

Dear Editors,

The manuscript was reorganised and the modelling section was revised. Also, we added one author, who participated in the analysis of MODIS data. Furthermore, we rephrased the title to: "Effects of urban agglomeration on surface UV doses: a comparison of Brewer measurements in Warsaw and Belsk, Poland, for the period 2013-2015". All changes are shown in the revised manuscript with tracked changes at the end of the file.

Best regards,
Authors

Response to Editor's (Stelios Kazadzis) comments

Here are my comments concerning the publication to ACP

line 9: you have to explain what exactly you mean smoothness. What is the algorithm?

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Answer:

An explanation of the algorithm is contained in the current version of the manuscript, P4, L20-24:

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“Cloudless-sky conditions are identified using a two step algorithm. The first step is a preliminary search for such days using the criterion: the solar UV irradiance derivative with solar zenith angle is negative. In the next step, the smoothness of the time series for the day which fulfilled the first criterion, is examined, i.e. the bell-shape of the UV time series must be identified. There is no strict mathematical criterion applied here, but rather an intuitive inspection of the time series shape.”.

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Figures 1 and 2. How much stray light issues mentioned before in the text affect the ratio especially on low elevation (winter) and cloudy (low signal) conditions?

Answer:

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We take into consideration only doses around local noon, when the effect of stray light on instruments is the weakest, thus we assume that it does not have a significant influence on the ratio.

Why a 6h cloudless period with the model when you measure 3h with the BS?

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Answer:

In the revised manuscript, this discrepancy was removed. We did not simulate the ratio between doses, but the ratio between irradiances for a fixed SZA or time. Please, see the section 3.3.

analysis: 1. The real day to day AOD has to be used in order to quantify the real AOD effect 2. A sensitivity study has to be included in order to specify the effect of ozone variability within the 6 hour period to the model results 3. Using the same TOC for the two locations the solar zenith angle effect of the 60 km distance on erythemal dose can be exactly quantified with the model help. 4. Figure 3 TOC differ within 5 % which can be ± 15 DU. This can not be considered negligible. 5. There is a clear solar zenith angle dependence on the ratios in the order of 5% (for all albedos) probably related with the solar zenith angle differences 6. A 6 to 12 % albedo in the UV without snow.

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Is there any publication or theoretical document to support this?

Answer:

The revised manuscript contains a new section 3.3, where these problems were explained taking into account the Editor's suggestions. The albedo values are based on the reports of Castro et al. (2001). The reference is used in the text (P8, L11): Castro, T., Mar, B., Longoria, R., Ruiz-Suárez, L. G., and Morales, L.: Surface albedo measurements in Mexico City metropolitan area. *Atmósfera*, 14(2), 69-74, http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0187-62362001000200002&lng=en, 2001.

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AOD from cimel you have to specify the wavelength and the level (1.5 or 2) of data used and also to mention that Cimel SSA is measured at the visible region and you have assumed that it can be extrapolated to the UVB. In addition there is no documentation for the uncertainties of CIMEL SSA for AOD <0.4 so since you are using it you should comment on this.

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Answer:

In the revised manuscript, we do not use AOD from CIMEL, but AOD from measurements with MODIS at 550 nm. Measured values of AOD were used in simulations with LibRadtran, where the type of aerosol was selected to rural. As for SSA, we included this information in the text, P5, L6-12:

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“Other input parameters are constants representing typical values used in the UV modelling, e.g. albedo of 0.03 for rural surfaces and SSA=0.92, which is a mean value measured by the CIMEL sunphotometer at Belsk (level 1.5 from AERONET – Aerosol Robotic Network) at 440 nm (<http://aeronet.gsfc.nasa.gov>). We used SSA at 440 nm as a constant for the whole ultraviolet spectrum, as it was found that monthly averages estimated from BS at Uccle were in close agreement with the CIMEL measurements at 440 nm, especially for 320 nm (Nikitidou et al., 2013). Furthermore, Liu et al. (1991) performed Mie calculations for the rural aerosol model (Shettle and Fenn, 1979) and suggested that for this type of aerosol, SSA is approximately independent of wavelength. There are no measurements performed for SSA at the UV wavelength range.”

5
10 **Figure 5. Erythemal : there is a clear solar zenith angle dependence of the ratio. You can show this if you plot this ratio against minimum solar zenith angle for each of the days used.**

Answer:

15 This issue is discussed in the modelling section (section 3.3 of the current version of the manuscript). Also, we added Figure 6 to show the dependence.

Discussion

Line 11: It is not straight forward to extrapolated AOD amplification factors and percentages from 550nm to the UV.

20 Answer:

In this version of the manuscript, the AOD effect on ratios was calculated directly using measured AOD at 550 nm (from MODIS) and LibRadtran, where the type of aerosol was selected to rural.

25 **The paper needs clear restructuring in order to quantify different effects: Here we have spatial and temporal related differences mixed that are also linked with AOD, ozone, and albedo variability.**

30 **First issue is the 60Km distance. Using the model you can quantify this. It is related with the 6h window and also ozone (and partly aerosol effects). To make things easier I would suggest to use a constant solar zenith angle (e.g. X +/- 1 degree) for both places in the comparisons to get rid of this problem or to try to homogenize the series based on the model results. In addition, using a constant solar angle you get rid of problems like ozone variability over the 6 hour period, AOD changes, averaging (measurement frequency) issues. What remains is a. the ozone difference, b. the AOD difference, c. the albedo possible differences d. instrumental issues such as stray light and absolute calibration. Its important to try to separate them for example starting from UVA where ozone plays no role so to quantify the AOD effects.**

35 **Also working in a constant solar zenith angle provides the possibility to calculate indirectly the AOD that has to be used in order to match the Belsk and Warsaw measurements for a constant SSA. Then to compare your results with the MODIS related study.**

40 **In the end if all do not add up you can quantify the SSA needed to be used in order to match the measurements of the two sites.**

Answer:

45 We reorganised the paper and calculated separately all possible factors that may have an impact on the ratios between the sites. The results are in section 3.3 and in the discussion.

SHICRIVM: Since you are not actually measuring the UVA1 but you are using SHICRIVM to simulate the spectrum, this adds an additional uncertainty especially for the single monochromator measurements.

50 Answer:

In the revised paper, we have used a single wavelength (324nm) for UV-A, which is measured directly by both BSs, instead of UV-A1, to eliminate additional uncertainty connected with the SHICRIVM method.

Response to Anonymous Referee's #1 comments

General comments

5 The paper by Czerwińska et al provides useful information regarding the effect of an urban
agglomeration on the levels of the solar UV irradiance. It highlights the importance of the aerosol optical
properties for the determination of the UV irradiance that reaches the earth surface and has the potential
to contribute in the better understanding of the complex interactions between aerosols, clouds, surface
10 albedo and UV radiation in an urban environment. The authors compare the erythemal and UV-A1 (340-
400 nm) doses measured by the Brewer spectrophotometers in Warsaw (52.3°N, 21.0°E) and Belsk
(51.8°N, 20.8°E) and are trying to quantify the effects of differences in surface albedo, cloudiness, aerosol
optical depth and aerosol single scattering albedo.
However, the main problem in the data analysis is that the effect of different latitude (thus of different
SZAs for the measured UV doses) has not been removed (or quantified) properly leading to biases in the
15 quantification of the effect of other factors (such as the aerosol SSA and the cloudiness). The effect of
different latitude changes periodically in the year and is more pronounced in winter (higher SZAs, which
means that the difference of 0.5° becomes more important). The authors considered the effect of different
SZAs to be invariant during the year which is not correct. Thus, I suggest to re-analyze the data and
either quantify the effect of different latitude properly (e.g. with the use of a radiative transfer model) or
20 perform the comparison for standard SZAs.

