

## General remarks

The authors compare broad-band solar UV radiation exposure data derived from measurements by Brewer spectrometers taken in the city of Warsaw and outside the city. The paper is logically separated into sections. The abstract gives an overview of the paper. It mentions its most significant results. The SI is used throughout the paper. The title uses 'UV exposure', though 'UV dose' is used in the text. The same name should be used in the title and in the text. The number of Figures is adequate to illustrate the text. However, as will be addressed in more detail below, Figure captions need to be clear and provide sufficient details on what is presented. If a Figure consists of two graphs, the Figure caption should address both parts separately, for example by numbering them as a) and b). The axis names should be completed to mention the parameters in the graph.

Answer:

The title and figures were changed.

**It is recommended to apply corrections to English grammar and language style of the manuscript, and also correct for the many writing errors.**

Answer:

The corrections were made. The manuscript was significantly improved.

**The method of separation between the albedo effect on the one hand, and the aerosol and cloud effects to UV exposure at the sites on the other hand is not clear. The authors assume that the albedo is 3% at Belsk and 6% at Warsaw. This difference of surface albedo is shown by model calculations to compensate for the difference in solar height (or latitude) between the sites, if the aerosol load would be the same. The remaining differences in the UV measurements are then interpreted as a result of differences in aerosol loads and cloudiness between the sites. Have you checked the real albedo at the sites? How about seasonal differences in albedo for example due to snow cover?**

Answer:

We modeled values for different albedos in Warsaw only for the period without snow cover, because in that period UV radiation is the strongest and can cause sunburns or DNA damage. The values of albedo used for modeling refers to the article of Castro et al. (2001) – for Belsk albedo is 0.03 (green grass) and for Warsaw we examined a set of albedo values 0.03, 0.06 and 0.12 (reference have been added to the references list). Such albedo values are taken into consideration, because in the measuring site the terrain is a mixture of surfaces – from green grass to asphalt. We did not check the real albedo at the sites. The effect of seasonal differences in albedo was discussed in the previous version of the manuscript (last paragraph of section 3.2 and sixth paragraph of section 4). It was removed from current version of the manuscript, as the main seasonal difference is found to be the effect of the difference in latitude between the sites.

## Detailed comments

**Page 1, line 20: 'increase of UV exposure for peoples' replace by 'higher UV exposure for people'**

**Page 3, Section 2: Coordinates of the sites and the types of the immediate surroundings should be included here, not only mentioned in the abstract.**

**Page 3, line 8: 'Its'**

**Page 3, line 10: replace 'diffusive' by 'diffuse'**

**Page 4, line 17: replace 'moment' by 'time period'**

**Page 6, line 11: replace 'an increase of BS064/BS207' by 'a higher BS064/BS207'**

**Page 6, line 31: replace 'decline' by 'difference'**

**Page 7, line 7: 'radiation'**

Answer:

Suggested changes were made.

**Page 3, second paragraph: Is the higher contribution of diffuse irradiance to global irradiance the cause of the higher internal stray light of instruments, or is it just the lower global irradiance?**

Answer:

The higher contribution of diffuse irradiance to global irradiance is the cause of the higher internal stray light of instruments.

**Page 3, fourth paragraph: Do you really mean 'clear sky conditions' that refer to no aerosol or low aerosol load, or do you mean 'cloudless conditions'? If you refer to the latter, the changed wording needs to be applied to the whole text.**

Answer:

We meant 'cloudless conditions'. Changes in the text were made.

**Conditions of cloudless sky (or clear sky) were separated from the relative increase of irradiance over time around noontime. Using only this criterion, the separated 'cloudless cases' may still contain cases of clouds that do not occlude the sun. Have you checked by cloud observations or cloud imaging data, how good your selection criterion to find real cloudless cases is?**

Answer:

We checked all separate spectras by observing the shape of the UV irradiance curves. The day was omitted, when the shape was different from the "bell" shape and values of the UV irradiance were far from expected.

**Page 3, line 28: You refer to the erythemal action spectrum by CIE (1987). Probably, you have taken into account the corrections, as discussed by Webb et al. (2011), Photochem. Photobiol. 97, 483 – 486. If so, the citation should be added.**

Answer:

We used the original action spectrum by CIE (1987) without corrections. Uncertainties between values weighted with different action spectra are not more than 2%. Taken into consideration that we calculated ratios, uncertainties are even smaller and comparable with the measurement error.

**Page 5, last paragraph: You state that the main cause of scatter in the interpolated UV irradiance values is the first and last spectrum of the time period. Why did you not leave those two spectra?**

Answer:

This issue was clarified in the manuscript: “The main reason for this scatter is the interpolated erythemal (or UV-A1) irradiance value at the beginning (3.5 h before local noon) and at the end (local noon-0.5h) of the calculated period. BS observations were rarely made exactly at the starting and ending moments. Thus linear interpolated values were used taken from observations closest to the beginning or to the end of the period, i.e. the irradiance values just outside the observing period were taken into account.”

**Figure captions are incomplete and partly confusing. The caption of Fig. 3 says ‘The same as Fig. 1’, but the ratios are calculated for total ozone values measured simultaneously at Belsk and Warsaw’. Does the upper part of Fig. 3 show ratios of erythemal exposure? Is it measured or modelled? Or, does it show ratios between measured column ozone at the sites? The vertical axis only states ‘Belsk/Warsaw’. The lower panel does obviously show total ozone at the sites, but it is not mentioned in the Figure caption. Caption of Fig. 4 should mention that it refers to ‘modelled ratios’. Figure 5 should mention that it refers to ‘measured ratios’.**

Answer:

The captions and vertical axis names were changed.

# An urban agglomeration effect on surface UV exposuredoses: Comparison of the Brewer measurements in Warsaw and at Belsk, Poland, for the period 2013-2015

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**Abstract.** The specific aerosols and cloud properties over large urban regions seem to generate an island, similar to the well-known city heat island, with lower intensity of the UV radiation compared to the surrounding cleaner areas, thus creating a shield against excessive human exposure to the UV radiation. The present study focuses on differences in the erythemal and UV-A1 (340-400 nm) doses measured by the Brewer spectrophotometers in Warsaw (52.3°N, 21.0°E) and at Belsk (51.8°N, 20.8°E), which is located in a rural region at a distance of about 60 km in the south-west direction from the city.- The ratio between ~~the~~ erythemal and UV-A1 partly daily doses, obtained during all-sky and ~~clear~~cloudless-sky conditions in the period May 2013-December 2015, are analyzed to infer specific clouds and -aerosols forcing on the surface UV doses over Warsaw. Radiative model simulations are carried out to assess impact of the Warsaw-Belsk differences in total ozone, geographical location, and albedo on the mean ratio between the doses. Higher surface albedo over the city compensates the effect of its more northern location as the mean total ozone values appear almost the same over both sites. It is found that urban agglomeration induced 8% and 65% attenuation of the erythemal and UV-A1 doses, respectively, which ~~is mainly could be~~ caused by larger UV absorptions by the urban aerosols ~~(lower value of single scattering albedo of the urban aerosols particles)~~. It appears that a slightly increased optical depth of the urban aerosols and properties of clouds generated over Warsaw are less important for the UV attenuation. Taking into account previously found ~10% ~~increase of higher~~ UV exposure for ~~peoples~~people in the upright position due to higher albedo of the city surfaces, it could be hypothesized that the urban pollution in Warsaw does not create a shield against incoming UV radiation.

