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**SPIE.**

Event: International Symposium on Optical Science and Technology, 2001, San Diego, CA, United States

# Comparisons between ground measurements of UV irradiance 290 to 380nm and TOMS UV estimates over Moscow for 1979-2000

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## ABSTRACT

We show comparisons between ground-based measurements of UV irradiance spectrally integrated from 290nm to 380nm using satellite TOMS UV retrievals within the whole period of TOMS measurements (1979-2000) over Moscow. We analyze the scale of temporal averaging of ground-based UV data taken with 1-minute resolution that should be used while comparing with TOMS data measured once per day within a relatively large footprint area (50-100 km<sup>2</sup>). Another objective is to study interannual variability of UV irradiance obtained by ground-based UV measurements and TOMS UV retrievals for the whole period of observation (1979-2000) over Moscow area. The analysis of interannual variations in satellite UV retrievals and ground-based UV irradiance is given together with examination of different atmospheric parameters, which are available from ground and satellite observations. Special attention is given to comparisons of UV radiation obtained from ground and satellite measurements during the spring season when maximum ozone loss is observed. This is done together with the analysis of interannual variations in snow characteristics (snow albedo, snow depth, etc) and in cloudiness. We describe the uncertainties in TOMS UV retrievals at specified atmospheric conditions by using ancillary information. The comparisons between TOMS and ground-based UV radiation in cloudless atmosphere with different aerosol optical properties are of particular concern.

## KEYWORDS

ground UV irradiance, TOMS UV retrievals, aerosol, cloud attenuation, surface snow albedo

## 1. INTRODUCTION

Over the last decades the total ozone content has significantly decreased in the Earth's atmosphere so that it may strongly affect the level of UV irradiance. In addition, other variations in atmospheric factors (for example, cloudiness, aerosol, surface albedo, etc) may also noticeably change UV irradiance level. TOMS measurements which began in 1979 are a good tool for UV irradiance retrievals and detecting UV trends due to relatively good temporal and spatial resolution. Long-term measurements of UV irradiance at wavelengths less than 380nm at Meteorological Observatory (MO) of Moscow State University (MSU) cover the whole period of TOMS observations. Therefore, we are able to verify interannual changes in UV irradiance obtained from TOMS data. In addition, due to a lot of ancillary information available at MO MSU, we can evaluate the uncertainty of UV estimates in different atmospheric conditions and, hence, give a key for improvement of the TOMS UV retrieval algorithm.

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## 2. DATA DESCRIPTION

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

Ultraviolet irradiance in the range of 300-380nm is measured by a UV radiometer designed at MO MSU<sup>1</sup> which utilizes a special selenium barrier-layer photocell with high response in the UV region of the spectrum. A special UV glass filter of 8 mm in thickness is used to cut off the visible spectrum. Figure 1 represents its typical relative spectral responsivity, which characterizes the joint effect of the spectral sensitivity of the photocell and of the transmittance of the UV glass filter. The UV radiometers designed at the MO MSU have a cosine correction factor less than 5-8% within solar elevations ( $h$ ) higher than 20°. The cosine correction factor for diffuse irradiance is applied to the measurements of diffuse and global UV irradiance. Quality control of the recorded UV data is provided by daily inspection and by comparisons with measurements of a calibrated primary standard UV radiometer in different atmospheric conditions about 20 - 30 times a month. The calibration of the primary standard UV radiometer is checked several times per year mainly in a warm period under clear sky conditions. More information about the MO MSU UV radiometer and the process of calibration is given in a prior document<sup>2</sup>.

In order to clarify the nature of the discrepancy between ground measurements and TOMS estimates we use additional meteorological and radiative information. Table 1 represents the data that were used in the comparisons with satellite UV retrievals.

Table 1.