Answer:

We revised the modelling part. In the revised manuscript, we took into account the effect of different latitude and
25 re-analysed data with the use of the LibRadtran simulations. Please see P7, L6-11:
“The difference in the geographical coordinates for the sites, which are based on the simulations of the erythemal
and UV-A irradiances at 10:40 a.m. (i.e. near local noon) throughout 2015 leads to slightly higher values at
Belsk. The modelled ratio changes with SZA (Fig. 6). The average ratio over the whole year is 1.03 ± 0.02 (1σ)
for the erythemal irradiance and 1.02 ± 0.01 (1σ) for UV-A (324 nm). For the warm period (from 15 May to 14
30 September) modelled ratios were 1.01 ± 0.003 (1σ) and 1.01 ± 0.002 (1σ), but for the cold period (from 15
September to 14 May) modelled ratios were 1.04 ± 0.01 (1σ) and 1.03 ± 0.01 (1σ) – for erythemal and UV-A
(324 nm) irradiances, respectively.”.

**The second important issue that has to be solved prior to publication in ACP is the large number of
35 editorial, grammatical and linguistic errors in the manuscript. The authors have to try hard to improve
the manuscript. If possible, I suggest that the manuscript should be edited by a native English speaker.**

Answer:

40 We did our best to improve the manuscript.

**Additionally, I suggest reorganizing sections 3 and 4 as follows: 3.1. Comparison between measurements
at Belsk, 3.2. Comparison between measurements at Belsk and Warsaw, 3.3. Quantification of the factors
which are responsible for the differences, 3.4. Long-term change of the erythemal irradiance at Belsk. In
45 section 3.3 you can include the numerical simulations (now section 3.3) and part of the discussion from
section 4 (e.g. the results reported in P8, L15 – 31 regarding the effects of cloudiness). I also suggest
moving figure 8 (and the relative discussion) in section 3.4 and expand the discussion. This way, I believe
that it will be easier for the reader to follow the discussion.**

50 Answer:

The paper was reorganised following the Referee's #1 suggestions.

**The effect of different SZA (presented in paragraph 3.2) should be initially studied for UV-A1. Then, the
55 combined effect of SZA and TO3 could be studied for the erythemal dose. Although the effect of SZA is
stronger for lower wavelengths (due to stronger Rayleigh scattering and increased absorption by TO3 for
larger SZAs) and the effects of SZA and TO3 on erythemal irradiance are not independent to each other,
this way you could get a quantitative estimation regarding the effect of differences in TO3. However, the
most effective way to quantify the effect of different TO3 is to study the ratios of UV-A1 and erythemal
60 irradiance for specific SZAs (or small SZA intervals).**

Answer:

We did the calculation for specific SZAs or time. Please see the results in section 3.3.

5

Specific comments

10

Please define a specific acronym to use in the document for each Brewer. For example, Brewer with Serial Number 207 is referred as BS No. 207, BS 207 and BS207 (without defining what the number 207 is) at different points of the document. Please choose a single acronym and use it everywhere (in the manuscript and the figures). E.g. you could define at the beginning of the methodology section that each BS with serial number xxx will be referred as BSxxx and then refer to each Brewer the same way.

15

Answer:

We changed the acronyms throughout the paper. They were defined on P3, L20-21:

20

“(…) by the single monochromator BS, serial number 64 (BS064), and in Warsaw since 2013 by the double monochromator BS, serial number 207 (BS207)”.

Abstract

25

P1, L7-8: replace “well-know” with “well-known”

P1, L8: replace “cleaner” with “less polluted”

P1, L9-11: replace the sentence:

“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.”

30

With

“The present study focuses on differences between the erythemal and UV-A1 (340-400 nm) doses measured by the Brewer spectrophotometers in Warsaw (52.3°N, 21.0°E) and Belsk (51.8°N, 20.8°E). The latter is a rural region at a distance of about 60 km south-west of the city of Warsaw.”

35

P1, L18: replace “by larger aerosol absorption” with “mainly by larger aerosol absorption over Warsaw”

P1, L18-19: The meaning of the phrase: “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.” is not clear at this point. I would suggest replacing with something like:

“Differences between the aerosol optical depth and cloud optical properties over the two sites are found to be less important.”

40

P1, L19-20: replace “In this work we are showing that the higher city surface albedo compensates for the solar UV attenuation caused by urban aerosol load in the city of Warsaw.”

With something like:

“We show that the higher surface albedo in Warsaw compensates for the stronger attenuation of the solar UV radiation by the urban aerosols.”

45

Answer:

Suggested changes were made.

50

Introduction

P2, L5: add appropriate references

P2, L6: add appropriate references

Answer:

55

The references were added on P2, L9:

Greinert, R., de Vries, E., Erdmann, F., Espina, C., Auvinen, A., Kesminiene, A., and Schuz, J.: European Code against Cancer 4th edition: Ultraviolet radiation and cancer, *Cancer Epidemiol. Biomarkers Prev.*, 39, S75-S83, 2015,

Marionnet C., Pierrard, C., Golebiewski, C., Bernerd, F. et al.: Diversity of Biological Effects Induced by Longwave UVA Rays (UVA1) in Reconstructed Skin, PLoS ONE 9(8): e105263, doi:10.1371/journal.pone.0105263, 2014.

- 5 **P2, L8: replace “depended” with “dependent”**
P2, L11: replace “surface UV attenuation” with “attenuation of the solar UV radiation”

Answer:

10 Suggested changes were made.

P2, L10-12: add references to support your statement that “The absorption by SO₂ (in the UV-B range) and NO₂ (mostly in the UV-A range) is important for the surface UV attenuation only in extreme concentrations of such gases.”

15 Answer:

The sentence was changed to: “In the spectral range up to ~330 nm, absorption by ozone is usually much stronger than absorption by other main trace gases (SO₂, NO₂) (Cede et al, 2006)” (P2, L11-12). The reference is:

20 Cede, A., Herman, J., Richter, A., Krotkov, N., and Burrows, J.: Measurements of nitrogen dioxide total column amount using Brewer double spectrophotometer in direct Sun mode, J. Geophys. Res., 111, D05304, doi:10.1029/2005JD006584, 2006.