## 1 Introduction

Excessive exposure to the ultraviolet radiation (UVR) reaching the Earth's surface has a detrimental impact on the human health. Overexposure to UV-B radiation (290-315nm) can cause erythema (redness of the skin ~~after overexposure~~), DNA and cellular damage (due to generation of reactive oxygen species), and immunosuppression. Longer UV wavelengths, UV-A (315-400nm), can be ~~can~~ cancerogenic but also responsible for photoaging, and various eye diseases, including cataract. Both overexposure to UV-B and ~~UV-A~~ could lead to increased risks of cutaneous melanoma, non-melanoma skin cancers, and various health problems (e.g. Marionnet et al., 2014; Greinert et al., 2015). While UV-B is strongly dependent on the latitude and thickness of the ozone layer, UVA, especially UV-A1, the so-called long-wave UV-A (340-400nm), is ozone independent, more intense, and less variable with latitude (Sabziparvar et al., 1999). The surface intensity of UV depends on the amount of cloudiness and aerosols. The negative trends in these variables, found over many of the northern hemisphere midlatitudinal sites in the 1980s and 1990s, lead to increases of both the UV-B and UV-A irradiance (e.g. Krzyściński et al., 2011; Zerefos et al., ~~2013~~2012; De Bock et al., 2014).

An attenuation of the incoming solar radiation seems to be higher over the large urban agglomeration relative to the surrounding rural areas due to the excessive light scattering and absorption by the anthropogenic aerosols. Papayannis et al. (1998) found ~~the~~ differences between UV ~~clear~~cloudless-sky irradiances measured over Athens and its suburbs. In Athens the concentration of atmospheric ~~aerosol~~aerosols was higher than at the outskirts site. The erythemal irradiance at the centre of Athens was 30% lower than at the suburbs with ~~similar~~ values of total ozone ( $TO_3$ ) for ~~days with~~ increased pollution in the air. Similar difference was noticed on the basis of the numerical simulations of UV-B irradiance with input from measurements of the  $TO_3$  and aerosols optical thickness (AOT) by the Brewer spectrophotometer (BS) at the outskirts of Athens. Acosta and Evans (2000) measured the erythemal irradiances in the centre and suburbs of Mexico City in the period 1994-1995. During the winter, the erythemal irradiance was 9% greater at the suburbs than in the centre of Mexico, while during the summer, the recorded values were up to 43% greater (the mean value was 21%). Even larger attenuation of the UVR due to atmospheric aerosols of ~ 60% was reported in Guangzhou, China, in the dry season from October up to January (Deng et al., 2012). ~~Fountoulakis~~Fountoulakis et al. (2016) noticed that the surface UVR measured in Thessaloniki may be sensitive to another characteristic of the atmospheric aerosols, the single scattering albedo of aerosols, which may counteract the effects of AOT changes there.

The atmosphere over Poland is one of the most dust polluted in Europe. The PM10 and PM2.5 levels measured in Warsaw, as well as in most larger cities in Poland, exceed the tolerable PM limit many times during the year (Polish Ministry of Environment, 2012). However, Zawadzka et al. (2013) analyzed the measurements taken by the Microtops II and CIMEL sunphotometer and stated, that the mean difference ~~for~~ AOT at 500 nm between Warsaw and a rural site (Belsk), which is in ~60 km distance from the city in the south-west direction, was not larger than 2%, whereas for greater

values of wind velocity the difference reached 4%. The difference calculated from satellite measurements with the MODIS spectroradiometer was ~5%. The authors did not claim any significant differences in the ~~Angstrom~~~~Angström~~ parameters between the sites for the visible ranges, so it could be hypothesized, that ~~the~~ AOT values in UV range also differ only slightly.

5 The geophysical variables possibly affecting the differences in the ground level of the surface UVR between a city and remote sites are: clouds, aerosols, and surface albedo. It seems possible that large urban agglomeration could produce specific cloud properties (due to heat island effect and creation of a specific cloud condensation nuclei consisting of urban aerosols), higher loading of aerosols, and higher albedo. The working hypothesis is that the Warsaw agglomeration produces a kind of shield against the incoming UV radiation. We will strive to support (or disprove) the hypothesis by comparing the  
10 erythemal and UV-A1 radiation measurements by BSs in Warsaw and at Belsk for the period May 2013-December 2015.

## 2 Methodology

Monitoring of the UV spectra by BS -is carried out by the Institute of Geophysics, Polish Academy of Sciences (IGF PAS), at the Central Geophysical Observatory Belsk since 1992 by the single monochromator BS No. 64, and in Warsaw since 2013 by the double monochromator BS No. 207 installed on the roof of IGF PAS main building. Previously,  
15 BS 207 was working at Belsk (2010-2013). ~~The Belsk observatory is located in a rural area (the largest orchard region in Poland), away from the urban and industrial developments.~~ Comparison of BS No. 64 and BS No. 207 for that period will allow us to assess the differences between the measured UV doses due to the instrumental differences. In the middle of 2013 BS 207 was moved to Warsaw.

The present study focuses on differences in the erythemal and UV-A1 (340-400 nm) doses measured by BSs in Warsaw (52.3°N, 21.0°E) and at Belsk (51.8°N, 20.8°E), which is located in a rural region (the largest orchard region in Poland) at a distance of about 60 km in the south-west direction from the city (far from the urban and industrial developments). The Warsaw measuring site is located in the area, which is a mixture of different surfaces: grass, trees, concrete constructions (buildings, pedestrian footpaths), and asphalt roads.

25 BS064 is an older generation instrument - Mark II type, which is equipped with the single monochromator. ~~Its~~ spectral range is 290-325 nm in 0.5 nm steps and the spectral resolution 0.6 nm (FWHM). The spectra accuracy decreases for greater values of AOT and for larger solar zenith angles, i.e. for cases with enlarged participation of the ~~diffusive~~~~diffuse~~ component in the total UV radiation, that increases the stray-light effect on the instrument. Furthermore, it does not have a ventilation system. The quality control of its performance has been assessed by almost yearly calibration against the travelling world standard BS No. 17. The estimated  $1\sigma$  uncertainty of the erythemal irradiance is about 5% .