Type of measurements	Time resolution	Comments
<b>Direct parameters for comparisons:</b>		
Global and diffuse UV irradiance spectrally integrated from 290nm to 380nm	1 min resolution averaged over 1 and 3 hours.	
<b>Indirect parameters:</b>		
Global shortwave irradiance ( $\lambda < 4.5\mu\text{m}$ )		For retrieval of cloud optical thickness in cloudy overcast conditions from the ground <sup>3</sup>
Total and low level cloud amount at MO MSU	Once per hour	Visual observations
Direct shortwave irradiance	1 min resolution	Two parameters are used to retrieve aerosol optical thickness at 550nm <sup>4</sup>
Water vapor content	Typically once per 3 hours	
Snow coverage and snow depth	Once per day	For detection of snow or snow-free conditions

### 2.3 The description of UV estimates by TOMS method

NASA's Total Ozone Mapping Spectrometer (TOMS) UV algorithm first estimates a clear-sky surface irradiance,  $F_{\text{clear}}$ , which is adjusted to actual surface irradiance by using estimated cloud and aerosol transmittance factor,  $C_T$  :

$$F_{\text{cloud}} = F_{\text{clear}} C_T \quad (1)$$

Calculation of  $F_{\text{clear}}$  in the UV range from satellite-derived spectral extraterrestrial solar irradiance and TOMS measurements of total column ozone, aerosols and surface reflectivity is described in detail in <sup>5-7</sup>, including estimates of the various error sources. The calculation procedure is based on table lookup of  $F_{\text{clear}}$  and either 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). The surface albedo and snow effects are estimated using the TOMS monthly minimum Lambertian Effective surface Reflectivity (MLER) global database <sup>8</sup>.

### 2.3.1 Cloud/non-absorbing aerosol correction

Currently non-absorbing aerosols and clouds are treated similarly. Cloud fraction and cloud optical thickness cannot be simultaneously derived on the basis of one TOMS radiance measurement (the TOMS instantaneous FOV is about 50 x 50 km<sup>2</sup> in nadir). To estimate the average cloud transmittance at the overpass time, CT(t0), TOMS uses the homogeneous cloud model embedded into Rayleigh scattering atmosphere with known surface reflectivity, RS<sup>6</sup>. The cloud optical thickness  $\tau_C$  is assumed spectrally independent and that  $\gamma_C$  corresponds to the C1-cloud model. CT table is pre-calculated at wavelengths corresponding to FClear tables for a wide range of cloud optical depths (0-100), surface albedo (0-1) and solar zenith angles (0-88o). The cloud height and geometrical thickness is fixed (3.5-5km). The same cloud model is used to pre-calculate the angular distribution of the 380nm radiances at the top of the atmosphere (TOA). The algorithm for calculation of effective cloud optical thickness interpolates the TOA radiance cloud lookup tables 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 surface reflectivity are used as input parameters to derive the spectral CT factor from the cloud irradiance tables.

The original semi-empirical CT model, which accounts for reduction of Fclear caused by clouds, haze and non-absorbing aerosols<sup>9-11</sup> was based on a concept of Lambert Equivalent Reflectivity (LER), R360. The LER is derived from the radiance measurements at 360nm in the case of Earth probe TOMS<sup>12</sup>:

$$C_T = 1 - \frac{R_{360} - R_s}{1 - 2R_s} \quad \text{for } R_s < R_{360} < 0.5 \quad (2)$$

$$C_T = 1 - R_{360} \quad \text{for } R_{360} > 0.5$$

It was shown that model (2) provides reasonable  $C_T$  estimates that compares with ground-based data as well or better than more complicated cloud correction algorithms<sup>6,9</sup>. Equation (2) provides a simple but efficient algorithm for cloud correction for global (diffuse plus direct) irradiance.

### 2.3.2 Absorbing aerosol correction

Equation (2) accounts for UV irradiance reduction from both clouds and non-absorbing aerosols, but needs an additional correction in the presence of absorbing aerosol plumes, where UV irradiance reduction is stronger. Plumes of absorbing aerosols are detected using the TOMS aerosol index (AI) data, permitting the UV irradiance to be corrected using following equation<sup>5,7</sup>:

$$\frac{F_{aerosol}}{F_{Clear}} = e^{-g(H_A)AI} \quad (3)$$

where the conversion factor  $g$  is a function of aerosol height,  $H_A$ . One method for obtaining  $H_A$  is by using the GSFC wind-data assimilation model to estimate aerosol plume heights by matching modeled and observed plume trajectories over several days. This method, and comparisons with sunphotometer data, show that the aerosol plumes in tropics and at large distances from their sources are usually located between 3 and 4 km altitude, and are repetitive at a given location from year to year. Error estimates for uncertainties in equation (3) are given in<sup>7</sup>. The high altitude absorbing aerosols (biomass burning, dust) are typical for tropical regions. The TOMS is not sensitive to the boundary layer absorbing aerosols normally encountered in mid-latitude. This inability to detect aerosol absorption in the boundary layer causes TOMS UV irradiances to be overestimated for industrial regions in mid-latitudes.