- 25 **P2, L12: Replace “surface intensity of UV” with “intensity of the solar UV radiation at the earth surface”. Furthermore, in addition to the properties, the amount of aerosols and clouds also affect UV radiation.**
P2, L12-14: Change the phrase: “The negative trends in these variables, found over many of the northern hemisphere mid-latitudinal sites in the 1989s and 1990s, lead to increases of both the UV-B and UV-A irradiance”

30 **With**

“Increases of both the UV-B and UV-A irradiance have been reported over several mid-latitudinal sites of the northern hemisphere since the beginning of the 1990s, which have been mainly attributed to decreasing attenuation by aerosols and clouds.”

35 **P2, L15: Replace “An” with “The”.**

P2, L15: Replace “the large urban agglomeration” with “large urban agglomerations”.

P2, L17: Replace “UV cloudless sky irradiances” with cloudless-sky UV irradiances”. Also replace “its suburbs” with “a sub-urban area near Athens”.

P2, L19: Replace “The erythemal irradiance at the centre of Athens was 30% lower than at the suburbs with similar values of total ozone (TO₃) for days with increased pollution in the air.”

40 **With**

“The erythemal irradiance at the centre of Athens was up to 30% lower than at the outskirts site during days with increased air pollution over Athens basin and similar values of total ozone (TO₃) over the two sites.”

45 Answer:

Suggested changes were made.

- 50 **P2, L20-21: What you write here is not clear. Please be more specific. Do you mean differences from the measurements or differences by corresponding simulations over the Athens basin?**

Answer:

55 The sentence was clarified (P2, L22-23): “A similar difference was noticed in the modelled UV-B irradiance with input from measurements of the total ozone (TO₃) and aerosols optical depth (AOD) by the Brewer spectrophotometer (BS) at the outskirts of Athens.

P2, L23: Delete “the” before “winter” and “summer”. Replace “Mexico” with “Mexico City”.

60 **P2, L23-24: Are 9% and 21% the differences between the annual mean levels for winter and summer? Please be more precise.**

P2, L24-25: “ Corr et al. (2009) ... 0.7 – 0.85”. This sentence is not clear. Please rephrase.

P2, L26: Delete “atmospheric”

P2, L30: Delete “of aerosols”

5 Answer:

Suggested changes were made.

10 **P3, L3-8: Notice that for a typical Angström parameter of ~1.5, the differences in AOD becomes ~2 times larger for UV-B wavelengths. I suggest that you should provide quantitative estimations of the changes in UV irradiance due to the reported differences in AOD (e.g. for a low SSA = 0.85) at this point, to prove that the reported differences in AOD do not induce large differences in UV irradiance. That can be easily achieved by performing modeling simulations. Furthermore, it should be mentioned that for organic particles, the absorption in the UV range may be even larger than that predicted by interpolating using the Angström parameter for the visible range of the spectrum (e.g. see Bais et al. (2015)* and references therein).**

15 *** Bais, A. F., R. L. McKenzie, G. Bernhard, P. J. Aucamp, M. Ilyas, S. Madronich, and K. Tourpali (2015), Ozone depletion and climate change: impacts on UV radiation, *Photochemical & Photobiological Sciences*, 14(1), 19-52, doi:10.1039/c4pp90032d.**

20

Answer:

We performed numerical simulations of the ratio with the use of measured AOD for both sites in the revised manuscript (section 3.3). The reference was added on P3, L8-10:

25 “However, for organic particles, the absorption in the UV range may be larger than predicted using Angström parameters for the visible range of the spectrum (Bais et al., 2015).”

P3, L4: Remove “,” after “stated”.

P3, L6: “the difference” instead of “it”

30 **P3, L11: Delete “a specific”**

P3, L14: Delete “at”

Methodology

35 **P3,L23: Replace “at Belsk (51.8°N, 20.8°E, 190 m amsl), which is located in a rural region” with “Belsk (51.8°N, 20.8°E, 190 m amsl). The latter is a rural region”**

P3, L25: Replace “the area” with “an area”

P3, L28: Replace “spectra accuracy” with “spectral accuracy”

40 Answer:

Suggested changes were made.

P4, L3: Please provide reference(s) regarding the fact that the estimated uncertainty in the erythemal irradiance is 5%.

45

Answer:

The reference is:

50 Gröbner, J., and Schreder, J.: Protocol of the intercomparison at the Polish Geophysical Institute, Warsaw, Poland, May, 20-22 2004 with the travelling standard spectroradiometer B5503 from ECUV within the project QASUME, http://www.pmodwrc.ch/wcc_uv/qasume_audit/reports/2004_05_poland_warsaw_PGII.pdf, 2004.

55 **P4, L8: In this section you describe how each Brewer (207 and 64) is calibrated. Was the calibration procedure for the two Brewers the same before and after BS207 was moved to Warsaw? Is BS207 also calibrated against BS017? Please add some more information to convince the reader that the changes in the ratio are not due to a change in the calibration procedure or due to change of the BS207 characteristics during transportation from the one site to the other.**

60 Answer:

We added information about the BS207 calibrations on P4, L11-13:

“BS207 was calibrated against BS017 in 2012 and 2013. After the calibration in 2013, it was moved to Warsaw. Furthermore, it has been calibrated 3 to 4 times per year since 2010 with a set of standard lamps that allows elimination of instrument ageing (loss of its sensitivity to UVR).”

5

P4, L11: Replace “The erythemal action spectrum follows CIE (1987)” with “The erythemal action spectrum is that suggested by the Commission internationale de l'éclairage (CIE) (CIE, 1987)”

Answer:

10

The suggested change was made.

P4, L13: Were there any criteria for the selection of the partly daily doses used for the comparison between Belsk and Warsaw? Is there a minimum amount of measurements (or measurements per 1 or 2 hours) below which the data are rejected? Calculation of the integral from only a small number of measurements and/or large gaps in the 3- or 6-hour period may lead to large differences between the integrals for the two sites. If not already done, I would suggest using a filter (e.g. use only time intervals with at least one measurement per 1 - 2 hours).

15

20

Answer:

We used a filter to 10 measurements per day. BS064 takes measurements 3 times per hour, while BS207 takes measurements 2 times per hour. It changes only if one of the BSs does not work properly, and then the previous filter should be enough. We added the filter for specific time intervals and a few points were removed. Although, that did not have any impact on the ratios.

25

P4, L15: How confident are you for your cloud detection method? Are there cloudy cases that cannot be detected? Can you estimate if, and in what extent, they affect your results?

30

Answer:

The answer to this question was incorporated in the text on P4, L23-24:

“There is no strict mathematical criterion applied here, but rather an intuitive inspection of the time series shape.”

35

P4, L23-30: The specific paragraph is carelessly written. Please try to re-write it more carefully.

Results

Figure 1: Add some more information in the manuscript for LOWESS filter and/or proper references.

P5, L8-9: I think that the phrase “The most of the differences lie within $\pm 5\%$ range” is not necessary here since in the previous paragraph the 1σ uncertainty (which by the way is 7%) is given.

40

Answer:

Suggested changes were made. We added information and reference to LOWESS method on P4, L29-30: “The LOWESS (Locally Weighted Scatterplot Smoothing) filter (Cleveland, 1979) was used for smoothing of the curves.”

45

The reference is:

Cleveland W.S.: Robust Locally Weighted Regression and Smoothing Scatterplots, Journal of the American Statistical Association 74(368): 829-836, 1979.