30 BS207 is ~~at~~the newest type - Mark III, that is equipped with ~~thea~~ double monochromator reducing significantly the stray-light effect. It is also equipped with the ventilation system, which prevents overheating of the instrument during hotter days. The spectral range is 290-363nm in 0.5 nm steps with almost similar to BS064 spectral resolution. BS207 is calibrated

with a set of standard lamps yielding ~5% of measurement spectrum error. For both instruments the SHICRivm software has been used to extend the spectra up to 400 nm and to eliminate erroneous spectra (Slaper et al., 1995).

The erythemal (and UV-A1) irradiance is calculated as the integral over wavelength of the 290-400 nm BS spectra after the SHICRivm standardization, which are weighted by the erythemal action spectrum (not weighted for UV-A1). The erythemal action spectrum follows CIE (1987). Further the partly daily erythemal and UV-A1 doses are calculated as the time integral of the pertaining irradiances for 6h period for all sky-conditions (noon  $\pm$  3h) and 3h period for clearcloudless-sky conditions (noon-3.5h, noon-0.5h). Solar noon is computed from the astronomical formulas corresponding to the specific day of the year. ClearCloudless-sky conditions are identified using following two steps algorithm. First step is the approximate searching for such days using the following criterion: before (after) solar noon the measured irradiance is higher (lower) than the previous one. In the next step the smoothness of the time series for the days-selected-in-day, which meet the first step criterion, is examined and in case of a jumpjumps in the dataserie such day is omitted.

The ratios between the doses measured by BS064 and BS207, based on collocated observations at Belsk- in the period October 2010 – April 2013, allow us to estimate the uncertainty range for the ratio related to differences in BS instrumental characteristics and in time of observations. The BS measurements are not synchronized as the spectrum length is different. The same ratio is measured in the period of the Warsaw observations (May 2013 to December 2015) by BS207 to assess the urban agglomeration impact on the erythemal and UV-A1 radiation.

Numerical simulations for the clearcloudless sky conditions of the ratio between the partly daily doses measured in Warsaw and at Belsk permit us to estimate the UV differences between the sites, caused by the geographical location, as Belsk is more to the south,  $TO_3$ , and the surface albedo (lower for surfaces covered by plants). The FastRT model for cloudless sky is used to calculate the spectral irradiance (Engelsen and Kylling, 2005) and the erythemal doses. The following model input parameters are selected for such calculations: daily mean total ozone routinely measured by BS, fixed aerosols characteristics representing the mean values derived from the Belsk's CIMEL sunphotometer (AOT at 340 nm=0.32, single scattering albedo=0.92), fixed albedo of 0.03 for Belsk and a set of albedo values for Warsaw that is typical for the various urban surfaces.

## 3 Results

### 3.1 Instruments comparison at Belsk

In the period from October 2010 to April 2013 both BSs were working simultaneously at Belsk. Figure 1-(top)1a shows the time series of the measured ratio (BS064/BS207) between the 6h erythemal all-sky doses. The mean value of the ratio is  $1.02 \pm 0.07(1\sigma)$ . Figure 1-(bottom)1b illustrates that the 1-1 relation between the doses is appropriate for the whole range of the measured irradiances. The coefficient of determination based on this data set is 0.99. The mean ratio for UV-A1 range is  $1.01 \pm 0.07(1\sigma)$  for all-sky conditions.

The most of the differences lie within  $\pm 5\%$  range but sometimes outliers greater than 10% appear as the measurements were not taken exactly at the same ~~moment~~time period. The measured spectra were not synchronized. It is difficult to have synchronized measurements by our BSs as scanning time is different, because of the length of the spectrum, i.e. 290-325 nm for BS064 and 290-363 nm for BS207. Thus local cloudiness may be a source of large standard deviations of the mean ratios calculated during-all sky conditions. To remove the effect of cloudiness, we analyze the ratios derived from 3h clearcloudless-sky measurements before solar noon. The clearcloudless-sky doses were calculated for the shorter period compared to those for the all-sky ~~condition~~conditions as clearcloudless-sky conditions in Poland usually prevail before noon.

Figure ~~2-(top)~~2a shows the time series of the measured BS064/BS207 ratio for the clearcloudless-sky conditions and the corresponding scatter plot (Fig. ~~2-bottom~~2b). The mean value of the ratio is  $1.01 \pm 0.03$  ( $1\sigma$ ) and there is almost a 1-1 relation between the erythemal doses by both BSs. That is also supported by high value (0.998) of the coefficient of determination. For UV-A1 doses, the ratio is  $1.00 \pm 0.04$  ( $1\sigma$ ). Thus performance of BS064 and BS207 was practically the same during the Belsk's intercomparison. The agreement between output of both BSs was almost perfect, suggesting that the instrumental differences did not have much influence ~~over~~on the ratio between the doses.

### 3.2 Numerical simulations

The distance between the Belsk and Warsaw observatory sites is about 60 km. Thus part of the measured difference between both BSs, may be a result of the more northern location of the Warsaw site comparing to the Belsk site, different  $\text{TO}_3$  over the sites, and surface albedo. In this sub-section, the model calculated clearcloudless-sky doses over 6h period symmetrical around local noon are analyzed for Warsaw and Belsk. FastRT (Engelsen and Kylling, 2005) is used in the simulations taking into account real  $\text{TO}_3$  values (i.e. daily mean  $\text{TO}_3$  measured by BS using the so-called direct sun observations), fixed aerosol characteristics based on averaged results of CIMEL observations at Belsk, and prescribed values of surface albedo equal to 0.03 at Belsk and a set {0.03, 0.06, 0.12} in Warsaw.

Figure ~~3-(top)~~3a shows the time series of the daily ratio of  $\text{TO}_3$  measured at Belsk and in Warsaw. Figure ~~3-(bottom)~~3b illustrates the scatter plot of the daily data. The mean ratio (BS064/BS207) from all data points presented in Fig. ~~3a~~3a is  $1.00 \pm 0.01$  ( $1\sigma$ ). The correspondence between  $\text{TO}_3$  values is found for the whole range of  $\text{TO}_3$  variability at Belsk. All data points are in close proximity to the diagonal line representing the 1-1 relationship between the variables shown in the scatter plot. Thus,  $\text{TO}_3$  is not a factor responsible for the UV difference between the sites. The erythemal doses calculated for the 6h near noon period with use of these ozone values, give the mean ratio  $1.02 \pm 0.02$  ( $1\sigma$ ) for simulations assuming the surface albedo is equal to 0.03 (typical for rural regions) for both sites (see Fig.4 for the results with the mark "alb=0.03"). Thus, the  $\text{TO}_3$  spatial variability and the geographical location of the site contribute only slightly to the UV differences between the sites.

