**Comparisons between ground measurements of broadband UV irradiance (300 – 380 nm) and TOMS UV estimates at Moscow for 1979-2000**

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## ABSTRACT

We show the comparisons between ground-based measurements of spectrally integrated (300nm to 380nm) UV irradiance with satellite estimates from the Total Ozone Mapping Spectrometer (TOMS) total ozone and reflectivity data for the whole period of TOMS measurements (1979-2000) over the Meteorological Observatory of Moscow State University (MO MSU), Moscow, Russia. Several aspects of the comparisons are analyzed, including effects of cloudiness, aerosol, and snow cover. Special emphasis is given to the effect of different spatial and temporal averaging of ground-based data when comparing with low-resolution satellite measurements (TOMS footprint area 50-

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200 $km^2$). The comparisons in cloudless scenes with different aerosol loading have revealed TOMS irradiance overestimates from +5% to +20%.
A-posteriori correction of the TOMS data accounting for boundary layer aerosol absorption (single scattering albedo of 0.92) eliminates the bias for cloud-free conditions. The single scattering albedo was independently verified using CIMEL sun and sky-radiance measurements at MO MSU in September 2001. The mean relative difference between TOMS UV estimates and ground UV measurements mainly lies within ±10% for both snow-free and snow period with a tendency to TOMS overestimation in snow-free period especially at overcast conditions when the positive bias reaches 15-17%. The analysis of interannual UV variations shows quite similar behavior for both TOMS and ground measurements (correlation coefficient $r \approx 0.8$). No long-term trend in the annual mean bias was found for both clear-sky and all-sky conditions with snow and without snow. Both TOMS and ground data show positive trend in UV irradiance between 1979 and 2000. The UV trend is attributed to decreases in both cloudiness and aerosol optical thickness during the late 1990's over Moscow region. However, if the analyzed period is extended to include pre-TOMS era (1968-2000 period), no trend in ground UV irradiance is detected.

KEYWORDS

surface UV irradiance, TOMS UV retrievals, aerosol, cloud attenuation, spatial and local surface snow albedo

# 1. INTRODUCTION

Over the last decades, the significant decrease in total ozone content in the Earth's atmosphere has affected the level of UV irradiance observed at the ground. At the same time, variations in other factors (cloudiness, aerosol, surface albedo, etc) may also noticeably change UV irradiance. The satellite UV estimates from NASA Total Ozone Mapping Spectrometer (TOMS) (1978 to present) are a good tool for UV irradiance monitoring and trend detection because of its daily temporal and 100 km spatial resolution, and its well-maintained calibration (1% per decade). Long-term measurements of broadband UV irradiance (spectrally integrated from 300nm to 380nm) at Meteorological Observatory (MO) of Moscow State University (MSU)[1] cover the whole period of TOMS observations (1978-2000)[2-5]. Therefore, we were able to verify interannual changes in UV irradiance obtained from TOMS data. In addition, using ancillary information available at MO MSU, we can evaluate the comparison statistics in different atmospheric conditions and, hence, give recommendations for improvement of the TOMS UV retrieval algorithm.

# 2. DATA AND METHOD DESCRIPTION

## 2.1. Description of TOMS UV algorithm

NASA's Total Ozone Mapping Spectrometer (TOMS) UV algorithm [2-5] first estimates a clear-sky surface irradiance, $F_{clear}$, at solar zenith angles corresponding to the center of the Field of View (FOV) at the overpass time. Next, $F_{clear}$ is corrected by using TOMS estimated cloud and aerosol transmittance factor, $C_T$:

$$F_{cloud} = F_{clear} C_T \tag{1}$$

Calculations of $F_{clear}$ from satellite-derived spectral extraterrestrial solar irradiance (SUSIM ATLAS3 data) and TOMS measurements of total column ozone, and surface albedo are described in detail in [3-5], including estimates of the various error sources. The calculation procedure is based on table lookup for $F_{clear}$ and the use of either a cloud/non-absorbing aerosol correction or absorbing aerosol correction. The type of correction is selected based on the two threshold values of the aerosol index (AI) (calculated from 340nm and 380nm radiances) and the Lambertian Equivalent Reflectivity (LER) (380nm or 360nm). It should be noted that the threshold value of aerosol index AI>1[4] was rarely reached over the MO MSU site. Therefore, $C_T$ was estimated almost exclusively using a conservative plane-parallel cloud model embedded in a Rayleigh atmosphere with an average ozone profile[5]. To estimate the average cloud transmittance at the overpass time, $C_T(t_0)$, TOMS uses the homogeneous C1 cloud model with known regional surface albedo, $A_S$[5]. The model is used first to pre-calculate the angular distribution of the 380nm (360nm in case of Earth Probe TOMS) radiances at the top of the atmosphere (TOA). The algorithm for calculation of effective cloud optical thickness interpolates the TOA radiance cloud lookup table to fit the measured radiance at 360nm or 380nm (after a small Ring correction). The inferred effective $\tau_C$, together with solar zenith angle, estimated surface pressure and regional surface albedo are used as input parameters to derive the spectral $C_T$ factor from the cloud irradiance tables. The cloud optical thickness $\tau_C$ is assumed spectrally independent. The $C_T$ look-up table is pre-calculated using equation (1) at all wavelengths corresponding to $F_{clear}$ for a wide range of cloud optical depths (0-100), surface albedo (0-1) and solar zenith angles (0-88$^{o}$). The cloud height and geometrical thickness is fixed (3.5-5 km). The surface albedo was assumed 0.03 for snow-free days according to the observed minimum *LER* value over Moscow. For snow conditions the value 0.4 was selected as appropriate for snow covered urban/suburban-populated areas containing at least moderate densities of roads, houses, and trees [3,5]. (see also discussion in 2.3.). However, if TOMS measured reflectivity on days with snow, *LER*, is less than 0.4, cloud free conditions are assumed and snow albedo is set equal to *LER* and $C_T$=1. The presence of snow was detected using ground observations.

### 2.2. Description of UV radiometer and ground database used in the comparisons

Broadband ultraviolet (UV) irradiance in the spectral range of 300 - 380 nm is measured by UV radiometers designed at MO MSU[6]. They utilize a selenium barrier-layer photocell with high response in the UVA spectral region. A special 8 mm UV glass filter is used in addition to cut off the irradiance at visible wavelengths. In order to improve the cosine response of the instrument, an integrating sphere is used as a diffuser. The cosine correction factors of the UV radiometers are determined in the laboratory. The MO MSU UV radiometers have cosine correction factor less than 5÷8% at solar elevations (h) higher than 20°. The cosine correction is applied for both direct and diffuse UV irradiance using the technique described by Chubarova and Nezval[1]. Quality control of the recorded UV data is provided nearly everyday by comparisons with measurements of a calibrated primary standard broadband UV radiometer in different atmospheric conditions. The calibration of the primary standard UV radiometer is checked several times per year in warm periods under clear-sky conditions. The calibration procedure is carried out by comparisons between the direct UV irradiance measured by the primary standard UV radiometer installed in a special tube to measure the direct UV irradiance component, and the direct UV spectral irradiance integrated over 300-380 nm. Direct UV spectral irradiance is measured by the the Boyko's Solar Quartz Monochromator which has been designed and calibrated at the Institute of Metrology (St. Petersburg, Russia)[7]. More information about the MO MSU UV radiometer and its calibration is given in previous documents [1,7].