50

Figure 2a: In the specific figure there are two data points near 0.9. Is there any explanation for this large difference between the results from the two instruments for the particular days?

Answer:

55

Yes, they were probably affected by clouds and were removed.

P5, L22: Please specify that the higher latitude of the site at Warsaw means that for the same time, the solar zenith angle over Warsaw is always lower by $\sim 0.5^\circ$ compared to Belsk.

60

P5, L23: replace “surface albedo” with “different surface albedo”

P5, L25: replace “in” with “to perform”

P5, L27: Replace the phrase “prescribed values of surface albedo equal to 0.03 at Belsk and a set {0.03, 0.06, 0.12} in Warsaw” with “standard values of surface albedo equal to 0.03 for Belsk and 0.03, 0.06 and 0.12 for Warsaw”

5 P5, L28: Replace “of” before TO3 with “between” and delete “in”

P5, L30: Do you mean “coincidence” instead of “correspondence”? In this case it is for the entire range of the TO3 variability of both sites and not only of Belsk.

P6, L1: “assuming that” instead of “assuming”

10 Answer:

Suggested changes were made.

15 **Figure 4: There is an obvious annual cycle of the ratio. I suppose that this is due to the stronger effect of the 0.5° difference in SZAs in winter, when the SZAs are larger. Thus, the effect of larger albedo compensates for the effect of different latitude only for a specific period of the year. The same annual cycle is obvious in Figure 5, possibly due to the remaining effect of the difference in SZA. Given that in Figure 4 there are no results for December and January, when the effect of SZA is expected to be even larger, while in Figure 5 there are results for the particular months, I believe that the deviation of the**
20 **mean ratio from unity is partially due to the effect of different SZAs. I suggest that you should either quantify the remaining effect due to different SZAs and take it into account in the discussion of the results presented in Figures 5 and 6, or alternatively compare the irradiances for specific SZAs (thus slightly different time).**

25 Answer:

Yes, we do agree with the Referee #1. We restructured the modelling section (now section 3.3) and performed a set of numerical simulations with LibRadtran. The dependence of the ratio on SZA was shown in Figure 6.

30 P6, L11: remove “of”

P6, L11: remove “in”

P6, L15: replace

“in the periods symmetrical around local noon for 6h for all-sky and 3h before noon for cloudless sky conditions”

35 with

“for 6h symmetrical periods around local noon for all-skies, and 3h periods before local noon for cloudless skies”

P6, L17: Delete “previously”

P6, L19: Replace “The” with “A”

40

Answer:

Suggested changes were made.

45 **P6, L23: It seems to me that the ratio oscillates around ~1.05 and not 1. As already commented, I believe that part of the spread in the calculated ratios is due to the remaining effect of the difference in the latitude of the two sites.**

Answer:

50

Yes, we do agree with the Referee #1. It was changed on P6, L15: “The ratio oscillates around 1.05 within the range between 0.9 and 1.2.”.

55 **Figure 5: I suppose that the slightly different pattern of the temporal evolution of the ratios for the erythemal doses and the UV-A1 doses are again because of the effect of the different SZA. The effect of different SZAs is stronger for lower wavelengths, being partially responsible for the larger ratios of the erythemal doses compared to those of the UV-A1 doses.**

We do agree with the Referee #1.

60

P7, L6: “attenuates” instead of “attenuate”
P7, L10: “emissions” instead of “emission”

Answer:

5

Suggested changes were made.

P7, L11: add references to support your statement that “causing numerous cases over the EU air quality threshold”

10

Answer:

The reference was added on P7, L27-28: “(...) causing numerous cases over the EU air quality threshold (Monitoring System of Air Quality in Mazowieckie Region, <http://sojp.wios.warszawa.pl/>).”.

15

P7, L12: what do you mean with the phrase “makes specific boundary layer”? Please explain (e.g. is the upper limit of the boundary layer higher compared to the nearby rural areas?).

P7, L12-13: Add references.

20

Answer:

The explanation and references were added on P7, L29-31:

“(…) i.e. in the boundary layer factors like wind, temperature, moisture, turbulence and energy budget fields differ from nearby rural sites (e.g. Fortuniak et al., 2005, Miao et al., 2009, Haberlie et al., 2015).”.

25

P7, L15: “higher AOD at 500 nm over Warsaw” instead of “higher Warsaw AOD values at 500 nm”

P7, L16: “similar differences” instead of “similar values”

P7, L21: “~2% more attenuation” is more accurate than “~2% attenuation”.

30

Answer:

Suggested changes were added.

35

P7, L21-24: Again, these numbers may change after re-evaluation of the effect of the SZA.

Answer:

Re-evaluated numbers were added on P8, L2-7:

“(…) the Belsk/Warsaw ratio between the erythemal and UV-A (324 nm) doses is ~1.06 and ~1.04, whereas the ratio is ~1.08 and ~1.06 for all-sky conditions, respectively. The aerosol effects are responsible for ~2% larger erythemal and UV-A near-noon doses at Belsk. The cloud effects add 2%, enlarging the Belsk-Warsaw difference. The SZA effects due to the longitudinal/latitudinal difference between the sites lead to 3% (or 2%) greater erythemal (or UV-A) doses at Belsk. The difference is even larger in the cold period of the year (for higher SZAs). The unexplained 1% higher doses at the rural site for the erythemal doses ratio could be attributable to instrument issues.”.

40

45

P7, L30-31: “An Indirect method for BS has been proposed by Bais et al. (2005)” instead of “Indirect method for BS has been proposed (Bais et al., 2005)”

50

Answer:

The suggested change was made.

55

P8, L2: add appropriate reference to support that the typical SSA for rural sites is 0.92.

Answer:

The explanation was added on P5, L7: “(...) SSA=0.92, which is a mean value measured by the CIMEL sunphotometer at Belsk (...)”.

60

P8, L2-4: Since the overall difference is 6% and AOD difference is responsible for 2% (according to what is written in the previous paragraph) then SSA differences should compensate for 4% - and not 5% - of the difference. However, this might be different if you take into account the effect of the SZA.

5

Answer:

The discussion about SSA and AOD effect was changed, after taking into account the effect of SZA. It is in section 4 (P8, L8-18):

10 “It seems possible that urban aerosols lead to higher absorption of the UV irradiance, i.e. small SSA values (<0.9) could characterise such aerosols. On the other hand, the albedo of urban surfaces is higher in the snowless period, that may compensate the effects of lower urban aerosols’ SSA. Analysing the UV radiation in the Mexico City metropolitan area, Castro et al. (2001) found the urban albedo of 0.12 over asphalt and grey surface cement sites. This is four times larger than the commonly used albedo of 0.03 over grass. Parisi et al. (2004) found that
15 over some non-shaded parts 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. We performed RTM simulations with the observed TO3 and AOD values over Warsaw to fully compensate (by absorbing aerosols) the UV increase due to changes in albedo from 0.03 to 0.12. SSA=0.86 and 0.85, for SZA=60° and 30°, respectively, are found for the city site, i.e., 0.06 and 0.07 less than the value previously used in our RTM simulations for rural aerosols. Such
20 estimate looks probable, as the Warsaw observing site is among the most polluted parts of the city because of abnormal vehicle emissions in the nearby main city roads.”