### 2.3.3 Snow correction

Equation (2) can be used for a surface UV irradiance calculation in the presence of snow if the regional (FOV average) snow albedo is known from outside data. MLER is a reasonable estimate of the surface albedo for either snow-free conditions or regions with permanent snow cover (Antarctica, Greenland). However, MLER is not a good estimator of actual snow albedo at mid-latitudes in winter season when surface albedo varies daily depending on the presence and thickness of snow cover. The TOMS UV algorithm uses a climatological snow/ice flag (probability of the presence of snow on a given day at a given

location). If snow is detected (or likely), the TOMS algorithm first determines a snow albedo threshold (SAT). The SAT is the largest between MLER for a given day and constant value of 0.4. 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 (e.g., Toronto) <sup>6</sup>. For Moscow region the SAT value is also close to 0.4. The final estimation of  $R_s$  is based on comparison of SAT with the TOMS measured LER value at 360nm or 380nm. If LER is less than SAT, the cloud free conditions with snow are assumed and  $R_s$  is set equal to LER ( $C_T=1$ ). If LER is more than SAT,  $R_s$  is set equal to SAT and all additional measured reflectivity is assigned to a cloud.

### 3. RESULTS

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

The differences between satellite and ground UV data strongly depend on the field of view of satellite instrument and, hence, on the time of ground data averaging. To assess the best time averages for eliminating the difference in UV fluxes over the large footprint area measured by TOMS instrument and UV fluxes measured by local UV sensor, we analyze one-minute resolution UV data with different time averaging against the moment of satellite overpass over MO MSU. The results are shown in Figure 1. It is clearly seen that the correlation between satellite UV flux and ground UV measurements has nonlinear dependence up to  $\pm 60$  minutes of averaging. Hence, while comparing UV ground measurements with TOMS footprints we should take no less than 2 hours of 1 minute averaging ground data to eliminate the bias due to large TOMS footprint area.

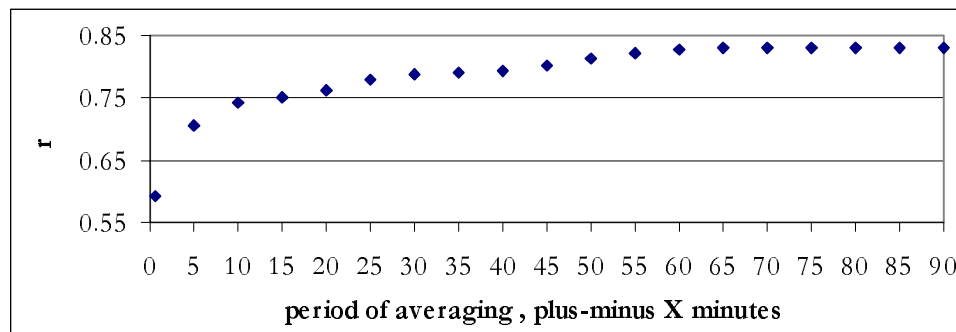
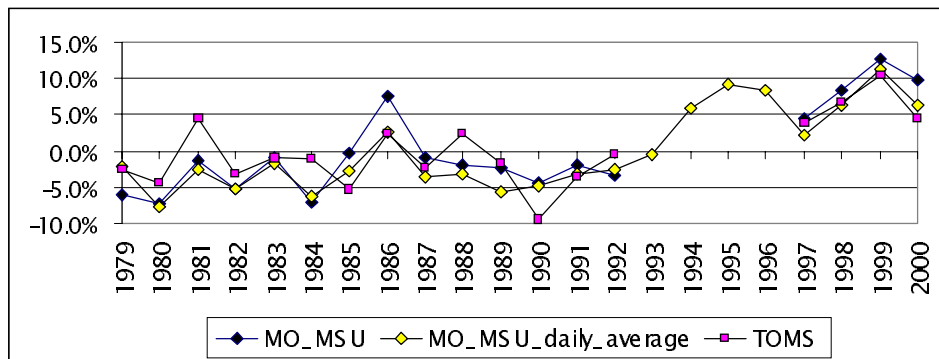


Fig. 1. The correlation between TOMS UV retrievals and ground UV measurements taken with different period of averaging.