In order to clarify the nature of the discrepancy between ground measurements and TOMS UV estimates we use additional meteorological and radiative information available at MO MSU site. Table represents the ground-based data that were used in the comparisons with satellite UV retrievals.

**2.3. Spatial and local snow UV albedo at the MO_MSU.**

Snow albedo is one of the key parameter in TOMS UV algorithm [5]. Therefore, we paid special attention to the evaluation of snow albedo at the MO MSU site. Speaking about surface albedo, we should distinguish local surface albedo, which is measured directly by forming the ratio of upward and downward irradiances at a given point describing a particular underlying surface. It should be noted that mean local snow UV albedo measured directly at the MO MSU site is about 0.73 and may change within 0.54-0.77 depending on the quality and age of snow[10]. This value can significantly differ from the

Table. The characteristics of the ground-based measurements

| Type of measurements | Time resolution | Comments |
|---|---|---|
| ***Direct parameters for comparisons:*** | | |
| Global and diffuse UV irradiance spectrally integrated from 300nm to 380nm | 1 min resolution. | |
| ***Indirect parameters:*** | | |
| Total and low level cloud amount at MO MSU | Once per hour | Visual observations |
| Global shortwave irradiance ($\lambda$<4.5$\mu$m) | | For retrieval of cloud optical thickness in cloudy overcast conditions from the ground[8] |
| Direct shortwave irradiance | 1 min resolution | These two parameters are used to retrieve aerosol optical thickness at 550nm[9] |
| Water vapor content | Typically once per 3 hours | |
| Snow coverage and snow depth | Once per day | For detection of snow or snow-free conditions |

Lambertian equivalent spatial snow albedo $<A_S>$, which is responsible for downward global irradiance enhancement due to reflection over larger surrounding area (including trees, buildings, roads, not necessarily covered by snow). Using equation (2) we can indirectly estimate the $<A_S>$ value from ground UV irradiance measurements in clear sky conditions:

$$Q=Q\ (A_s=0)/(1-<A_s>\ <S_b>), \qquad (2)$$

where $Q$ is broadband UV irradiance measured from the ground. We use different symbols for the surface irradiance measured from the ground to clearly distinguish from the TOMS estimate of the same quantity (equation (1)). The $\langle S_b \rangle$ is the diffuse reflectance of the atmosphere illuminated from below by Lambertian source [3,4,11] integrated over 300 nm-380 nm spectral interval. $\langle S_b \rangle$ is estimated from radiation transfer calculations to range between 0.3-0.35 in cloud-free conditions depending on aerosol properties. Applying equation (2) to cloud-free days with and without snow one could estimate the spatial snow albedo, $\langle A_S \rangle$, from the following equation:

$$< A_S(snow) >= \frac{X - 1 + A_S(no\_snow)S_b}{XS_b} \qquad (3)$$

where $X = Q(snow)/Q(no\_snow)$ is surface irradiance enhancement due to snow measured from the ground on cloud-free days at the same solar elevation and aerosol optical thickness.

According to this method the mean $\langle A_s(snow) \rangle$ is only 0.38±0.05 at 95% confidence level for Moscow conditions with snow depth higher 15cm. Such a large difference between local snow albedo and $\langle A_s(snow) \rangle$ is due to effects of surface heterogeneity (i.e. trees, buildings, etc) in Moscow.

Fig. 1 shows the frequency distribution of the TOMS measured reflectivity on clear days with snow, which is representative of the Lambert equivalent regional snow albedo over Moscow. Both cloud and snow screening was according to visual observations at MO MSU. Only days with snow depth larger than 15 cm were selected for comparisons. The existence of the maximum around 0.4 allow us to consider the treatment of snow albedo of 0.4 in TOMS UV algorithm for Moscow winter conditions to be quite close to the real values of spatial snow albedo over this area.

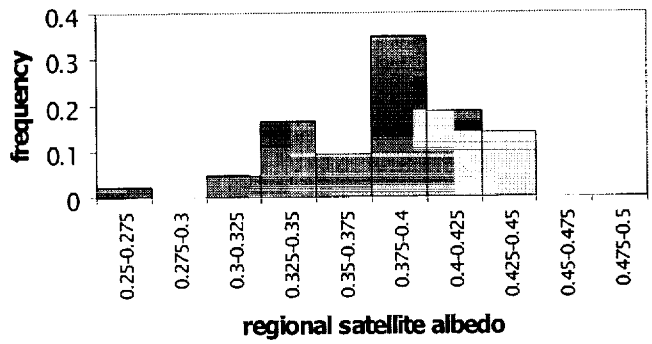


Fig. 1. Frequency distribution of regional satellite albedo observed in clear sky days according to ground measurements at MO MSU in snow conditions. 1979-2000.

## 3. RESULTS

### 3.1. Difference between satellite and ground measurements due to variation in temporal averaging of ground-based data.

The difference between satellite and ground UV data (S_G UV difference) can be simply due to the differences in corresponding fields of view (FOV) of satellite and ground instrument. The two are equal only in the idealized case of horizontally homogeneous atmosphere and the surface. In a real situation, even the mean atmospheric conditions could be quite different within a satellite FOV and the much smaller field of view of a ground-based instrument. In order to resolve this problem, it is necessary to apply a time averaging procedure to the ground-based data. For example, for broken cloud conditions a ground instrument should average both the measurements in and outside cloud shadows to provide a meaningful estimate of the spatially average irradiance. It is also intuitively clear that time averaging should be proportional to the size of the satellite FOV: the larger the FOV, the longer the time averaging.

To quantify the best time-averaging interval for ground-based UV measurements we analyze the data with one-minute resolution taken with different time averaging around the moment of the TOMS overpass over MO MSU site. Figure 2 shows a nonlinear dependence of correlation coefficient (r) between TOMS UV retrievals and ground UV measurements on the time averaging between ±1 min and ±90 min. The correlation coefficient monotonically increases up to 0.85 for 2-hour time interval (±60 min), but remains nearly constant for larger time intervals.

