Delta_m(WE)|< 5$ DU, respectively. Figure 4 shows that range of variability of monthly means of TOC in the N-S direction prevails over that in the W-E direction.

The seasonal character of latitudinal (in the N-S direction) and longitudinal (in the W-E direction) variability of derived differences $\Delta_{MY}$ between multiyear monthly means of TOC, $<X>_{MY}$ at two pairs of sites is shown in Fig. 5. Values of $<X>_{MY}$ were obtained from multiyear averaging of monthly means of TOC $<X>_{m;}$ $<X>_m$ were derived from combined TOMS and OMI multiyear datasets of daily means of TOC during the period of observations from 1978 to 2008. One can clearly see the presence of seasonal variability of $\Delta_{MY}$, in particular, TOC difference for pairs of border sites in the N-S direction is positive with $\Delta_{MY}(NS) < 3$ DU for January-August period and negative one for September-December period with $\Delta_{MY}(NS) \sim -1$ DU. The difference of TOC for pair of border sites in the W-E direction is positive with $\Delta_{MY}(WE) \sim 1$ DU for June-August; for other months, it is negative with $\Delta_{MY}(WE) > -1.5$ DU.

The variability of multiyear monthly means of TOC $<X>_{MY}$ at the Briceni, Chisinau and Vulcanesti sites situated along the N-S direction is shown in Fig. 6. The ground observations carried out at the ARG station in Chisinau from 2004 to 2008 are also shown in Fig. 6. It is clearly seen that the seasonal variability has a distinct maximum of TOC in March-April with $<X>_{MY}$ ~378 DU and a minimum of TOC in October-November with $<X>_{MY}$ ~289 DU.

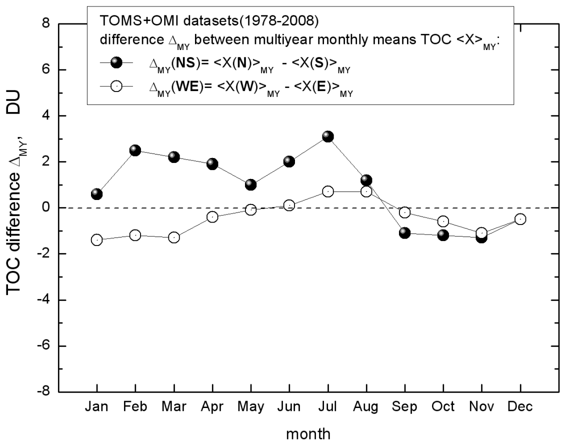


Fig. 5. Latitudinal and longitudinal variability of difference $\Delta_{MY}$ (in DU) between multiyear monthly means of TOC, $<X>_{MY}$ derived from TOMS and OMI multiyear datasets for two pairs of border sites in the N-S and W-E directions. Period of observations: 1978-2008.

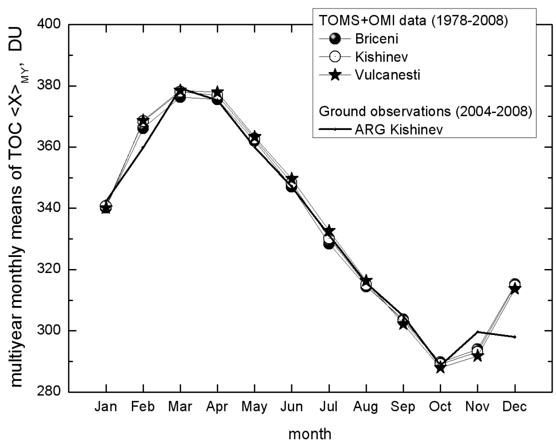


Fig. 6. Variability of multiyear monthly means of TOC $<X>_{MY}$ retrieved from TOMS and OMI datasets at the sites Briceni, Chisinau, and Vulcanesti during the period of observations from 1978 to 2008 and from ground observations at the ARG station in Chisinau from 2004 to 2008.