P8, L5-7: I suggest moving the sentence “Kazadzis et al. (2009b) ... quality there” to P7, L27, after “... to SSA changes.”

25 **P8, L6: “in Thessaloniki” instead of “in the Thessaloniki”**

Answer:

Suggested changes were made.

30

P8, L20 – 31: As already commented, the effect of difference in SZA is more pronounced during the cold period (larger SZAs) and less pronounced during the warm period (smaller SZAs). The effect of different SZAs has to be removed – or taken into account - properly, so that you can get more accurate conclusions.

35 Answer:

It was reconsidered.

40 **Figure 8: I recommend adding a paragraph (e.g. 3.4) and expand the discussion relative to Figure 8. Furthermore, the discussion regarding the agreement of your results with the results of other recent studies (e.g. Zerefos et al. (2012), de Bock et al. (2014), Fountoulakis et al. (2016)), as well as the reasons for this agreement could be expanded.**

Answer:

45

We have decided to remove this figure and the part of the discussion as it is not connected with the Belsk-Warsaw comparison.

50 **P8, L24 - 26: “Thus, it seems possible that increased cloudiness over urban areas does not necessarily mean increased attenuation of solar radiation, since modification of the cloud structure and properties by the urban aerosols may lead to the formation of clouds which attenuate the solar radiation less effectively” instead of**

55 **“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”**

P8, L27: “the” instead of “an”

P8, L32: “level” instead of “levels” and “higher than in the past” instead of “high”

Answer:

60

Suggested changes were made.

P8, L33: Zerefos et al. (2012) discuss the trends of the UVR after the mid-1990s. Thus, in the particular study they do not discuss the increase of the UVR due to the decrease of ozone until the mid-1990s.

5 **P9, L2-3: Add proper reference to support your statement that that the environmental pollution was enormous in the mid-1970 and early-1980. Furthermore, the UV increases because aerosol and clouds decrease relative to the past – not because they were high in the past.**

P9, L6: I do not think that 5-8% is “slightly” lower. I suggest removing the phrase “only slightly”.

10 Answer:

This part of the manuscript was removed. The long-term trend is out of main scope of the revised manuscript.

P9, L8: “parts” instead of “part”

15

Answer:

Suggested change was made.

Response to Referee's #2 (Uwe Feister) comments

General remarks

5 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.
10 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.

15 Answer:

The title and figures were changed.

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

Answer:

25 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?

30 Answer:

35 We modelled 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 modelling 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 –
40 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. 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.

45

Detailed comments

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

50 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'

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

Page 7, line 7: ‘radiation’

Answer:

Suggested changes were made.

5 **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:

10 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:

15 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?

20 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.

25 **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.

30 **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:

35 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.”

40 **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:

- 5 The captions and vertical axis names were changed.

~~An~~Effects of urban agglomeration ~~effect~~ on surface UV doses: Comparison ~~a comparison~~ of ~~the~~ Brewer measurements in Warsaw and ~~at~~ Belsk, Poland, for the period 2013-2015

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Abstract. ~~The specific~~Specific aerosols and cloud properties over large urban regions seem to generate an island, similar to the well-~~known~~known city heat island, leading to lower UV radiation intensity compared to the surrounding ~~cleaner~~less polluted areas, thus creating a shield against excessive human exposure to ~~the~~ UV radiation. The present study focuses on differences ~~in the~~between erythemal and UV-~~A1 (340-400A)~~(324 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~~. ~~The latter~~ is ~~located in~~ a rural region ~~at a distance of~~located about 60 km ~~in the~~ south-west ~~direction from of~~ the city. ~~The ratio~~Ratios between erythemal and UV-~~A1A~~ partly daily doses, obtained during all-sky and cloudless-sky conditions ~~in for~~ the period May 2013-December 2015, ~~are analyzed~~were analysed to infer a specific cloud and aerosol forcing on the surface UV doses over Warsaw. Radiative model simulations ~~are were~~ carried out to ~~assess impact~~find sources of the ~~Warsaw-Belsk~~observed 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 solar elevation differences due to latitude differences as the mean total ozone values appear almost the same over both~~ ~~between the~~ sites. It ~~is was~~ found that Warsaw urban agglomeration induced 8% and ~~56~~56% attenuation of the erythemal and UV-~~A1A~~ doses, respectively, ~~which could be caused by~~ mostly due to the lower Sun elevation in Warsaw during the near-noon measurements, and the larger aerosol absorption. It appears that a slightly increased optical depth of the city aerosols and increased cloudiness. It could be hypothesised that the expected stronger absorption of the solar UV radiation by urban aerosols and properties of clouds generated over Warsaw are less important for the UV attenuation. In this work we are showing that the is compensated here by a higher city surface albedo compensates for the solar UV attenuation caused by urban aerosol load in the city of Warsawsurface reflectivity over the city.

1 Introduction

Excessive exposure to the ultraviolet radiation (UVR) reaching the Earth's surface has a detrimental impact on the human health. ~~Overexposure~~The overexposure to UV-B radiation (290-~~315nm~~315 nm) can cause erythema (redness of the skin), DNA and cellular damage (due to the generation of the reactive oxygen species), and ~~immunosuppression~~immunosuppression. Longer UV wavelengths, UV-A (~~315-400nm~~400 nm), can be ~~cancerogenetic~~cancerogenic but also responsible for photoaging, and various eye diseases, including ~~cataract~~. ~~Both overexposure to cataracts. Overexposure to both~~ 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 ~~depende~~dependent on the latitude and thickness of the ozone layer, ~~UVA~~UV-A, especially UV-A1, the so-called long-wave UV-A (~~340-400nm~~400 nm), is ozone independent, more intense, and less variable with latitude (Sabziparvar et al., 1999). ~~The absorption by SO₂ (in the UV-B range) and NO₂ (mostly in the UV-A range) is important for the surface UV attenuation only in extreme concentrations of such gases. The surface intensity of UV depends significantly on properties of clouds and aerosols. The negative trends in these variables, found over many of the northern hemisphere midlatitudinal sites in the 1989s and 1990s, lead to increases of both the UV-B and UV-A irradiance (e.g. Krzyścin et al., 2011; Zerefos et al., 2012; De Boek et al., 2014).~~ In the spectral range up to ~330 nm, absorption by ozone is usually much stronger than absorption by other main trace gases (SO₂, NO₂) (Cede et al., 2006).

~~An~~The intensity of the solar UV radiation at the earth's surface depends significantly on properties and amount of clouding and aerosols. Upward UV-B and UV-A trends have been reported over several mid-latitudinal sites of the northern hemisphere since the beginning of the 1990s, which have been mainly attributed to decreasing attenuation by aerosols and clouds (e.g. Krzyścin et al., 2011; Zerefos et al., 2012; De Bock et al., 2014).