This means that the temporal averaging of at least 2 hours is needed to sample the cloud field within average TOMS field of view (~100km). Close, but slightly larger optimal time-averaging intervals were obtained in TOMS UV data comparisons with Brewer measurements taken with 15 minute resolution [5]. In our further analysis we will use 3 hour ground UV irradiance averages (i.e. ±90 minutes of TOMS overpass the MO_MSU).

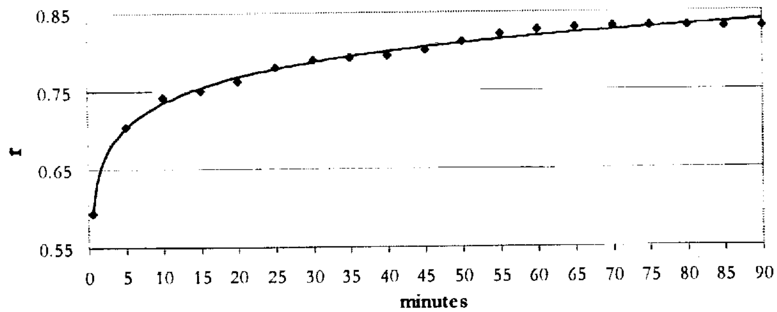


Fig. 2. The dependence of correlation coefficients between TOMS UV retrievals and ground UV measurements taken with different period of averaging (± N minutes around the moment of the TOMS overpass over MO MSU site).

**3.2. Difference between satellite and ground measurements due to variation in spatial averaging of ground-based data.**

Another question, which arises in the process of S_G UV comparisons, is the effect of the size of the satellite field of view (FOV), and the threshold in distance between the exact coordinates of the ground-based measurements and the center of the TOMS FOV. Our analysis shows no systematic effect of the S_G UV difference with the size of the FOV. During our analysis the threshold in distance between the coordinates of MO MSU and the center of TOMS FOV was taken to be 40 km. So we assume that the difference between satellite and ground-based measurements may negligibly increase towards the edges of the analyzed 40 km spot. Figure 3a represents the spatial distribution of mean absolute difference between TOMS UV retrievals and ground UV measurements as a function of distance between exact coordinates of MO_MSU and the center of TOMS FOV. In addition to several random high points at the edges of the analyzed area we can see the systematically higher uncertainties at its northwestern part. This part of Moscow region is also characterized by relatively high surface elevations (Fig. 3b) of 250 m. These small hills at the northwestern part of the area may be the natural barrier leading to the changes in the intensity of atmospheric cyclones (and, hence, cloudiness) over this region and, as a result, to the increase of the S_G UV difference.

### 3.3. Comparisons between satellite and ground-based UV measurements in different atmospheric conditions.

In order to validate the treatment of aerosols, cloudiness, and snow albedo in the TOMS UV algorithm, we considered separately cloud-free and cloudy conditions with and without snow. Snow-free periods were determined as periods when satellite flags as well as snow height and spatial cover of snow were equal to zero. Snow days were selected according to ground observations. We also excluded cases when snow height was less than 15 cm and when the spatial cover of snow was not contiguous. To determine the cloudless conditions we use hourly visual observation of cloud amount, which should be zero at the time closest to TOMS overpass as well as at next and at previous hour.

#### 3.3.1. Comparisons in the cloudless atmosphere.

**Snow-free conditions.**

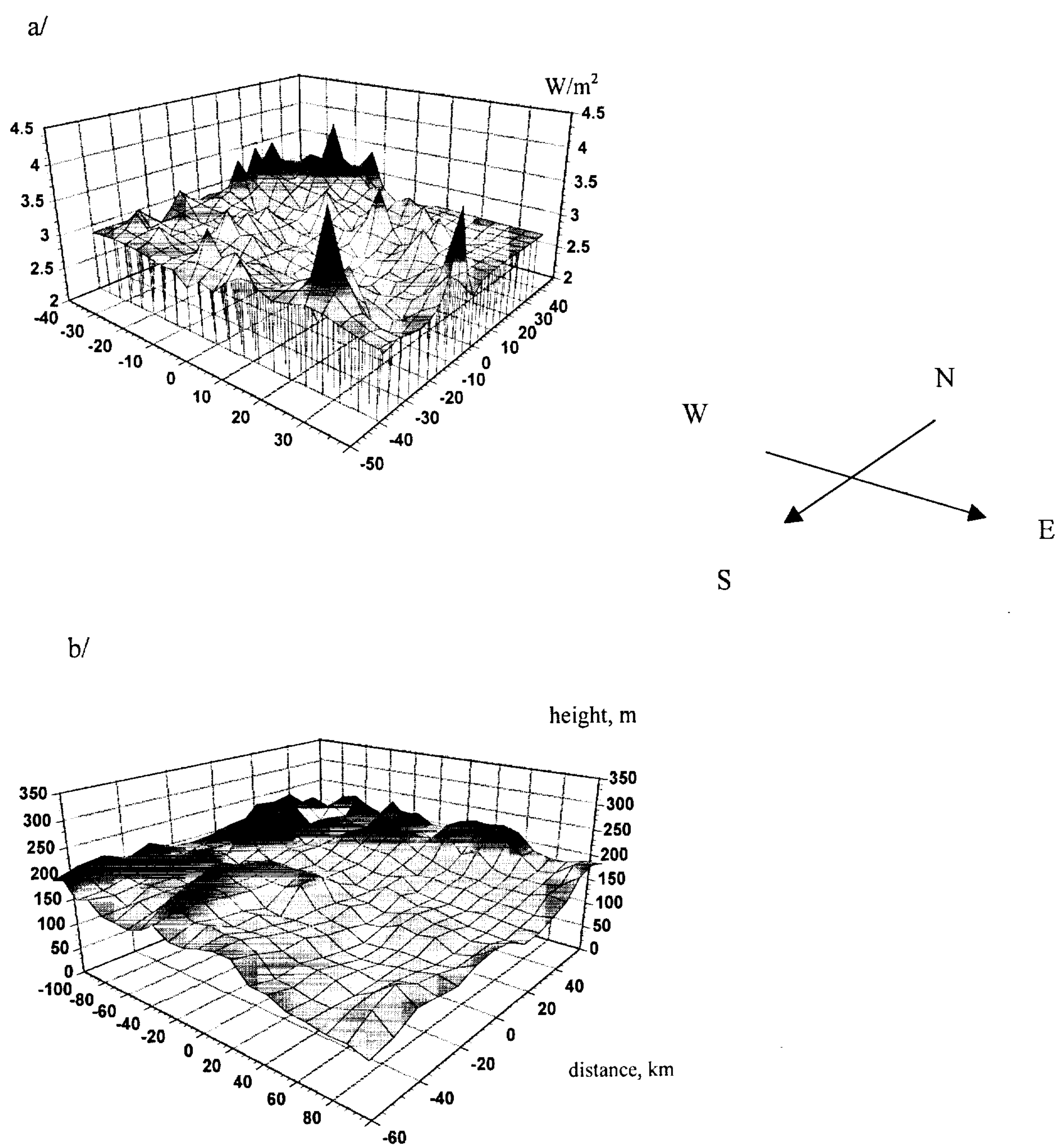


Fig. 3. Spatial distribution of mean absolute difference between TOMS UV estimates and ground UV measurements due to the different distances of TOMS FOV center against MO MSU site (0,0 km) (a);

b/ grid distribution of the mean surface elevations over Moscow region.