The variability of zonal monthly means of TOC $<X>_m$ derived from multiyear OMI observations in the northern hemisphere at belt for latitudes from 45°N to 50°N and ARG ground observations in Chisinau are shown in Fig. 7. One can clearly see a fairly good resemblance between belt data from OMI observations and local measurements at ARG ground station. Meanwhile, there is an appreciable discrepancy with value on the order of ~15-30 DU between OMI belt and ARG observations for data regarding the winter season.

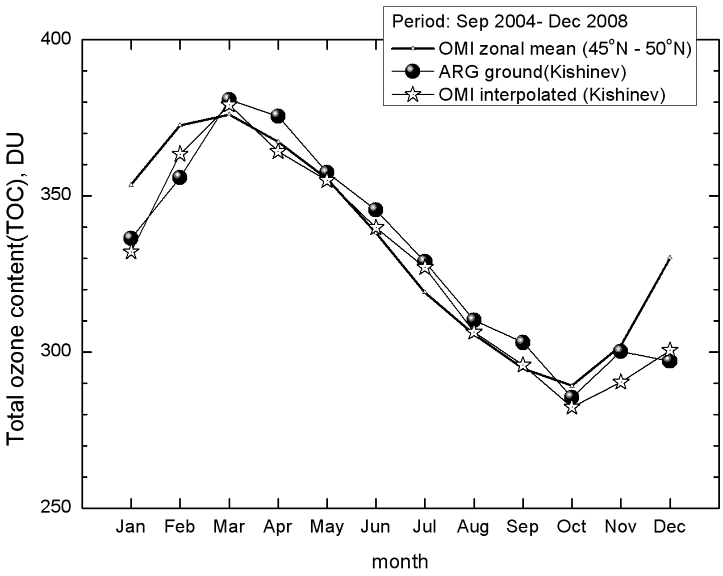


Fig. 7. Variation of zonal monthly means $<X>_m$ derived from multiyear satellite OMI observations in the northern hemisphere at belt of latitudes from 45°N to 50°N and from ground observations at the ARG station in Chisinau during the period from 2004 to 2008.

The multiyear monthly means of TOC retrieved from TOMS and OMI observations (1978-2008) and ground observations ARG (2004-2008) at the Chisinau site are presented in Table 2. One can clearly see a good coincidence of monthly means retrieved from satellite (platforms N7, M3, EP, and Aura) observations with those acquired from direct observations at the ground ARG station. Some discrepancies between monthly mean statistics for satellite observations and ground measurements (see Fig. 6 and Table 2) may be attributed to low representativeness of statistical set of direct ground observations of TOC in the course of some periods, mainly in November and December of 2004, 2006, and 2007. It was due to the presence a large number of days with cloudy or overcast conditions. During these days, direct ground observations of TOC were impossible.

Table 2. Multiyear monthly means of TOC retrieved from TOMS and OMI observations (1978-2008) and direct ground ARG observations (2004-2008) at the Chisinau site.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TOMS+OMI | 341 | 368 | 378 | 377 | 363 | 348 | 330 | 315 | 303 | 289 | 293 | 315 |
| ARG | 342 | 360 | 379 | 375 | 360 | 347 | 331 | 316 | 305 | 289 | 300 | 297 |

To make assessments of variability of seasonal means of TOC, $<X>_s$ respective datasets of daily means TOC were retrieved from combined multiyear series of TOMS and OMI observations during the period from 1978 to 2008 and interpolated at specific sites (Table 1) across the territory of Moldova. Interpolated daily means of TOC for selected sites at the borders were grouped into the seasons as follows: winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November). It was found that the variability of seasonal means $<X>_s$ in latitudinal and longitudinal directions for border's set of sites is small. The differences $\Delta_s$ between seasonally mean values of TOC retrieved from satellite observations at the respective pairs of sites at the borders in the N-S and W-E directions are presented in Table 3. Differences $\Delta_s(NS)$ and $\Delta_s(WE)$ range from -1.2 DU to 2.1 DU and from -1.0 DU to 0.5 DU, respectively. It should be noted that the change in the sign of the difference $\Delta_s$ both to the N-S and W-E directions occurs in summer.