#### 3.2 Interannual variability of broadband UV measurements and TOMS UV estimates over the whole period of measurements

Figure 2 represents interannual relative changes of measured and estimated UV irradiance as well as of main atmospheric parameters that were observed during 1979-2000. It can be noticed that there is a slight positive trend in UV irradiance for the analyzed period both for estimated and measured UV values. There is a high correlation between estimated and measured UV values ( $r=0.78$ ), which is higher when we compare the TOMS estimates with interannual changes in daily UV doses ( $r=0.82$ ), that can be explained by better temporal averaging of the irradiance. The main factor that changes the level of UV irradiance is cloudiness and, mainly, cloud amount<sup>5</sup>. Figure 2b shows interannual variations of total (NA) and low level (NL) cloud amount as well as Lambertian effective reflectivity (LER) that can be used as a cloud attenuation parameter in several TOMS methods of UV retrievals<sup>3</sup>. There is a correlation ( $r=0.5$  and  $r=0.58$ ) between total and low level cloud amount respectively, and LER. The correlation between interannual changes of measured and estimated UV fluxes is also significant and is higher for low level cloud amount reaching  $r=0.4-0.6$ . It is clearly seen that the observed 5-10% increase of UV irradiance during the last years is mainly due to the decrease of cloud amount (also see <sup>12</sup>).

a/



b/

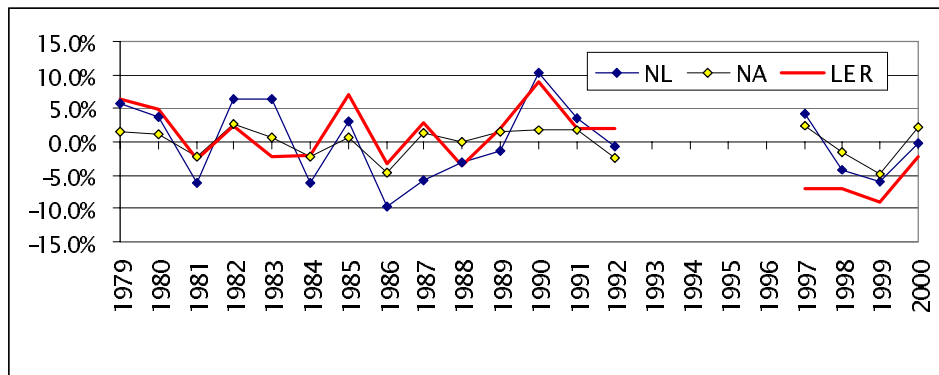


Fig.2. Interannual relative changes in estimated and measured UV irradiance less 380nm normalized at  $h=30^\circ$  (a) and in different cloud parameters (b).

We analyze relative differences between measured and estimated UV fluxes for the whole period of TOMS observations since 1979 (Fig.3). In order to retrieve possible effects of snow we divided all cases into two groups (with and without snow) to see the possible snow effects on retrievals of UV irradiance.

It is clearly seen that TOMS UV retrievals are larger than UV ground-based measurements by 5- 20% , with larger overestimation during the winter period (when snow cover was observed).

In addition, we analyze one of the spring months (March), when interannual changes of UV fluxes have the most complicated changes, and when the ozone loss is most pronounced. Fig. 4a represents interannual relative changes in estimated and observed UV fluxes over Moscow and Fig.4b represents the changes in cloudiness, snow depth, as well as the relative differences in albedo values obtained from TOMS climatology data and effective spatial surface albedo evaluated from ground measurements. These values were calculated using the characteristics of spatial snow coverage, which are measured at meteorological stations all over the world. During the last years there is a distinct growth of UV irradiance during March, for wavelengths less than 380nm, obtained both from ground and satellite measurements. But the increase of UV irradiance from TOMS data is much lower. The reason for this discrepancy can be explained if we look at Fig.4b. There are two circumstances: the decreasing of low level cloud amount and the absolute maximum in snow heights, which were observed in 1999. This means that the surface albedo should be high, as is confirmed by indirect measurements of surface albedo from ground and the negative difference between TOMS climatology surface albedo values and observed ones. Hence, in conditions with high surface albedo and increasing of frequency of broken cloudiness, the effects of multiple scattering between the low boundary of clouds and bright surfaces can greatly increase the UV level measured at the ground