Fig.4 shows the dependence of relative S_G UV difference on solar elevation in cloudless atmosphere during snow-free period for the whole period of observations since 1979. The error bars show 95% confidence level of the mean S_G UV difference for each solar elevation bin (±2.5°) .The figure shows ~10% positive bias (overestimation of TOMS UV retrievals) with no dependence on solar elevation. The bias is explained below.

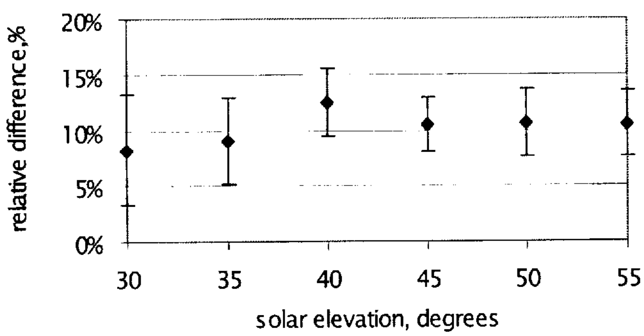


Fig. 4. Relative difference in TOMS UV estimates against ground UV measurements ($UV_{TOMS}/UV_{MO\_MSU}-1$) as a function of solar elevation with 95% error bar, %. Snow-free period, 1979-2000.

The standard TOMS UV algorithm utilizes the assumption of non-absorbing cloud layer embedded into the Rayleigh atmosphere (see section 2.2.1). In urban areas boundary layer aerosol could absorb UV radiation due to possible contamination by soot and other pollutant substances. The urban absorbing aerosols could have single scattering albedo (SSA) substantially less than unity [12]. According to aerosol measurements by CIMEL at MO_MSU site over clear sky conditions in September 2001 the average SSA value obtained from standard AERONET inversion algorithm[13] was 0.86 with the uncertainty of 0.05 at 440 nm. The comparisons between RT calculations and radiative measurements at MO_MSU[14] show the best agreement with application of continental aerosol model, which is characterized by SSA=0.9 in UV and visible spectral region.

Fig.5 shows the bias of standard TOMS UV estimates as a function of aerosol optical thickness. Also shown are expected biases accounting for aerosol absorption[4]. The two conversion factors $k_d$=0.25 and $k_d$=0.4, correspond to the possible range of single scattering albedo at MO MSU accounting for retrieval uncertainties (SSA=0.92 and SSA=0.82) in the UV spectral region. With increasing of aerosol optical thickness the difference between standard TOMS UV estimates and ground based UV measurements also increases. Underestimating aerosol absorption (larger SSA) causes positive bias while overestimating aerosol absorption would result in negative bias (TOMS UV retrievals being lower). Thus, accounting for the typical aerosol absorption eliminates the bias and its dependence on aerosol optical thickness. On the other hand, overestimation of aerosol absorption results in over correction even if aerosol optical thickness is known precisely. Therefore, both aerosol optical thickness and single scattering albedo should be known to correct the

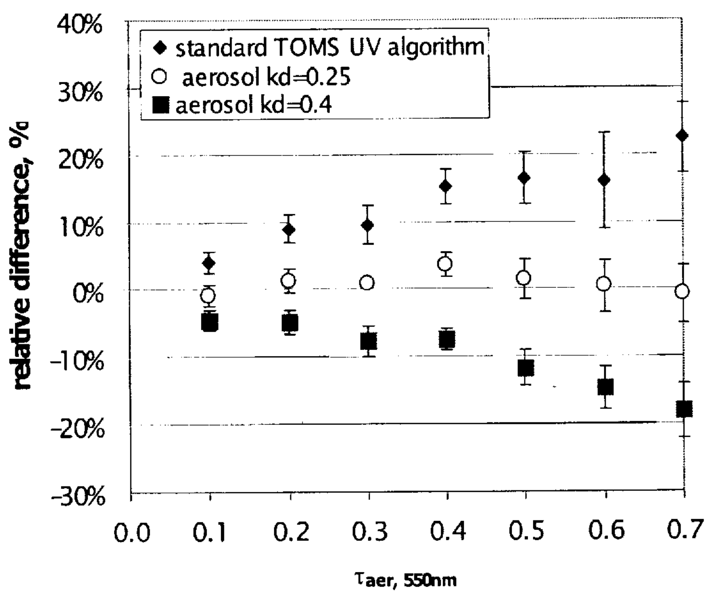


Fig. 5. The dependence of S_G UV relative difference ($UV_{TOMS}/UV_{MO\_MSU}-1$) within 95% confidence interval versus aerosol optical thickness at 550nm in clear sky conditions. Snow-free period, 1979-2000.

TOMS UV estimates over urban areas. For example, S_G UV difference over different geographical regions mentioned in [15] could be partly explained by various aerosol loading and absorbing properties of aerosol in these regions. We note that high altitude (>1km) plumes of absorbing aerosols (mostly smoke and dust) could be detected directly in TOMS Aerosol index data [16,17] and first order correction is applied to the TOMS UV product [3,4]. However, the TOMS AI method becomes less sensitive to boundary layer aerosols often observed in urban areas. Therefore aerosols are best accounted for by ground based measurements as shown in Figure 5.

**Snow conditions.**

In snow-covered conditions there are two factors that may play a vital role in producing the discrepancy: the non-accounting for absorbing aerosol properties in snow-free conditions and the use of incorrect value of snow albedo. Although the aerosol bias is always positive (TOMS overestimates UV irradiance more or less depending on the aerosol single scattering albedo), the snow albedo bias could be either positive or negative. The standard TOMS algorithm uses the $Rs$=0.4 for winter conditions and attributes the difference in measured *LER* and $Rs$=0.4 to the cloud attenuation. This algorithm underestimates surface UV irradiance (negative bias) if actual spatial albedo is larger than 0.4 and overestimates if opposite is true. Since the aerosol and snow biases may have different signs they may partly cancel each other.