Table 4 presents the seasonally means TOC values averaged over Moldova from TOMS and OMI observations from 1978 to 2008. A distinct seasonal dependence is observed. The fall season exhibits a low mean value of TOC $<X>_s$~295 DU, and the spring season reveals high means of TOC $<X>_s$ ~373 DU.

Table 3. Differences $\Delta_s$ between seasonal means of TOC $<X>_s$ retrieved from combined TOMS and OMI satellite observations at the pairs of sites at borders of Moldova in the N-S and W-E directions from 1978 to 2008.

| season | $\Delta_s$ (NS), in DU | $\Delta_s$(WE), in DU |
|---|---|---|
| winter | 0.9 | -1.0 |
| spring | 1.8 | -0.7 |
| summer | +2.1 | +0.5 |
| fall | -1.2 | -0.6 |

Table 4. Seasonal means of TOC $<X>_s$ retrieved from combined TOMS and OMI observations over the territory of Moldova from 1978 to 2008.

| season | TOC $<X>_s$, in DU |
|---|---|
| winter | 340 |
| spring | 373 |
| summer | 331 |
| fall | 295 |

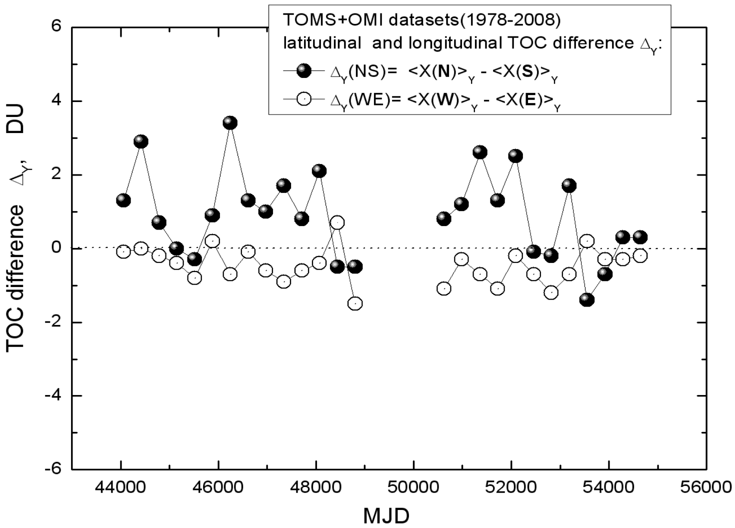


Fig. 8. Latitudinal and longitudinal variability of difference $\Delta_Y$ (in DU) between respective yearly means of TOC $<X>_Y$ derived from TOMS and OMI multiyear observations for two pairs of sites near the borders along the N-S and W-E directions. Period of observations: 1978-2008.

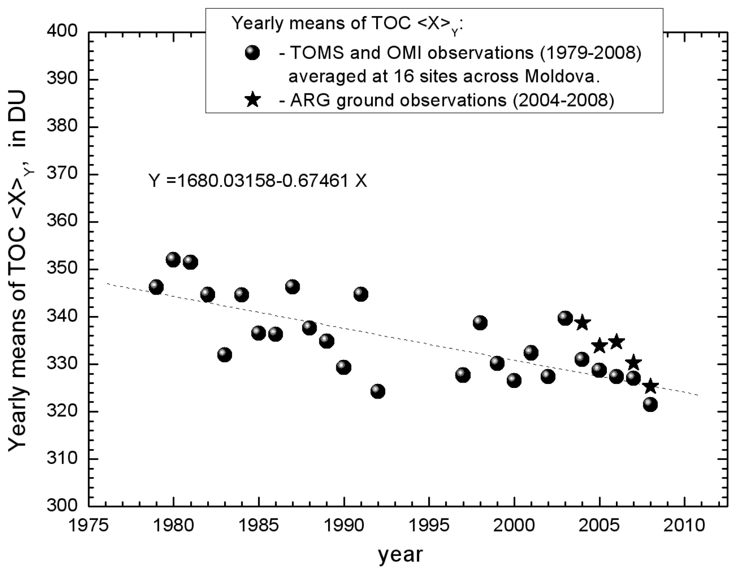


Fig. 9. Time-series of yearly means of TOC averaged at 16 sites across Moldova from TOMS and OMI multiyear observations. Period of observations: from 1979 to 2008.