and lead to the significant differences between TOMS UV estimates and ground-based UV observations. In other words, TOMS attributes the increased scene reflectivity to clouds, underestimating the true snow albedo and the surface UV irradiance <sup>6</sup>.

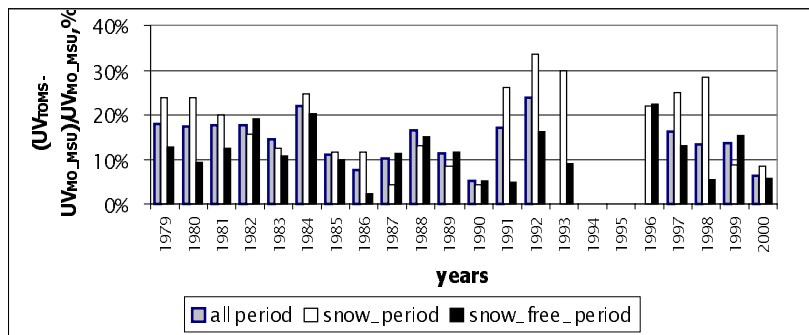
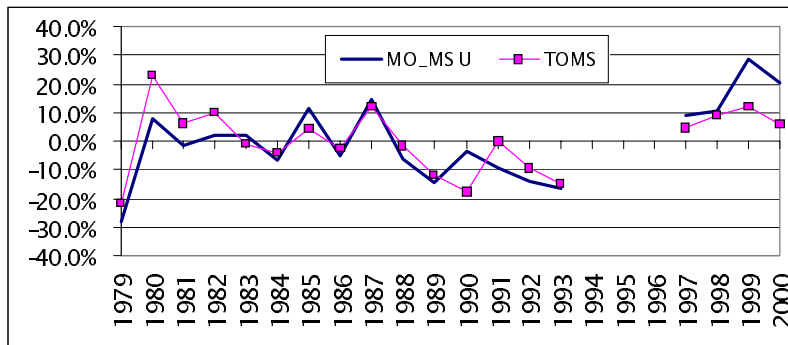


Fig.3. Mean relative difference between TOMS UV estimates and UV measurements at MO MSU. 1979-2000.

a/



b/

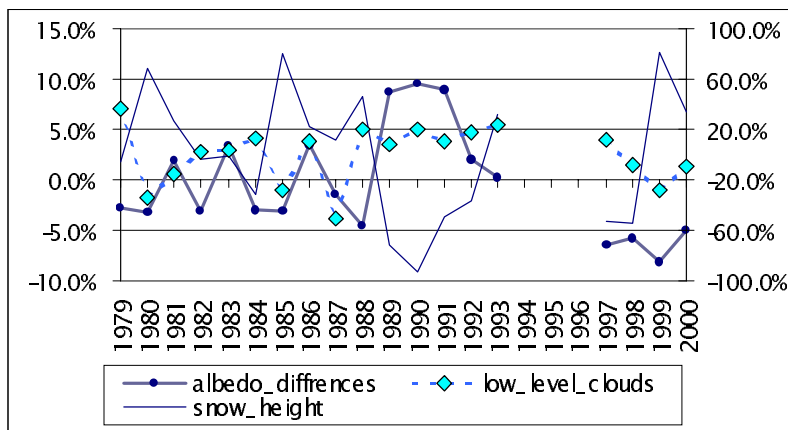


Fig.4. Interannual relative changes in UV irradiance 290-380 nm at MO\_MS U and TOMS UV estimates normalized at 30° (a) and atmospheric parameters variations (b): low-level cloud amount and snow height (right axis), relative differences between TOMS and ground surface albedo (left axis). March.