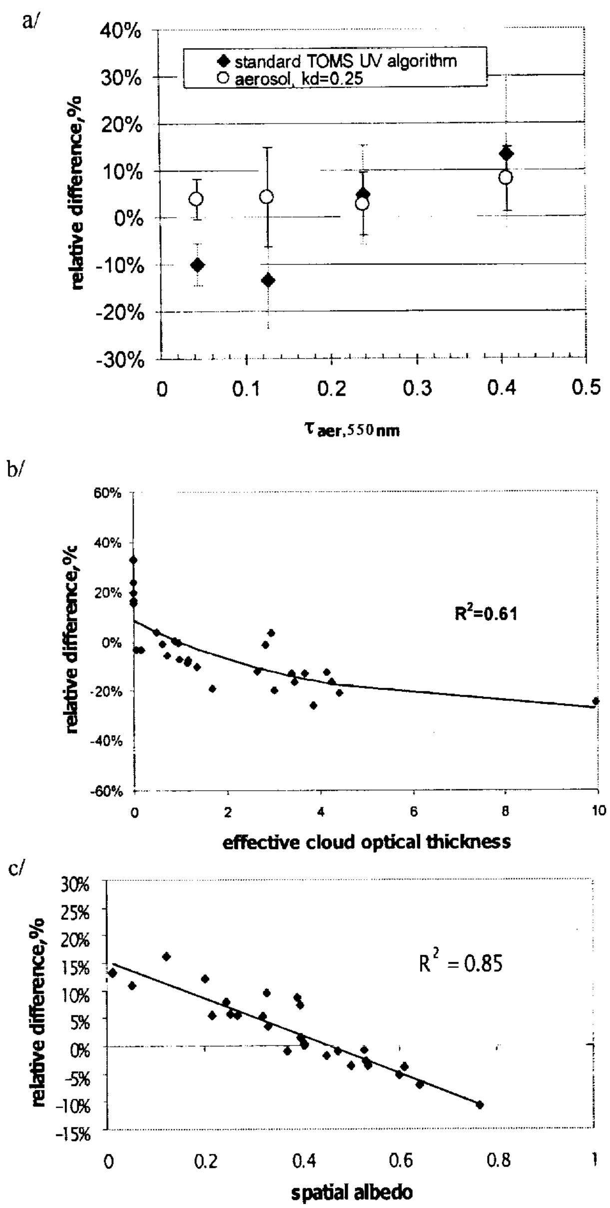


Figure 6a shows the TOMS bias as a function of aerosol optical thickness for snow conditions. Use of the standard TOMS UV algorithm leads to distinct underestimation of UV fluxes in cases of small aerosol optical thickness and overestimation of 13% at high $\tau_{aer,550}$. If we look at the changes of relative S_G UV difference with the effective $\tau_{cl}$ calculated from the difference in measured *LER* and *Rs*=0.4 ( Fig.6b), we can notice that underestimated TOMS UV irradiance (negative relative difference) corresponds to the significant $\tau_{cl}$ values, which in fact should be zero. This illustrates the snow

Fig. 6.a/ S_G relative UV difference within 95% confidence interval versus aerosol optical thickness in clear sky conditions for standard TOMS algorithm (diamonds) and for UV calculations with accounting for the absorbing aerosol and removing the effective cloud optical thickness (circles). Snow period, 1979-2000

b/ Relative UV difference as a function of effective cloud optical thickness retrieved as a difference between *TOMS LER* and given snow reflectivity *Rs*=0.4 for standard TOMS UV algorithm.

c/ Relative UV difference as a function of spatial albedo determined from ground measurements after removing the effects of effective cloud optical thickness and accounting for the absorbing aerosol.

bias, which is observed due to neglecting real $Rs$ and attributing the residual difference in measured $LER$ and $Rs$=0.4 to the effective $\tau_{cl}$. After excluding the effective cloud optical thickness and accounting for absorbing aerosol the S_G difference becomes much smaller as does the deviation within the each bin (see Fig.6a, circles). Fig 6c shows the S_G relative UV difference after accounting for absorbing aerosol and effective cloud optical thickness as a function of snow spatial albedo. Snow spatial albedo was calculated from ground-based data according the algorithm proposed in section 2.3. We clearly see the distinct dependence of the residual relative UV difference with 10-15% TOMS overestimation at the values of low snow albedo and underestimation of 10% in conditions of high snow spatial albedo observed in Moscow.

### 3.3.2. Comparisons in cloudy atmosphere.

Figure 7 shows the bias between TOMS UV estimates and UV ground measurements in all-sky snow-free conditions as a function of ground observation of low-level cloud amount (a) and *TOMS LER* (b). Figure 8 shows the same bias in snow conditions. We chose low level cloud amount as a parameter because of its stronger effect on ground UV irradiance as compared to total cloud amount. In order to remove solar zenith angle effect in each bin, (even small ones, about ±3°) we adjusted the absolute UV values in each cloud bin to SZA=40° and SZA=73° using the power law dependence respectively for snow-free and snow situations. Due to significant positive asymmetry ($S$) in distribution of S G relative UV difference ($S$=2.7 in snow-free and $S$=5.8 in snow conditions), both mean and median characteristics are shown for each cloud amount (or reflectivity) bin.

**Snow-free all-sky conditions.**

For snow-free conditions median values of S_G UV relative bias are within –5-+6% for various low level cloud amount (*Nl*) except overcast cloud conditions (*Nl*=10) (see Fig.7). There is a small but pronounced decrease of S_G relative difference with increasing of cloud amount up to *Nl*=9 or *LER* values less 0.7 (Fig.7b). For *LER* higher than 0.87 (or overcast cloud conditions, *Nl*=10) the bias sharply increases and reaches 15-17%. The same effect was shown in comparisons with Brewer measurements [18]. The high positive bias at overcast cloud conditions could be explained by the differences in the sizes of FOV for TOMS and much smaller FOV for ground observations. Large thunderstorm clouds tend to produce lowest levels of surface irradiance and highest satellite reflectance. At the Moscow latitude (55.7 N) the average size of the thunderstorm systems is typically ~20km that does not cover the whole TOMS FOV (~100 km on average). Because of this TOMS measured reflectivity is lower than it would be if the cloud would cover the whole TOMS FOV. As a result, the cloud transmittance ($C_T$) is overestimated. Cloud shadows also tend to produce lower reflectivity (and higher satellite estimate of cloud transmittance) compare to the flat plane parallel cloud model. Also the vertical extent of the thunderstorm clouds (up to about 10 km) is much larger than assumed in the TOMS cloud correction algorithm (plane-parallel cloud from 3km to 5.5km) and underestimating cloud vertical extension could also result in overestimation of cloud transmittance. We plan to carefully investigate the reason for enhanced bias in overcast conditions in a separate paper.