Time series of latitudinal and longitudinal variability of difference $\Delta_Y$ derived between yearly means of TOC $<X>_Y$ from combined TOMS and OMI multiyear observations for two pairs of sites at borders in the N-S and W-E directions is shown in Fig. 8. The difference $\Delta_Y$(NS) reveals a stronger irregularity with large amplitude in comparison with the $\Delta_Y$(WE) due to the significant non-uniform distribution of TOC in the N-S direction. The total ranges of yearly differences $\Delta_Y$(NS) and $\Delta_Y$(WE) are ~4.8DU and ~2.2 DU, respectively. It can be clearly seen from Fig. 7 that the difference $\Delta_Y$(WE) is negative nearly in all cases in the course of time-series of observations, thereby indicating the predominance of yearly means of TOC in the east region of Moldova. Meanwhile, yearly mean value of TOC $<X>_Y$ observed at the north region of Moldova, in most cases, prevails over the south yearly mean $<X>_Y$ data in the course of time-series. The range of difference $\Delta_Y$(NS) is 2.2 times as large as $\Delta_Y$(WE).

The time-series of yearly means of TOC data retrieved from TOMS and OMI combined observations over the territory of Moldova is shown in Fig. 9. Respective means of TOC were derived from averaging the observations acquired at 16 sites over the territory of Moldova. The results of five years of observations of TOC carried out at ARG ground station are also shown in Fig. 9. The trend of TOC over Moldova was derived relative to the climatic norm, and it was estimated to be -2% per decade. The linear regression equation is shown in Fig. 9. The climatic norm for yearly means of TOC $<X>_Y$ amounts to ~ 335 DU during the period of observations from 1979 to 2008.

## 4. Conclusions

Analysis of longitudinal and latitudinal variations of statistical means of TOC observed at the sites situated at borders across the territory of Moldova was carried out. It was based on using retrievals of daily means of TOC from TOMS and OMI observations during the period from 1978 to 2008. TOC values at specific coordinates of border sites in the N-S and W-E directions were determined by using linear interpolation from parent databases. Statistical means, such as monthly, seasonally and yearly means, were derived directly from interpolated daily means of TOC. Derived TOC values revealed both spatial and temporal variability. Longitudinal and latitudinal variability was found to depend upon the applied statistical means. Differences between statistically mean values of TOC retrieved for pairs of sites situated at the borders both in latitude (N-S) and longitude (W-E) were used for analysis. It was established that the ranges of differences between statistically derived TOC for respective pair of sites in the N-S and for pair of sites in the W-E directions amounted to ~25 DU and ~10 DU (for monthly means of TOC), to ~3.3 DU and 1.5 DU (for seasonally means of TOC), and to ~4.8 DU and ~2.2 DU (for yearly means of TOC). The range of difference $\Delta_Y$(NS) is 2.2 times as large as for $\Delta_Y$(WE). An analogous relation is specific to ratio of differences between the seasonally means $\Delta_s$(NS) and $\Delta_s$(WE).

The monthly means of total ozone content for all sites revealed a distinctive seasonal variation with maximum ~378 DU (in spring) and minimum ~ 289 DU (in fall). The seasonal means of TOC $<X>_s$ retrieved from combined TOMS and OMI observations, averaged over the territory of Moldova, ranged from ~295 DU (in fall) to ~373 DU (in spring) during the period from 1978 to 2008. The climatic norm for yearly means of TOC $<X>_Y$, derived from the averaging of respective values of TOC at 16 sites over the territory of Moldova from 1978 to 2008, amounts to ~335 DU; the trend of TOC over Moldova is -2% per decade.

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