Attenuation of the incoming solar radiation seems to be higher over ~~the~~ large urban ~~agglomeration~~agglomerations relative to ~~the~~ surrounding rural areas due to the excessive light scattering and absorption by ~~the~~ anthropogenic aerosols. Papayannis et al. (1998) found differences between ~~UV~~ cloudless-sky UV irradiances measured over Athens and ~~its suburbs~~suburban area near Athens. In Athens, the concentration of atmospheric aerosols was higher than at the ~~outskirts~~suburban site. The erythemal irradiance at the centre of Athens was up to 30% lower than at the ~~suburbs with similar values of total ozone (TO₃) for suburban site during~~ days with increased air pollution ~~in over~~ the air. ~~Similar~~Athens basin. A similar difference was noticed ~~on the basis of the numerical simulations of in the modelled~~ UV-B irradiance with input from measurements of the total ozone (TO₃) and aerosols optical depth (AOD) 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~~this period in winter, the erythemal irradiance was 9% greater at in the suburbs than in

the centre of Mexico City, while during the summer, the recorded values were up to 43% greater (the mean value was 21%). Corr et al. (2009) found ~~for Mexico City aerosols enhanced strong~~ absorption ~~at UV wavelengths with of UVR by urban aerosols over Mexico City with a~~ single scattering albedo (SSA) in the range 0.7-0.85. Even larger attenuation (~~~ 60%~~) of the UVR due to ~~atmospheric aerosols of ~60%~~ was reported in Guangzhou, China, in the dry season from October ~~up to~~ 5 January (Deng et al., 2012). Kazadzis et al. (2009a) found that ~~at for~~ some cloudless days, differences in AOD among three sites (~~an~~ urban, rural, and industrial area) located in Thessaloniki and at the outskirts of the city can ~~cause account for~~ up to 20% differences in ~~the~~ UV irradiance. ~~Meleti et al. (2011) and Fountoulakis et al. (2016) noticed that the surface UVR measured in trends in the amount of absorbing urban aerosols over Thessaloniki may be sensitive to another characteristic of the atmospheric aerosols, the single scattering albedo of aerosols, which may might~~ counteract the ~~effects expected UVR increase due to the long-term decrease~~ of AOD ~~changes~~ there.

The atmosphere over Poland is one of the most ~~dust particulate matter (PM)~~ polluted in Europe. ~~The~~ PM10 and PM2.5 levels measured in Warsaw, as well as in most ~~other~~ larger cities in Poland, exceed the tolerable PM limit many times during ~~the a~~ year (Polish Ministry of Environment, ~~2012~~2014). However, Zawadzka et al. (2013) analyzed ~~the~~ measurements taken by the Microtops II and CIMEL sunphotometer and stated, that a small positive bias for AOD at 500 nm between 15 Warsaw and a rural site (Belsk), which is ~~in ~60 km distance from the city in the south-west direction of the city~~ was not larger than 0.02, whereas for ~~greater lower~~ values of wind velocity ~~it the difference~~ reached 0.04. The bias calculated from satellite measurements with ~~the~~ MODIS (Moderate Resolution Imaging Spectroradiometer) was ~0.05. The authors did not ~~claim find~~ any significant differences in the Angström parameters between the sites for the visible ~~ranges range~~, so it could be ~~hypothesized, hypothesised~~ that AOD values in ~~the~~ UV range also differ only slightly.

20 ~~_____ The geophysical variables possibly affecting the However, for organic particles, the absorption in the UV range may be larger than predicted using Angström parameters for the visible range of the spectrum (Bais et al., 2015). Similar differences in the ground level of the surface UVR between a city and remote sites are: clouds, aerosols, and surface albedo. Warsaw and Belsk were reported by Chubarova et al. (2011), who analysed results of aerosol measurements by the CIMEL sunphotometers located in Moscow (megacity with a population over 10 million) and Zvenigorod (population of approx. 16 thousand).~~

25 ~~_____ It seems possible that a large urban agglomeration could produce generate specific cloud properties (due to the heat island effect and creation of a specific cloud condensation nuclei consisting of urban aerosols), higher loading of aerosols, and higher albedo, than that in urban sites. 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 erythemal and UV-A1A (324 nm) radiation measurements by the 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., serial number 64, (BS064), and in Warsaw since 2013 by the double monochromator BS-No., serial number 207 (BS207) installed on the roof (elevation ~25 m above street level) of the IGF PAS main building. Previously, BS-207BS207 was working at Belsk (2010-2013). Comparison of BS-No. 64BS064 and BS-No. 207BS207 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-207BS207 was moved to Warsaw in the middle of 2013.

The present study focuses on differences in the erythemal and UV-A1 (340-400A (324 nm) doses measured by the BSs in Warsaw (52.3°N, 21.0°E, 130 m amsl) and at Belsk (51.8°N, 20.8°E, 190 m amsl), which). The wavelength 324 nm was chosen because it is one of the longest wavelengths measured directly by both BSs and the gaseous absorption by the main trace gases (O₃, NO₂, and SO₂) is weak at this wavelength. The Belsk observatory 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, Surroundings of the city measuring site is located in the area, which is a mixture of different surfaces: consist of grass, trees, concrete constructions (buildings, pedestrian footpaths), and asphalt roads.

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 of 0.6 nm (FWHM). The spectraspectral accuracy decreases for greaterhigher values of AOD and for larger solar zenith angles, i.e. for cases with an enlarged contribution of the 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., serial number 17 -BS-No.-17(BS017). BS017 itself is regularly compared with the set of three Brewer instruments, so-called "Brewer reference triad" (Fioletov et al., 2005). BS-No. 64BS064 was also compared with Bentham DM-150 during the project Quality Assurance of Spectral Ultraviolet Measurements (QUASUME) in May 20142004 (Gröbner et al., 2005, 2006). The estimated 1σ uncertainty of the erythemal irradiance is about 5%-% (Gröbner and Schreder, 2004).

BS207 is the newest type instrument - Mark III, thatwhich is equipped with a 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. TheIts spectral characteristics are the same as BS064, however the spectral range is 290-363nm in 0.5 nm steps with almost similarwider extends to BS064 spectral resolution363 nm. BS207 iswas calibrated against BS017 in 2012 and 2013. After the calibration in 2013, it was moved to Warsaw. Furthermore, it has been calibrated 3 to 4 times per year since 2010 with a set of standard lamps yielding -5%that allows elimination of measurement spectrum error:instrument ageing (loss of its sensitivity to UVR). For both instruments, the SHICRivm software has beenwas used to extend the spectra up to 400 nm and to eliminate erroneous spectra (Slaper et al., 1995).