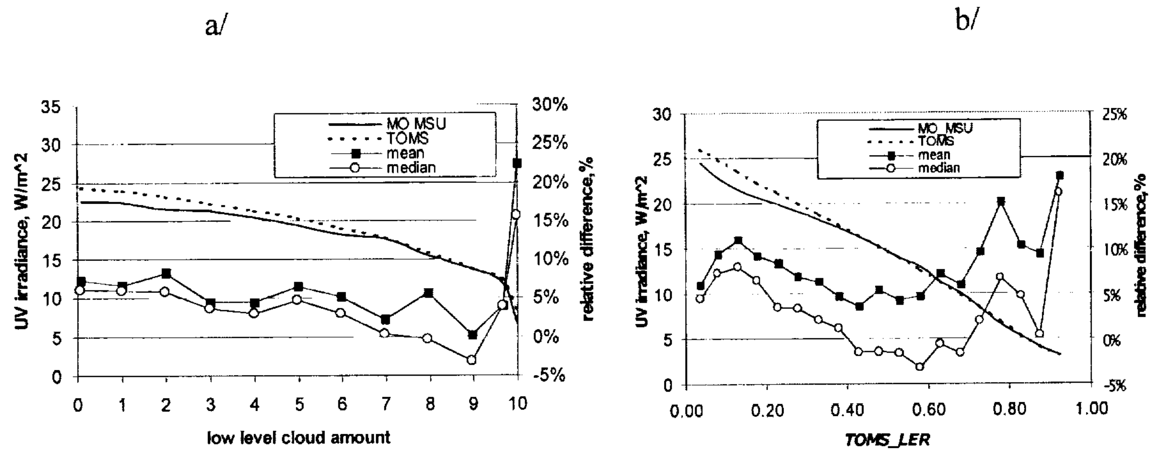


Fig. 7. The dependence of mean UV irradiances estimated from TOMS data and measured at MO MSU (left axis) as well as relative difference between TOMS and ground based UV measurements (right axis) as a function of low level cloud amount (a) and *TOMS LER*(b). Absolute UV irradiance is normalized to SZA=50°. Snow-free conditions.

It should be also noted that in standard TOMS UV algorithm embedding of cloud layer is not accompanied by accounting for boundary layer absorbing aerosol. For Moscow summer conditions typical aerosol optical thickness at 550nm is about 0.3 [19]. According to the results obtained for clear sky conditions this quantity of absorbing aerosol can be responsible for the 8-12% overestimation of ground UV fluxes (see Fig. 5). Therefore the overestimation in TOMS UV calculations in cloudy atmosphere may be partially attributed to not accounting for absorbing aerosol properties in TOMS standard UV algorithm.

From the practical point of view it should be emphasized that biological significance of UV irradiance in overcast conditions is negligible and even 20% of relative difference will be translated into small absolute difference (see calculated and measured absolute UV irradiance at *Nl*=10 or *LER* higher 0.8 in Fig. 7).

**Snow all-sky conditions**

During a snow period, the relative difference between ground-based UV measurements and TOMS UV retrievals changes within ±10% for the whole range of *Nl* and of *LER* (Figure 8). Generally, the winter bias is smaller than summertime bias (see Figure 7). We explain these results by much smaller aerosol optical thickness observed in winter ($\tau_{aer,550nm}$ =0.1 compared with $\tau_{aer,550nm}$ =0.3 for summer [19]) as well as the possible underestimation of snow albedo in cloudy conditions which are often accompanied by snow precipitation leading to the increase of spatial albedo from the mean value ($\langle As \rangle$=0.4). There is similar tendency of slight increasing of S_G UV relative differences in overcast cloud conditions (or *LER* higher 0.9) that is smaller than those in snow-free situations.

To summarize, even without taking into account for boundary layer absorbing aerosol properties the relative difference between TOMS UV estimates and ground UV measurements mainly lies within ±10% for both snow-free and snow period except overcast conditions in snow-free period when the discrepancy reaches 15-17%. But, as it was emphasized, the absolute UV difference in this case is very small.

a/ b/

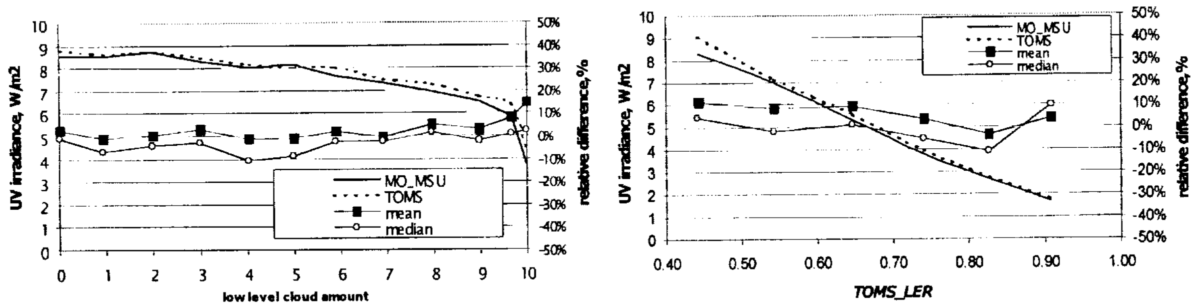


Fig. 8. The dependence of mean UV irradiance estimated from TOMS data and measured at MO MSU (left axis) as well as relative errors of TOMS UV estimates (right axis) as a function of low level cloud amount (a) and *TOMS_LER*(b). Absolute UV irradiance is normalized to SZA=73°. Snow conditions.

### 3.3.3. Interannual changes in relative bias between TOMS UV estimates and ground UV measurements.

We calculated interannual variations of the mean relative TOMS bias in clear sky conditions for standard UV algorithm as well as accounting for the absorbing properties of aerosol. The results are shown in Figure 9 along with the relative changes in the yearly average aerosol optical thickness over the same period in snow-free conditions. When the standard TOMS UV algorithm was applied one can see high variability of the bias. The bias is within 5% for years 1985,1987,1989, 1993,1997 and 2000, while is more than 15% for years 1981,1984, and 1996. The average bias is about 8% with standard deviation $\sigma$=5.2%. After accounting for absorbing aerosol properties as discussed above (see section 3.3.1) the average bias is close to zero with standard deviation ~3%.

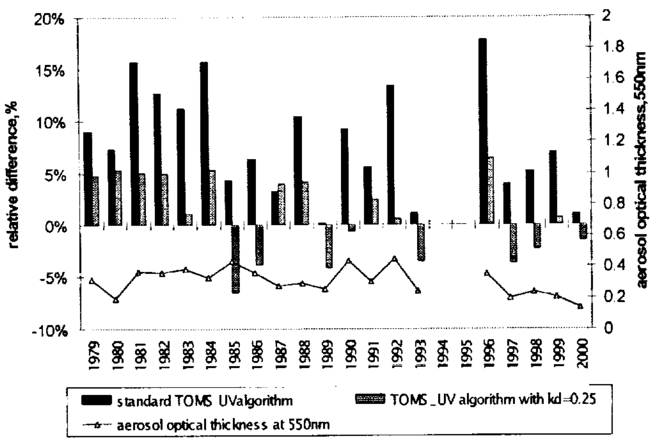


Fig. 9. Interannual variations of the mean S_G UV relative difference over MO_MSU and changes in aerosol optical thickness. Clear sky conditions. Snow-free period.