Usually (in snowless periods) the urban albedo is higher asthan that ~~for~~in rural site and it provides somewhat higher intensity of the surface UV. Figure 4 presents simulations of the ratio between 6h near noon erythemal doses between the

sites assuming the surface albedo is equal to 0.03 at Belsk but 0.06 or 0.12 in Warsaw. We ~~select~~have selected these values for the urban albedo in UV range based on Castro ~~et al.~~ (2001) experimental data over asphalt sites and grey surface-cement sites respectively, taken in Mexico City metropolitan area. The mean ratio derived from all the data points shown in Fig.4 is  $1.00 \pm 0.02$  ( $1\sigma$ ) and  $0.98 \pm 0.02$  ( $1\sigma$ ), for the Warsaw surface albedo equal to 0.06 and 0.12, respectively. The surrounding of the Warsaw measuring site is a mixture of areas with grass, asphalt, and grey-cement surface, so it could be assumed that surface albedo in the surrounding of the station is of 0.06. It means that a slightly higher albedo over the urban site compensates the latitudinal effect of the UVR differences between the sites. It seems possible that the rural albedo is higher in the cold period of the year due to larger and cleaner snow cover. However, the winter observations confirms that BS064/BS207 ratio is only slightly greater comparing to the overall ratio. Snow cover was rather a rare phenomenon in those years in Central Poland.

### 3.3 Comparison of erythemal and UV-A1 doses measured at Belsk and in Warsaw

BSs were working simultaneously in Warsaw and at Belsk in the period from May 2013 to December 2015. The erythemal and UV-A1 doses calculated for these sites in the periods symmetrical around local noon for 6h for all-sky and 3h before noon for ~~clear~~cloudless sky conditions, are analyzed to find the Belsk-Warsaw ratio between the measured doses (~~BS064/BS064~~BS064/BS207). If the ratio obtained during the ~~clear~~cloudless-sky ~~condition~~conditions for BSs operating in Belsk, it will allow us to estimate the urban aerosols effect on the surface UVR. The similar approach with the use of- all-sky data will provide an estimate of the urban cloud effect on the surface UVR.

Figure 5 shows the time series of BS064/BS207 measured ratio for the erythemal doses (~~top~~(Fig. 5a)) and the UV-A1 (~~bottom~~Fig. 5b) doses for ~~clear~~cloudless-sky conditions simultaneously appearing both in Warsaw and at Belsk during 3h before local noon. The ratio oscillates around 1 within the range  $\sim 0.9$ - $1.1$ . The main reason for this scatter is the interpolated erythemal (or UV-A1) irradiance value at the beginning (3.5 h before local noon) and at the end (local noon-0.5h) of the calculated period. ~~The~~BS observations were rarely made exactly at the starting and ending moments. Thus linear interpolated values ~~are based on the two~~were used taken from observations closest to the beginning or to the end of the period, i.e. the irradiance values just outside the observing period ~~are~~were taken into account. The mean value of ~~BS064/BS207~~the Belsk-Warsaw ratio is  $1.06 \pm 0.04$  ( $1\sigma$ ) and  $1.03 \pm 0.04$  ( $1\sigma$ ) for the erythemal and UV-A1 dose, respectively. The same values calculated for all 6h near noon doses (Fig.6) during all-sky conditions are  $1.08 \pm 0.19$  ( $1\sigma$ ) and  $1.05 \pm 0.17$  ( $1\sigma$ ), respectively. ~~The~~muchMuch larger uncertainty ranges of the estimates for all-sky conditions are due to the cloudiness ~~effect~~effects but the mean values of the ratio are only slightly larger than those found during the Belsk's intercomparison of ~~the~~ instruments. In spite of possible different cloud properties over Belsk and Warsaw during 6h measurements, the ~~determination~~ coefficient values are still high, i.e. equal to 0.96 and 0.95 for the erythemal and UV-A1 doses. The 1-1 correspondence between doses is kept for the whole range of the data (Fig.7).

Standard statistical test for the difference in the mean values taken from two large samples of unknown distribution (Daniel and Cross, 2013) is used to evaluate, if ~~an increase of a higher~~ BS064/BS207 mean ratio during Belsk-Warsaw comparison of BSs relative to the mean ratio found during Belsk intercomparison is statistically significant. The working hypothesis, that the mean values of ~~the~~ BS064/BS207 ratio (both for ~~clear~~cloudless-sky and all-sky conditions) are higher during the Belsk-Warsaw comparison, is supported by the test at the significance level  $> 0.01$ . We conclude that the urban agglomeration only slightly attenuate ~~the erythemal and UV-A1 radiation.~~ The aerosol effects are responsible for about 6% (or 3%) larger 3h erythemal (or UV-A1) doses at Belsk and ~~the clouds~~cloud effects only slightly enlarge ~~the Belsk-Warsaw~~ difference, i.e. ~2% - both for the erythemal and UV-A1 doses.

#### 4 Discussion and conclusions

Warsaw agglomeration has over 3.5 million population with high pollution due to the heavy vehicle emission and industry (mainly electric powers), causing numerous ~~exceedings of cases over the~~ EU air quality ~~standard~~threshold. Like other large cities, it is expected that Warsaw produces the ~~so-called~~well known heat island that makes specific boundary layer allowing anthropogenic aerosols to reach higher atmospheric layers that may enhance ~~AOT~~ and affect cloud properties (e.g. level of cloudiness, droplet size, liquid water content). Previous study of the Belsk-Warsaw differences in the aerosols properties (Zawadzka et al., 2010) revealed similar values of the ~~Angstrom~~Angström exponent and higher Warsaw AOT values at 500 nm - of about 0.02 i.e., ~10% of the overall mean AOT at Belsk for this wavelength. Similar values were reported by Chubarova et al. (2011) analyzing the results of aerosols measurements by CIMEL sunphotometers located in Moscow (megacity with population over 10 million) and Zvenigorod.

Using the value of the erythemal radiation amplification factor due to aerosols of 0.15, which is defined for AOT at 550 nm (Krzyścin and Puchalski, ~~1996~~1998), it could be estimated that ~~such~~10% AOT difference between Belsk and Warsaw would induce ~2% attenuation of the erythemal doses in Warsaw. ~~The present study, which is based on the measured UV spectra by BSs, shows higher~~ ~~declined~~difference (~6%) of the erythemal irradiance under ~~clear~~cloudless-sky conditions due to the urban pollution effect. It seems possible that higher absorption of UV irradiance ~~(i.e. smaller single scattering albedo (SSA) by the anthropogenic aerosols,~~ is a factor that may be responsible for larger attenuation of the surface UVR ~~in Warsaw.~~