### 3.3 The analysis of difference between ground measurements and TOMS estimates in cloud-free conditions. Snow free period

In order to understand the causes of the uncertainties in TOMS UV retrievals we divided the dataset into several groups to study the dependencies of  $UV_{TOMS}/UV_{MO\_MSU}$  relative differences on different parameters, including solar angle, aerosol and cloud properties in snow and snow-free conditions. Fig.5 shows the dependencies of relative errors in cloud-free conditions on solar elevation during snow-free period for the whole period of observations since 1979. The error bars show the 95% significant level of the mean value for each increment of  $UV_{TOMS}/UV_{MO\_MSU}$  relative differences. It is clearly seen that there is about a 10% overestimation of TOMS UV retrievals and no difference in the errors with changing solar zenith angle.

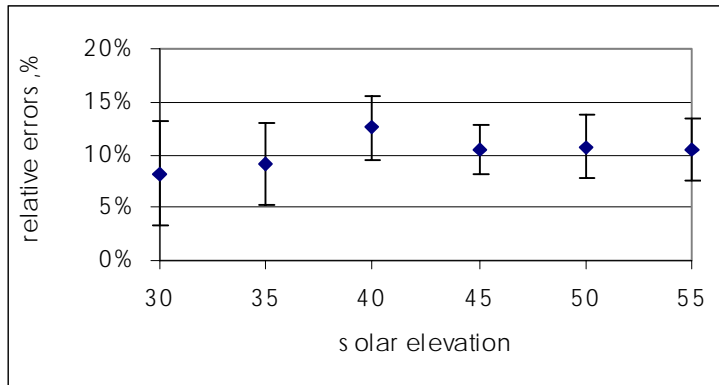


Fig. 5. Values  $(UV_{TOMS}/UV_{MO\_MSU} - 1)$  as a function of solar elevation with 95% error bar, in %. Snow-free period, 1979-2000.

Fig.6 represents the dependence of the same characteristics versus aerosol optical thickness. We obtained this dependence for UV retrievals based on the standard TOMS method (diamonds), and in addition, by accounting for absorbing aerosols using the conversion factor of  $0.25^5$  (triangles). After this procedure, the dependence of relative errors of TOMS UV estimates on aerosol optical thickness, which reached 20-25%, decreases to zero.

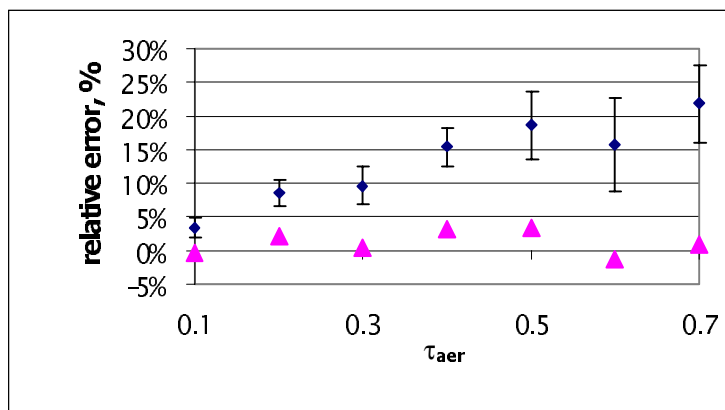


Fig.6. The dependence of TOMS relative errors  $(UV_{TOMS}/UV_{MO\_MSU} - 1)$  versus aerosol optical thickness at 550nm in case with accounting (triangles) and non-accounting (diamonds) of absorbing aerosol properties. Snow-free period. 1979-2000.

### 3.4 The analysis of difference between UV TOMS retrievals and UV observations for cloudy conditions. Snow and snow-free period.

Cloudiness is one of the main factors which can significantly change the level of downward UV irradiance. As a cloud parameters we used total (NA) and low level (NL) cloud amounts that were determined from visual observations from ground as well as Lambertian effective reflectivity (LER) evaluated from TOMS radiance measurements at 380 or 360nm. Figure 7 shows the mean and median values of TOMS UV retrieval relative errors versus LER for snow-free conditions. The systematic difference between mean and median values shows the significant skewness of the error distribution. There is a distinct growth of relative errors for LER values higher than 0.6. LER values are indirectly used in the evaluation of UV radiation. In addition, we used ground visual cloud amount observations. Fig. 8 shows the dependence of relative errors on low-level cloud amount. (We chose this characteristic because UV irradiance is much more sensitive to it (see discussion above)). We can see the same features: the increase of relative errors with the growth of low-level cloud amount up to 25%. The analysis was made for snow and snow-free period. For both periods the dependence is observed only for cloud amount higher than 8. It is interesting that for snow periods the difference between UV estimates and UV observations is about zero for the low-level cloud amount lower than 7, while for snow-free period there is 10% difference. This can be explained by the much smaller aerosol optical thickness observed in winter time.