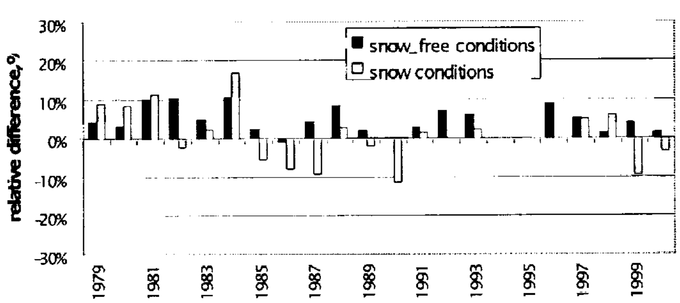


Fig. 10. Interannual S_G UV relative difference (median values) in all-sky snow and snow-free conditions over Moscow.

Figure 10 shows the median values of yearly average S_G UV difference in all-sky conditions (without absorbing aerosol correction). For snow-free period the median S_G UV relative difference lies within –1%÷+11% with mean value of 4.7% ± 1.5% at 95% confidence level. For snow periods the variability of the bias is higher, varying from –11% up to +16% with the mean value of 0.7%±3.5%. The larger interannual variability for snow conditions are explained by additional variability in snow albedo as well as by larger uncertainty of ground UV measurements at small solar elevations.

There is no statistically significant trend in the bias between TOMS UV estimates and UV ground measurements for both clear sky and all-sky conditions, but the accounting for boundary layer absorbing aerosol may significantly decrease the average bias and its interannual variability.

Therefore, as far as long-term UV trend and interannual UV variability TOMS UV estimates provide consistent results with direct ground-based UV measurements.

### 3.3.4. Interannual variation of UV irradiance according to ground-based UV measurements and TOMS UV retrievals.

The interannual variation of UV irradiance and its possible upward trend due to ozone depletion and observed climate change are the important environmental problem. The Nimbus-7 TOMS period of the TOMS measurements (1978-1992) has been used to examine the global erythemal UV trends [20,21]. At the same time the long-term ground UV measurements could validate TOMS derived UV trend at specific locations. At the same time, ancillary information available from the ground observations is valuable in determining the geophysical causes of the interannual variability and long-term trend in the satellite data.

Figure 11 shows the interannual variation of global broadband UV irradiance (300 nm to380 nm) for the whole period of observation in Moscow since 1968. Also shown are the interannual variations in ground and TOMS UV data for TOMS observation period 1979-

2000. There is no trend in broadband UV irradiance for the 1968-2000 period as discussed in details in Chubarova and Nezval [1].

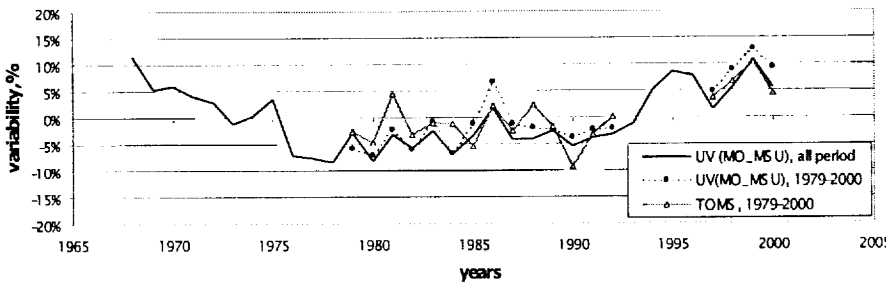


Fig. 11. Variability of global UV irradiance 300 to 380 nm since 1968, TOMS UV retrievals and ground UV irradiance 300 to 380 nm at TOMS overpass time since 1979.

However, for the TOMS observational period (1979-2000) we can observe the statistically significant upward trend both in ground and satellite UV data. There is a high correlation of $r$=0.79 between interannual changes of ground UV measurements and TOMS UV retrievals. The interannual relative changes in UV irradiance mainly reflect the UV changes observed in warm period with high solar elevations. The correlation coefficient between UV irradiance during all-year and snow-free periods is high: $r$=0.94. For snow-free period the absence of high surface albedo, which is the most variable and complicated parameter, allows us to evaluate the cause of the obtained upward trend. Figure 12 shows the interannual changes in aerosol and cloud characteristics over snow-free (May-September) period using ground-based (aerosol and cloud optical thickness retrievals, low level cloud amount) as well as TOMS Reflectivity data. The TOMS Reflectivity itself is a function of several parameters (cloud amount, cloud and aerosol optical thickness, aerosol absorbing properties, surface albedo) but the main parameter that regulating TOMS *LER* in snow-free conditions is low level cloud amount that was discussed in previous paper [22]. According to Moscow data there is a high correlation $r$=0.77 between these two characteristics. Figure 12 also shows the decrease in low-level cloud amount and aerosol optical thickness as well as in TOMS *LER* characteristic in the last years over Moscow. Similar changes were obtained over the whole of central Europe, western Russia and several other regions [23]. In some years accounting for changes in cloud optical thickness may play a vital role as an additional parameter to low layer cloud amount (*Nl*) to explain TOMS *LER* variability (see, for example, 1983 and 1997 years).

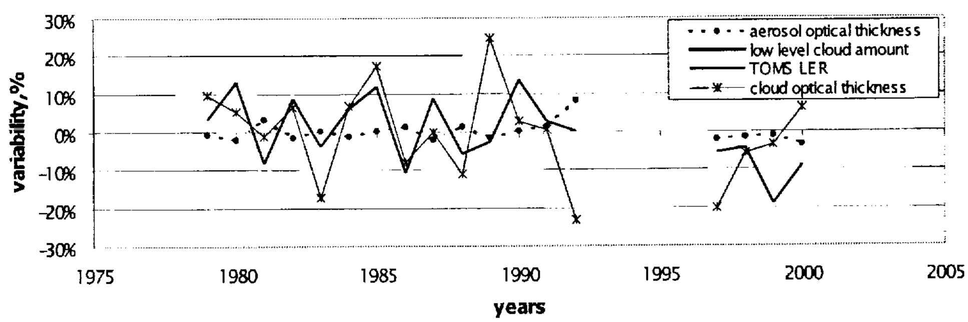


Fig. 12. Relative changes of cloud and aerosol characteristics over 1979-2000 period according to satellite and ground-based data. May-September period.

To summarize, the 5-10% increase in UV irradiance observed in 1999-2000 both from TOMS and ground UV measurements is explained by variations of cloudiness and aerosol. The similar 5-10% UV increase was observed at the end of 1960 s in the Moscow area and was attributed mainly to the significant drop in low-level cloud amount [1].