Fountoulakis et al. (2016) ~~disused~~discussed factors important for the UV spectra variability in Thessaloniki. They pointed out that the ~~clear~~cloudless-sky UV-A irradiances could be sensitive not only to AOT changes but also to ~~SSA~~ changes ~~in other aerosols characteristics, e.g. single scattering albedo (SSA).~~ Chubarova et al. (2011) analyzing results by CIMEL sun photometers located in Moscow and in Zvenigorod (less polluted site) found that uncertainty range of SSA is too high, precluding discussion of the SSA urban effects. However, they found that SSA in Moscow for the visible range of solar ~~radiations~~radiation was 0.02-0.03 smaller than that obtained over the clean site. It is worth mentioning that there is a lack of the direct retrieval to obtain SSA from spectral measurements. Indirect method for BS has been proposed (Bais et al.,

2005) depending on the assumed values of the asymmetry parameter, surface albedo, aerosol vertical profile, and the extraterrestrial solar spectrum. They found that frequently low SSA values  $< 0.7$  were observed in Thessaloniki ~~for aerosols~~ ~~with~~when AOT at 340 nm ~~was~~ less than 0.3 ~~that~~. It could induce 10%-20% attenuation of the irradiance at 340 nm relative to the case of  $SSA=0.92$  being typical for clean sites. Based on their results we could estimate that ~5% decline of UV irradiance, which ~~is~~ attributed to the more absorbing Warsaw aerosols, is caused by aerosols with  $SSA \sim 0.8$  at 340 nm. Such estimate looks probable as the Warsaw observing site is among the most polluted parts of the city because of the abnormal vehicle emission in the nearby main city roads.

For all-sky ~~condition~~conditions the attenuation of the surface UV radiation ~~in Warsaw~~ is only slightly higher than that found during ~~clear~~cloudless-sky ~~condition~~conditions, i.e. ~8% for erythemal doses and 5% for UV-A1 doses, which is ~2% greater than found for the ~~clear~~cloudless-sky case. Cloud effects should be more pronounced during warm period of the year where the city heat island may generate stronger convection than that existing in ~~the~~ cold period. Romanov (1999) analyzing NOAA satellite images retrieved higher cloud cover in summer ~~over~~ the central Moscow compared to its suburbs. Inoue and Kimura (2004) found that in Tokyo there were more low level clouds in ~~the~~ summer period (July-August) comparing to rural sites in Kanto region. Moreover, urban heat islands lead to more thunderstorm initiation episodes (e.g. Sheperd, 2005; Haberlie et al., 2015).

The classical theory (Twomey, 1977) states that when there are more aerosols high above the surface due to stronger updraft generated by the city warm island, aerosols serve as cloud condensation nuclei, reduce the size of cloud effective radius and increase number of droplets causing larger cloud optical thickness (COT) and finally higher ~~of~~ attenuation of radiation reaching the Earth's surface. Thus additional cloudiness generated over large cities may act as an umbrella against excessive UV radiation. We calculate BS064/BS207 ratio during Belsk-Warsaw comparison campaign taking into account measurements in the warm period, 15 May – 15 September. We expect to find ~~thea higher~~ ratio ~~increase~~ for that period according to the classical theory stated above. However ~~the~~ ratio ~~decreases~~is only slightly ~~lower~~, i.e.  $1.06 \pm 0.17(1\sigma)$  for the erythemal doses, and  $1.05 \pm 0.16(1\sigma)$  for UV-A1 doses. It may suggest that contrary to the expectation, COT is smaller over the urban area. Jin et al. (2005) discussed aerosol-cloud relationship over New York and Huston. They found that thick urban aerosols correspond to low COT there. Thus it seems possible that even higher cloudiness over urban areas does not mean higher attenuation of solar radiation, because the urban aerosols modify the cloud structure compensating the effect of increased cloud cover there.

A slightly higher BS064/BS207 ratio is found during the cold period because of an effect of seasonal albedo changes. i.e. value  $1.09 \pm 0.20(1\sigma)$  was obtain using the winter data comparing to  $1.08 \pm 0.19 (1\sigma)$  found in the all year data. During winter, snow cover melts faster in the centre of Warsaw, due to the city warm island. Furthermore, snow is systematically removed from the roads and pavements in the city. Snow during the Warsaw-Belsk comparison campaign was hardly observed thus the ratio was affected only slightly by the seasonal albedo differences.

Zerefos et al. (2012) discussed ~~that~~ present UV level over many sites in the northern mid-latitudes is high due to the positive trends in ~~the~~ UVR related to the decreasing total ozone (up to mid 1990s) and negative trends in amount of

clouds and aerosols (up to mid 2000s). Figure 8 shows the annual erythemal means for the period 1976-2015 based on [the](#) updated (for the period 2009-2015) time series of [the](#) broad-band- UV measurements at Belsk (Krzyściń et al., 2011). The UV increase in Poland for the period 1976-2015 is especially strong as the cloudiness and amount of aerosols in the atmosphere in the mid 1970 and early 1980s was large, because of the enormous environment pollution during the communist era. The UV level stabilizes around 2006 and the present level -of the erythemal -irradiance at Belsk is ~15% larger ~~that~~[than](#) that in the mid 1970s.

Our study proves that the UV level in Warsaw is only slightly lower (~5%-8%) than that found in cleaner surroundings of Warsaw. It seems that higher absorption of UV radiation by urban aerosols (lower SSA values) is the main source of the urban UVR attenuation there. However, Parisi et al. (2004)- found that over some non shaded part of the city with high albedo (e.g. concrete surface) there is an amplification of -the human exposure of up to 7% for people in the upright position. Thus- contaminated urban atmosphere over Warsaw cannot be treated as a shield against excessive human exposure.