The erythemal irradiance is calculated as the integral over ~~the~~ wavelength ~~of the range~~ 290-400 nm BS spectra after the SHICRivm ~~standardization~~ ~~standardisation~~, which ~~are~~ ~~is~~ weighted by the erythemal action spectrum. The ~~integration for~~ UV-A+A (324 nm) irradiance is ~~taken~~ without ~~any~~ weighting. The erythemal action spectrum ~~follows is that suggested by~~ the Commission Internationale de l'éclairage (CIE) (CIE, 1987). Further, the partly daily erythemal and UV-A+A (324 nm) doses are calculated as ~~the~~ time integral of the pertaining ~~irradiance~~ ~~irradiance~~ for ~~the~~ 6h period for all-sky-conditions (local noon-3h, local noon +3h) and ~~the~~ 3h period for cloudless-sky conditions (local noon-3.5h, local noon-0.5h). ~~Solar noon is computed from the astronomical formulas corresponding to the specific day of the year.~~ Cloudless-sky conditions are identified using ~~the following~~ a two ~~steps~~ ~~step~~ algorithm. ~~First~~ ~~The first~~ step is ~~the approximate searching~~ ~~a preliminary search~~ for such days using the ~~following~~ criterion: ~~the~~ solar UV irradiance derivative with solar zenith angle is negative. In the next step, the smoothness of the time series for the day, which ~~meet~~ ~~fulfilled~~ the first criterion, is examined, i.e. the bell-shape of the UV ~~spectrum~~ ~~time series~~ must be ~~preserved~~. ~~In case of jumps in the series such day is omitted.~~ ~~identified.~~ ~~There is no strict mathematical criterion applied here, but rather an intuitive inspection of the time series shape.~~

Ratios between doses measured by BS064 and BS207, based on collocated observations at Belsk ~~in~~ ~~for~~ the period October 2010 – April 2013, allow us to estimate the uncertainty range ~~for~~ ~~of~~ the ratio related to differences in BS instrumental characteristics and in time of observations. The BS measurements are not ~~synchronized~~ ~~synchronised~~, as the spectrum ~~length is~~ ~~ranges are~~ different. The same ratio is measured ~~in~~ ~~for~~ the period of the Warsaw observations (May 2013 to December 2015) by BS207 to assess the ~~impact of the~~ urban agglomeration ~~impact~~ on the erythemal and UV-A+A radiation. The LOWESS (Locally Weighted Scatterplot Smoothing) filter (Cleveland, 1979) was used for smoothing of the curves.

~~Numerical simulations for the cloudless 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, TO₃, 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 erythemal doses. 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 (AOD 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.~~

Numerical simulations for the cloudless-sky conditions of the ratio between Warsaw and Belsk were performed to calculate differences caused by various factors, such as the geographical location (Belsk is slightly to the south), TO₃, surface albedo, and aerosols properties (AOD, SSA). Simulations were performed with the radiation transfer model (RTM) libRadtran (Mayer and Kylling, 2005). The following model input parameters, which are from the simultaneous measurements at both sites, are used in calculations: daily mean total ozone by the BSs standard measurements, AOD at 550 nm measured by the MODIS for the period 2013-2015. MODIS Aerosol Product values are available globally and include AOD at 550 nm over land and ocean. Remote sensing of aerosol properties using MODIS is presented by Ichoku et al. (2004). In this study, we used arrays of Level 2 (MOD 04, Collection 6) data produced daily at the spatial resolution of

10×10 km pixelation. From satellite data, we selected daily mean values of AOD from the nearest pixel to the measurement sites. Other input parameters are constants representing typical values used in the UV modelling, e.g. albedo of 0.03 for rural surfaces and SSA=0.92, which is a mean value measured by the CIMEL sunphotometer at Belsk (level 1.5 from AERONET – Aerosol Robotic Network) at 440 nm (<http://aeronet.gsfc.nasa.gov>). We used SSA at 440 nm as a constant for the whole ultraviolet spectrum, as it was found that monthly averages estimated from BS at Uccle were in close agreement with the CIMEL measurements at 440 nm, especially for 320 nm (Nikitidou et al., 2013). Furthermore, Liu et al. (1991) performed Mie calculations for the rural aerosol model (Shettle and Fenn, 1979) and suggested that for this type of aerosol, SSA is approximately independent of wavelength. There are no measurements performed for SSA at the UV wavelength range. To identify the impact of the selected parameter on the ratio between the sites' doses we use the RTM model, allowing variability only for this parameter and keeping constant other RTM input parameters. For example, to quantify the dependence of the ratio on the geographical location of the sites the RTM simulations were performed using fixed TO₃, AOD, and time (10:40 GMT), but the simulations were for consecutive days throughout the whole year.

3 Results

3.1 ~~Instruments comparison~~ Comparison between measurements at Belsk

In the period from October 2010 to April 2013 both BSs were working simultaneously at Belsk. Figure 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 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 A (324 nm) is $1.0402 \pm 0.07(1\sigma)$ for all-sky conditions.

~~The most of the differences lie within ±5% range but sometimes outliers~~ Outliers greater than 10% sometimes appear, as the measurements were not synchronous. It is difficult to have ~~synchronized~~ synchronised measurements by our BSs, as ~~the~~ scanning time is different, because of the ~~length of the spectrum~~ various spectral ranges, i.e. 290-325 nm for BS064 and 290-363 nm for BS207. ~~BS-064~~ BS064 measures UV spectrum three times per hour, ~~while BS-207~~ BS207 only two times per hour. 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~~ analysed the ratios derived from 3h cloudless-sky measurements before solar noon. The cloudless-sky doses were calculated for ~~the~~ shorter period compared to those for the all-sky conditions, as cloudless-sky conditions in Poland usually prevail before noon.

Figure 2a shows the time series of the measured BS064/BS207 ratio for the cloudless-sky conditions and the corresponding scatter plot (Fig.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-A1A (324 nm) doses, the ratio is $1.00 \pm 0.04 (1\sigma)$. Thus, ~~the~~ performance of BS064 and BS207 was practically the same

during the Belsk's intercomparison. The agreement between the output of both BSs was almost perfect, suggesting that the instrumental differences did not have much influence on the ratio between the doses.

3.2 Numerical simulations

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 TO_3 over the sites, and surface albedo. In this sub-section, the modelled cloudless sky doses over 6h period (+/- 3h to solar noon) are analyzed for Warsaw and Belsk. FastRT (Engelsen and Kylling, 2005) is used in the simulations taking into account real TO_3 values (i.e. daily mean 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 3a shows the time series of the daily ratio of TO_3 measured at Belsk and in Warsaw. Figure 3b illustrates the scatter plot of the daily data. The mean ratio (BS064/BS207) from all data points presented in Fig.3a is $1.00 \pm 0.01 (1\sigma)$. The correspondence between TO_3 values is found for the whole range of 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, 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 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 than that 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 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.

3.3.2 Comparison of erythemal and UV-A1 doses measured between measurements 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 (324 nm) doses calculated for these sites in the for 6h periods symmetrical around (local noon - for 6h - 3h, local noon + 3h) for all skyskies, and 3h before-noon periods (local noon - 3h, local noon-0.5h) for cloudless sky eonditions, areskies, were analyzed to find the Belsk-Warsaw ratio between the measured doses (BS064/BS207). If the ratio obtained during the cloudless-sky conditions differs significantly from that previously obtained during the cloudless-sky

conditions ~~for~~during the Belsk's BSs ~~operating in Belsk~~intercomparison, it will allow us to estimate the effect of urban aerosols ~~effect~~ on the surface UVR. ~~The~~ similar approach with the use of all-sky data will also provide an estimate of the effect of urban cloud ~~effect~~ on the surface UVR.