## 4. CONCLUSIONS

- We have shown that a time averaging procedure of at least 2 hours is necessary in comparisons of ground-based UV data with TOMS spatially averaged UV data (~100km).
- The spatial distribution of the TOMS bias is not homogeneous around MO_MSU site. Even small variations in surface relief responsible for microclimate peculiarities, could account for significant differences in local UV climatology around Moscow. The spatial variations in local UV climatology should be thoroughly characterized for each ground UV station before making comparisons with low-resolution satellite UV data (TOMS, GOME). Especially important are those studies for the world best UV monitoring stations located in mountain regions. The spatial heterogeneity could be studied by using spatially distributed UV instruments or high-resolution long-term satellite data around each ground site (AVHRR).
- The analysis of differences between standard TOMS algorithm UV retrievals and UV measurements at MO MSU shows an overestimation of TOMS UV retrievals on 5-20% depending on atmospheric conditions in cloudless atmosphere. It was shown that accounting for observed absorbing aerosol properties, verified independently using CIMEL sun and sky-radiance measurements at MO_MSU, significantly improves the agreement in clear sky conditions and eliminates the dependence on aerosol optical thickness.
- The mean relative difference between TOMS UV estimates and ground UV measurements mainly lies within ±10% for both snow-free and snow period with a

tendency to TOMS overestimation in snow-free period especially at overcast conditions when the positive bias reaches 15-17%.

- Examination of the bias between TOMS UV estimates and ground UV measurements did not reveal a long-term trend both for clear-sky and all-sky conditions with snow and without snow.
- Both satellite and ground UV measurements show positive trend in UV irradiance between 1979 and 2000 over Moscow. The UV trend is explained by decrease in both cloudiness and aerosol optical thickness during late 90 over Moscow region. However, if the analyzed period is extended to include pre-TOMS era (1968-2000 period), no trend in ground UV irradiance is detected.

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*Table and Figures Captions:*

Table. The characteristics of the ground-based measurements

Fig. 1. Frequency distribution of regional satellite albedo observed in clear sky days according to ground measurements at MO MSU in snow conditions. 1979-2000.

Fig. 2. The dependence of correlation coefficients between TOMS UV retrievals and ground UV measurements taken with different period of averaging (± N minutes around the moment of the TOMS overpass over MO MSU site).

Fig. 3. Spatial distribution of mean absolute difference between TOMS UV estimates and ground UV measurements due to the different distances of TOMS FOV center against MO MSU site (0,0 km) (a); b/ grid distribution of the mean surface elevations over Moscow region.

Fig. 4. Relative difference in TOMS UV estimates against ground UV measurements ($UV_{TOMS}/UV_{MO\_MSU} - 1$) as a function of solar elevation with 95% error bar, %. Snow-free period, 1979-2000.

Fig. 5. The dependence of S_G UV relative difference ($UV_{TOMS}/UV_{MO\_MSU} - 1$) within 95% confidence interval versus aerosol optical thickness at 550nm in clear sky conditions. Snow-free period, 1979-2000.

Fig. 6.a/ S_G relative UV difference within 95% confidence interval versus aerosol optical thickness in clear sky conditions for standard TOMS algorithm (diamonds) and for UV calculations with accounting for the absorbing aerosol and removing the effective cloud optical thickness (circles). Snow period, 1979-2000

b/ Relative UV difference as a function of effective cloud optical thickness retrieved as a difference between *TOMS LER* and given snow reflectivity *Rs*=0.4 for standard TOMS UV algorithm.

c/ Relative UV difference as a function of spatial albedo determined from ground measurements after removing the effects of effective cloud optical thickness and accounting for the absorbing aerosol.

Fig. 7. The dependence of mean UV irradiances estimated from TOMS data and measured at MO MSU (left axis) as well as relative difference between TOMS and ground based UV measurements (right axis) as a function of low level cloud amount (a) and *TOMS LER*(b). Absolute UV irradiance is normalized to SZA=50°. Snow-free conditions.

Fig. 8. The dependence of mean UV irradiance estimated from TOMS data and measured at MO MSU (left axis) as well as relative errors of TOMS UV estimates (right axis) as a function of low level cloud amount (a) and *TOMS_LER*(b). Absolute UV irradiance is normalized to SZA=73°. Snow conditions.

Fig. 9. Interannual variations of the mean S_G UV relative difference over MO_MSU and changes in aerosol optical thickness. Clear sky conditions. Snow-free period.

Fig. 10. Interannual S_G UV relative difference (median values) in all-sky snow and snow-free conditions over Moscow.

Fig. 11. Variability of global UV irradiance 300 to 380 nm since 1968, TOMS UV retrievals and ground UV irradiance 300 to 380 nm at TOMS overpass time since 1979.

Fig. 12. Relative changes of cloud and aerosol characteristics over 1979-2000 period according to satellite and ground-based data. May-September period.

# Comparisons between ground measurements of broadband UV irradiance (300 – 380 nm) and TOMS UV estimates at Moscow for 1979-2000

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PK. Bhartia [c]

## Popular summary

We show the comparisons between ground-based measurements of broadband UV irradiance with satellite estimates from the Total Ozone Mapping Spectrometer (TOMS) for the whole period of TOMS measurements (1979-2000) over the Meteorological Observatory of Moscow State University (MO MSU), Moscow, Russia. Several aspects of the comparisons are analyzed, including effects of cloudiness, aerosol, and snow cover. Special emphasis is given to the effect of different spatial and temporal averaging of ground-based data when comparing with low-resolution satellite measurements. The comparisons in cloudless scenes with different aerosol content have revealed that UV irradiance calculated from TOMS data overestimates ground based UV irradiance from +5% to +20%. But the correction of the TOMS data for boundary layer aerosol absorption eliminates the bias for cloud-free conditions. The quantitative values of aerosol absorption were independently verified using CIMEL sun and sky-radiance measurements at Meteorological Observatory of Moscow State University.

For all-sky conditions the mean difference between TOMS UV estimates and ground UV measurements is ±10% for both snow-free and snow period with TOMS overestimation in snow-free period. At overcast conditions the bias increases up to 15-17%. The analysis of interannual UV variations shows quite similar behavior for both TOMS and ground measurements (correlation coefficient $r \approx 0.8$). No long-term trend in the annual mean bias was found for both clear-sky and all-sky conditions with snow and without snow. Both TOMS and ground data show positive trend in longwave UV irradiance between 1979 and 2000. The UV trend is attributed to decreases in both cloudiness and aerosol content during the late 1990's over Moscow region. However, if the analyzed period is extended to include pre-TOMS era (1968-2000 period), no trend in ground UV irradiance is detected.

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