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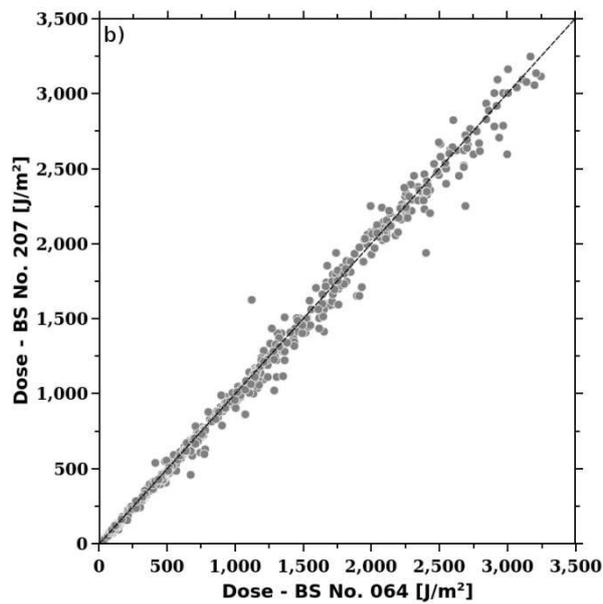
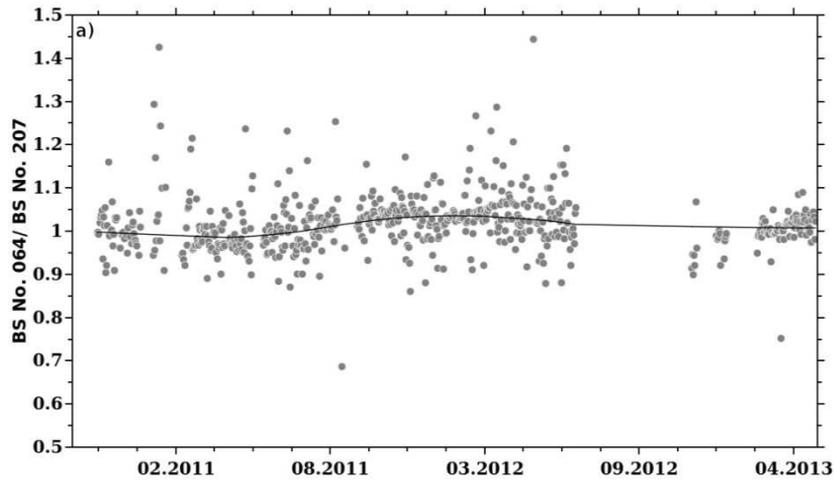
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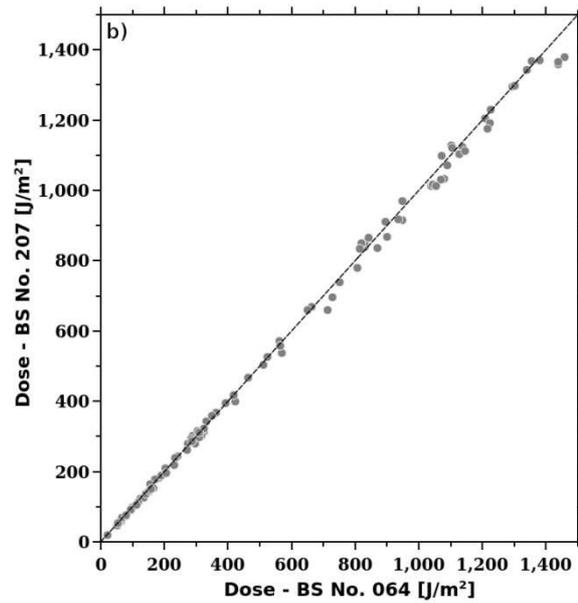
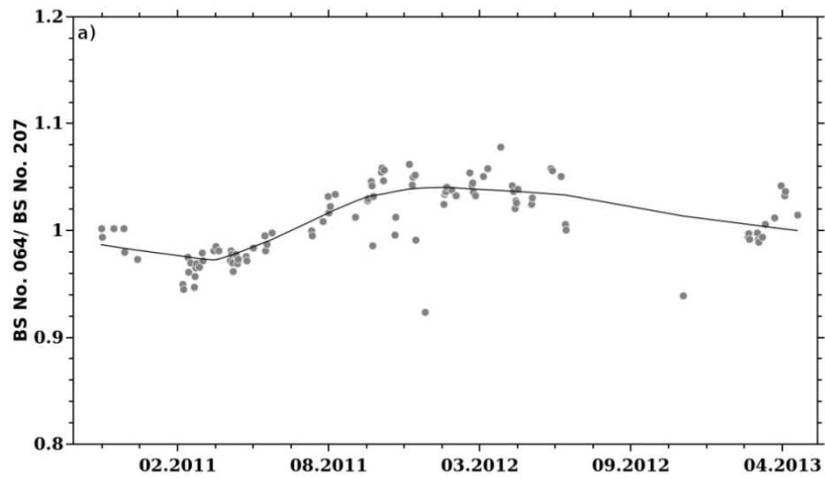
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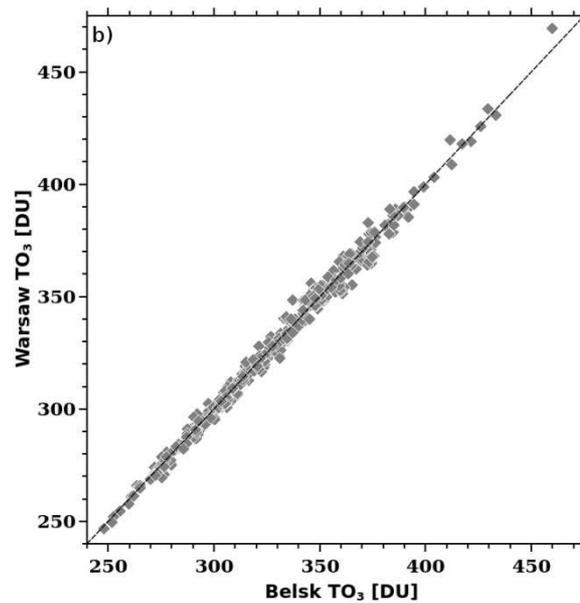
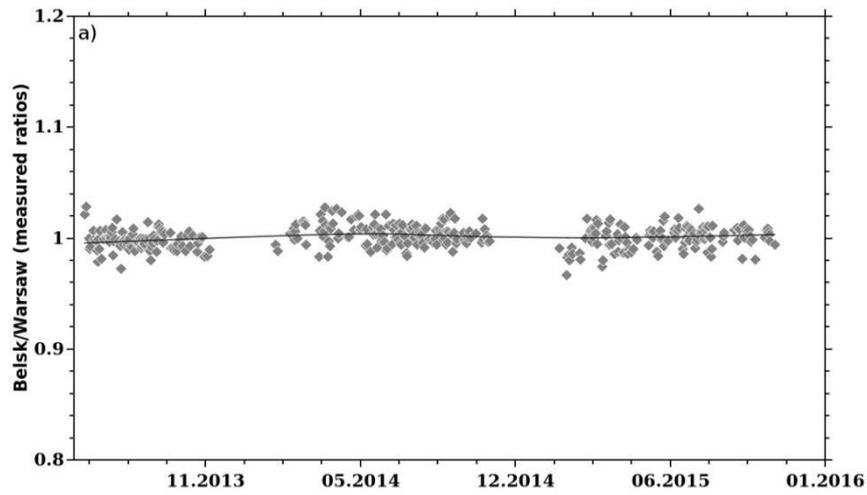
5 **Figure 1a:** The ~~(top) Ratio~~ratio between erythemal 6h (noon+/-3 hr) doses measured by the Brewer Spectrophotometer No.64 and No.207 while working simultaneously at Belsk (all-sky conditions).-~~(bottom) The doses measured by the Brewer spectrophotometer No.207 versus those by the Brewer spectrophotometer No.64.~~ The solid curve represent the smoothed data by LOWESS filter.

10 **Figure 1b:** The doses measured by the Brewer spectrophotometer No.207 versus those measured by the Brewer spectrophotometer No.64.



**Figure 2a:** The same as Fig.11a but for clear/cloudless-sky conditions and 3h doses calculated for the period before noon (noon-3.5h, noon-0.5h).