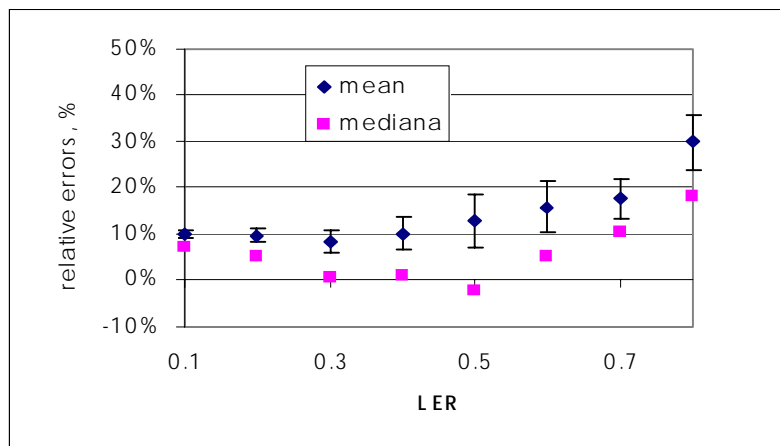


Fig. 7 The dependence of  $(UV_{TOMS}/UV_{MO\_MSU}-1)$  versus Lambertian effective reflectivity from TOMS data.

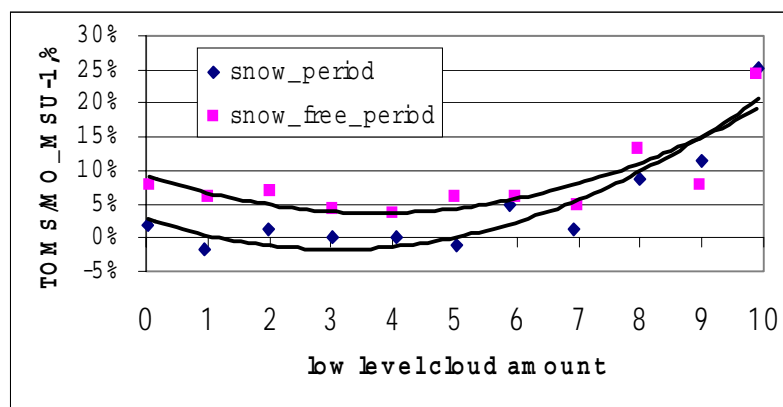


Fig.8. The dependence of  $(UV_{TOMS}/UV_{MO\_MSU}-1)$  relative errors of TOMS UV estimates versus low level cloud amount. Moscow, 1979-2000.

#### 4. CONCLUSIONS

- The results of intercomparison between TOMS UV estimates and UV measurements at MO MSU shows an overestimation of TOMS UV retrievals on 5-15% (up to 25 with snow) depending on atmospheric conditions.
- It was shown that accounting for absorbing aerosol properties significantly improves the agreement in clear sky conditions and eliminates the dependence on aerosol optical thickness.
- There is a dependence of UV TOMS retrievals on low-level cloud amount increasing up to 25% with overcast cloud conditions.
- The analysis of relative differences between ground UV measurements and satellite retrievals in springtime should be carried out taking into account the coupled system of cloud and surface albedo variations, which may significantly affect the differences between measured and calculated UV fluxes.

#### ACKNOWLEDGMENTS

The work described in this publication was partly funded by USDA Forest Service (International Programs and Forest Service Research) in the frame of the project "Solar Radiation and Weather Variability Influences On Russian Sub-Boreal Forest Phenology". Administrative assistance for the project is provided by the U.S. Civilian Research and Development Foundation for the Independent States of the Former Soviet Union (CRDF).

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