5 **Figure 2b:** The same as Fig.11b but the ratio is for cloudless-sky conditions and 3h doses calculated for the period before noon (noon-3.5h, noon-0.5h).



**Figure 3a:** The ratio between total ozone values measured by the Brewer Spectrophotometer No.64 and No.207 while working simultaneously at Belsk and in Warsaw for the period May 2013-December 2015. The solid curve represent the smoothed data by LOWESS filter.

**Figure 3b:** Total ozone values measured by the Brewer Spectrophotometer No.64 versus total ozone values measured by the Brewer spectrophotometer No.207 while working simultaneously at Belsk and in Warsaw for the period May 2013-December 2015.

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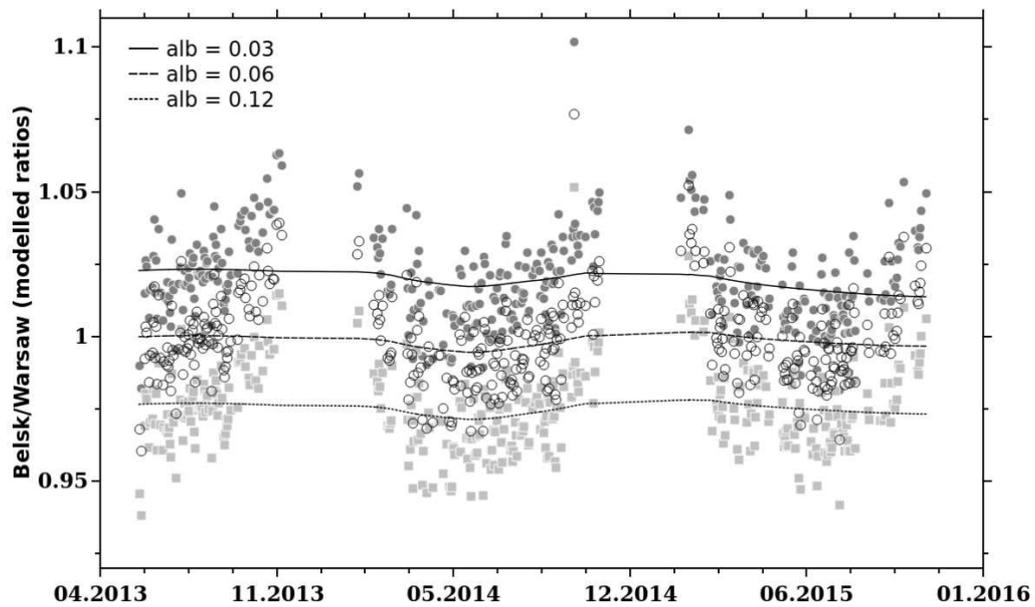


Figure 4: The Belsk/Warsaw ratio between -partially daily 6 hr doses (local noon +/- 3h) obtained/calculated by FastRT model with following input values: total column amount of ozone measured by the Brewer spectrophotometer, SSA=0.92, AOT=0.32 at 340 nm, surface albedo 0.03 at Belsk and {0.03, 0.06, 0.12} in Warsaw. **The solid curve represent the smoothed data by LOWESS filter.**

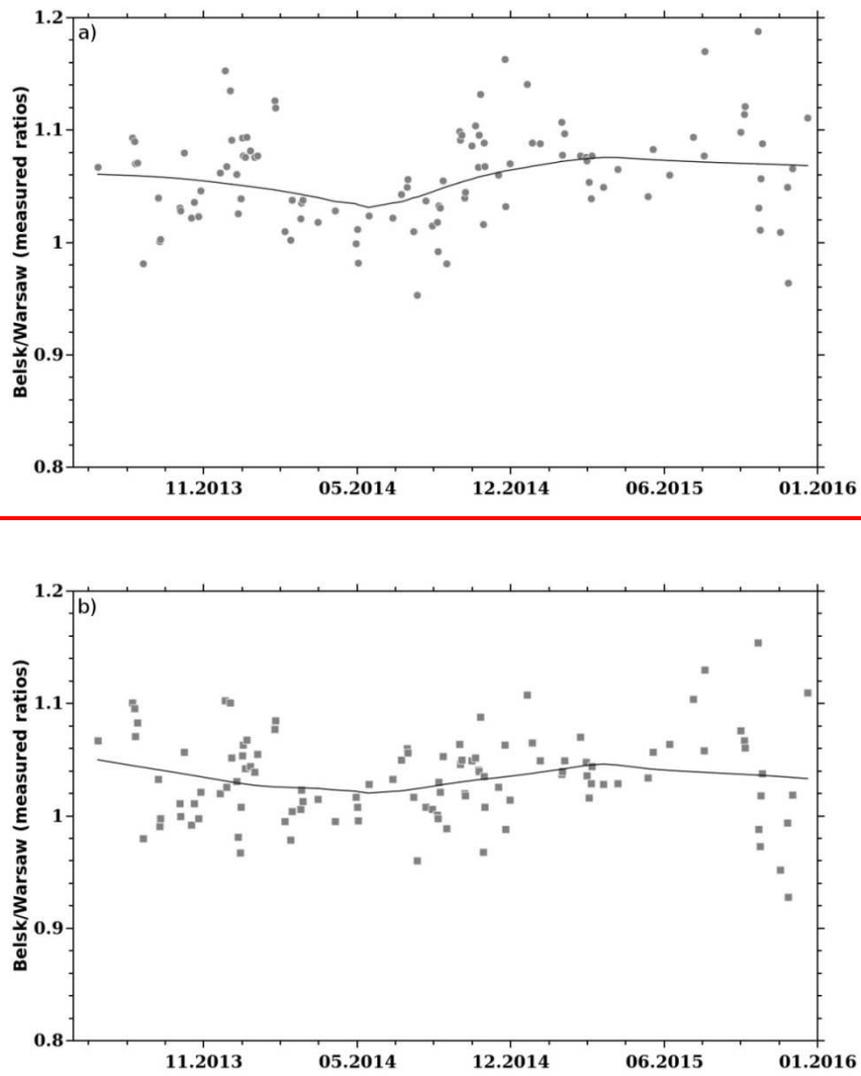


Figure 5: The Belsk/Warsaw ratio between the partially daily 3h doses (noon-3.5h, noon-0.5h) measured during clearcloudless-sky conditions existing over both sites. (top) for erythemal doses, (bottom) (a) and UV-A1 doses (b). Solid curves represent the smoothed data by LOWESS filter.

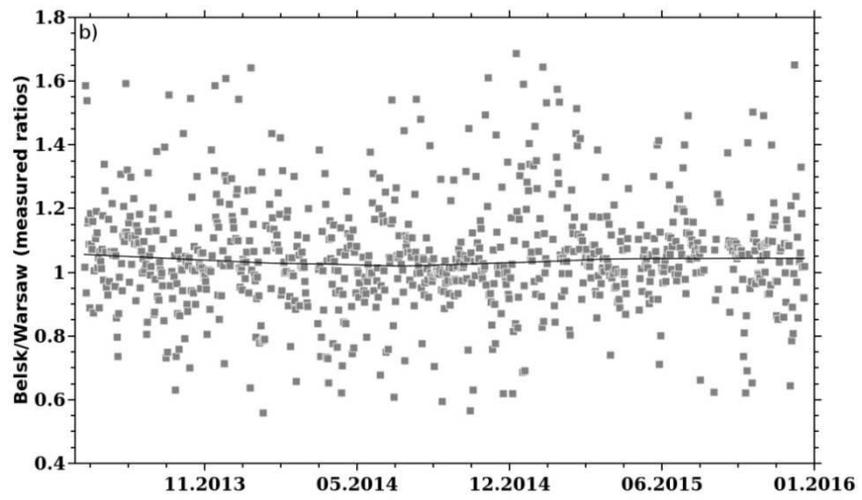
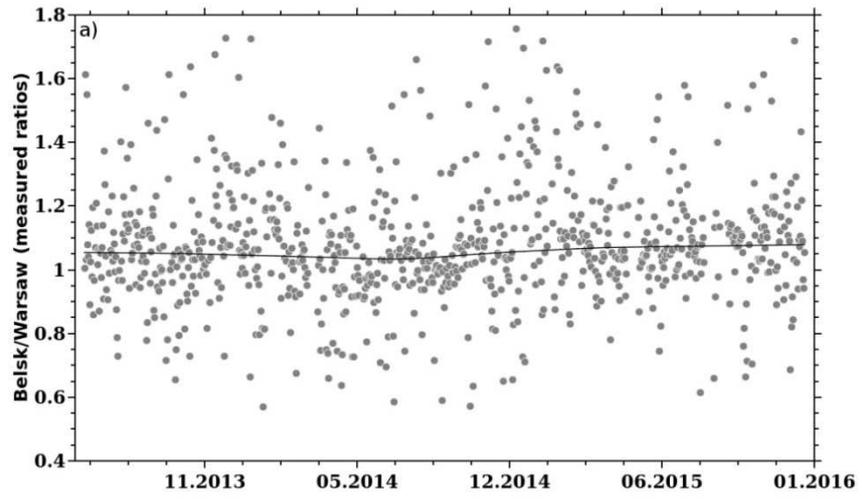


Figure 6: The same as Fig.5 but for the near noon partially daily dose (-noon-3h, noon+3h) for all-sky conditions. Solid curves represent the smoothed data by LOWESS filter.

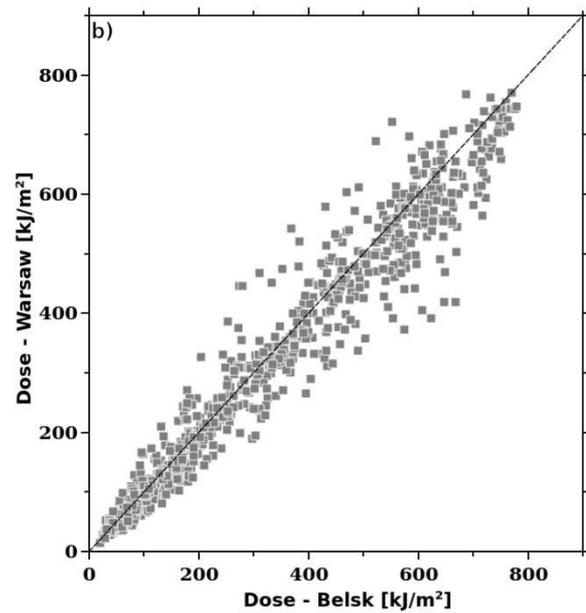
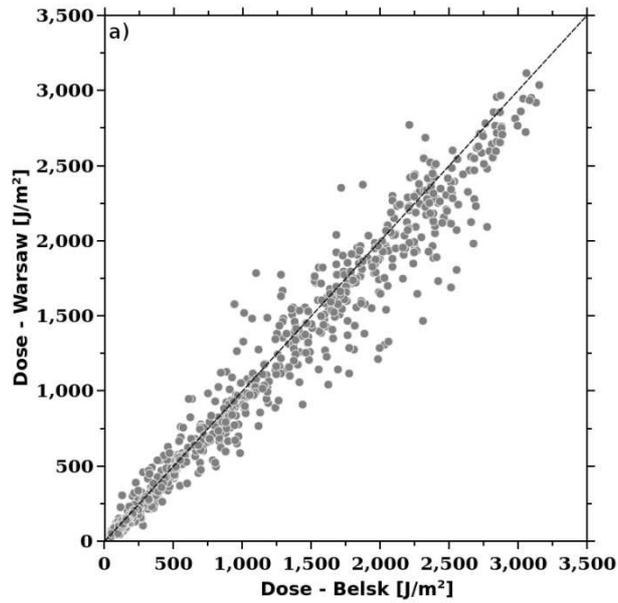


Figure 7: Partially daily near noon doses {local noon-3h, local noon+3h} measured in Warsaw versus those in Belsk: (top)—erythemal dose, (bottom)—doses (a) and UV-A1 dose.doses (b).

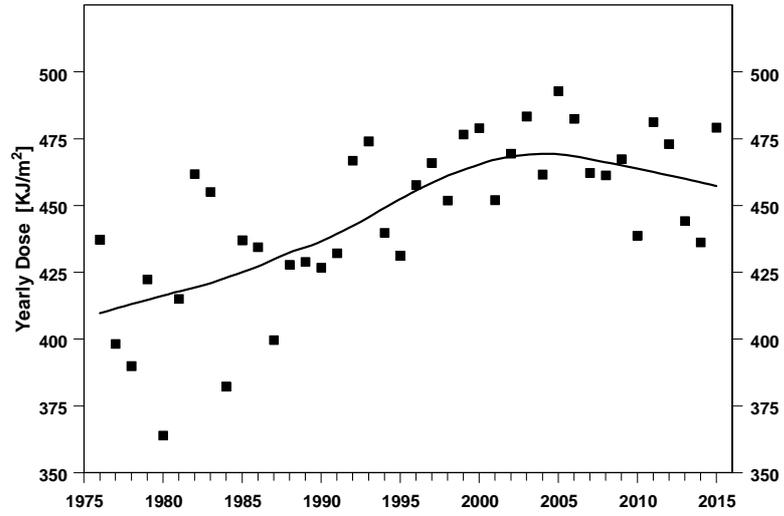


Figure 8: Yearly means of the erythemal dose measured for the period 1976-2015 at Belsk (squares). The solid curve denote the smoothed data by LOWESS filter.