Figure ~~53~~ shows the time series of BS064/BS207 measured ratio for ~~the~~ erythemal doses (Fig. ~~5a3a~~) and the UV-~~A1A (324 nm) doses~~ (Fig. ~~5b) doses3b~~) for cloudless-sky conditions simultaneously appearing both in Warsaw and ~~at~~Belsk during 3h ~~before local noon~~measurements. The ratio oscillates around 1.05 within the range ~~-between 0.9- and 1.42~~. The main reason for this scatter is using the interpolated erythemal (or UV-~~A1A~~) irradiance ~~value~~values at the beginning (~~3.5 h before~~local noon-~~3.5h~~) and at the end (local noon-0.5h) of the calculated period. BS observations ~~were~~rarely ~~made exactly at the starting and ending coincided with these~~ 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 also taken into account. The mean value of the Belsk-Warsaw ratio is 1.06 ± 0.04 (1σ) and 1.0304 ± 0.04 (1σ) for the erythemal and UV-~~A1A (324 nm)~~ dose, respectively. The ~~same~~corresponding values calculated for ~~all-6h near noon~~doses (~~Fig.6~~) during all-sky conditions (~~Fig.4~~) are 1.08 ± 0.19 (1σ) and 1.0506 ± 0.1718 (1σ), respectively. Much larger uncertainty ranges of the estimates for all-sky conditions are due to the cloudiness effects, but the mean values of the ratio are only slightly larger than those found during the ~~Belsk's~~Belsk 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-~~A1A (324 nm)~~ doses. The 1-1 correspondence between doses is ~~kept~~maintained for the whole range of the data (Fig.~~75~~).

~~Standard~~The standard statistical test for ~~the~~a difference in the mean values taken from two large samples of an unknown distribution (Daniel and Cross, 2013) ~~is~~was used to evaluate, find out if ~~a higher~~the BS064/BS207 mean ratio obtained during Belsk-Warsaw comparison of BSs relative to is significantly larger than the ~~mean~~ratio found during the Belsk intercomparison ~~is statistically significant~~. The ~~working~~ hypothesis, that the mean ~~values~~value of BS064/BS207 ratio (~~both for cloudless sky and all sky conditions~~) ~~are~~is higher during the Belsk-Warsaw comparison, is supported by the test at the significance level >better than 0.01. ~~We conclude that the urban agglomeration only slightly attenuate both for cloudless-sky and all-sky conditions.~~

3.3 Sources of the Belsk-Warsaw differences in the erythemal and UV-A1 radiation. The aerosol effects are responsible for about 6% (or 3%) larger 3h erythemal (or UV-A1A) doses

The more northern location of the Warsaw site results in lower SZA of ~0.5° at Belsk and cloud effects only slightly enlarge the Belsk-Warsaw the same time for BSs observations. Other factors affecting the ratio between the measured doses at the rural and urban site during cloudless conditions are differences in TO₃, surface albedo, and aerosol properties (AOD or SSA). In this sub-section, the modelled cloudless-sky irradiances are analysed for Warsaw and Belsk to discuss sources of the BS064/BS207 ratio variability.

The difference, in the geographical coordinates for the sites, which are based on the simulations of the erythemal and UV-A irradiances at 10:40 GMT (i.e. ~2% both near local noon) throughout 2015 leads to slightly higher values at Belsk. The modelled ratio changes with SZA (Fig. 6). The average ratio over the whole year is 1.03 ± 0.02 (1σ) for the erythemal irradiance and 1.02 ± 0.01 (1σ) for UV-A doses_A (324 nm). For the warm period (from 15 May to 14 September) modelled ratios were 1.01 ± 0.003 (1σ) and 1.01 ± 0.002 (1σ), but for the cold period (from 15 September to 14 May) modelled ratios were 1.04 ± 0.01 (1σ) and 1.03 ± 0.01 (1σ) – for erythemal and UV-A (324 nm) irradiances, respectively.

The total ozone difference between the sites is quite small (Fig.7). The mean TO₃ ratio (BS064/BS207) taken from all coinciding daily TO₃ values is 1.00 ± 0.01 (1σ). All data points are in close proximity to the diagonal line representing the 1-1 relationship between the variables (Fig. 7b). The mean modelled ratios between the erythemal and UV-A (324 nm) irradiances calculated for the selected fixed SZA and the site measured TO₃ values are 1.00 ± 0.01 (1σ) and 1.00 ± 0.002 (1σ), respectively, for all considered SZAs (30°, 40°, 50 ° and 60°). Thus, TO₃ is not a factor responsible for the UV difference between the sites.

The AOD effect on the Brewers' ratio is inferred from the RTM simulations based on the measured AOD at 550 nm by MODIS for the period 2013-2015 on days when the data were available for both sites. Daily AOD means are taken into consideration. The calculation was performed separately for various SZAs (40°, 60 ° and 70°) and fixed SSA=0.92. Fig.8 shows that AOD at 550 nm is slightly higher over the city. The mean AOD is equal to 0.26 and 0.20 over the urban and rural site, respectively. RTM simulations performed using the observed AOD values for various fixed SZAs (40°, 60 ° and 70°) yield the BS064/BS207 ratio is almost the same 1.02 ± 0.02 (1σ) for all considered SZAs, for the erythemal and UV-A (324 nm) irradiances.

4 Discussion and conclusions

Warsaw agglomeration has over 3.5 million population, with high pollution due to the heavy vehicle emissions and industry (mainly electric power), causing numerous cases over the EU air quality threshold. (Monitoring System of Air Quality in Mazowieckie Region, <http://sojp.wios.warszawa.pl/>). Like other large cities, it is expected that Warsaw produces the well-known heat island that makes specific boundary layer, i.e. in the boundary layer factors like wind, temperature, moisture, turbulence and energy budget fields differ from nearby rural sites (e.g. Fortuniak et al., 2005, Miao et al., 2009, Haberlie et al., 2015), allowing anthropogenic aerosols to reach higher atmospheric layers that may enhance AOD 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 Angström exponent and higher Warsaw AOD values at 500 nm of about 0.02 i.e., ~10% of the overall mean AOD 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.

The Warsaw agglomeration attenuates only slightly the erythemal and UV-A (324nm) radiation. Under cloudless conditions, the Belsk/Warsaw ratio between the erythemal and UV-A (324 nm) doses is ~1.06 and ~1.04, whereas the ratio is ~1.08 and ~1.06 for all-sky conditions, respectively. The aerosol effects are responsible for ~2% larger erythemal and UV-A near-noon doses at Belsk. The cloud effects add 2%, enlarging the Belsk-Warsaw difference. The SZA effects due to the longitudinal/latitudinal difference between the sites lead to 3% (or 2%) greater erythemal (or UV-A) doses at Belsk. The difference is even larger in the cold period of the year (for higher SZAs). The unexplained 1% higher doses at the rural site for the erythemal doses ratio could be attributable to instrument issues.

It seems possible that urban aerosols lead to higher absorption of the UV irradiance, i.e. small SSA values (<0.9) could characterise such aerosols. On the other hand, the albedo of urban surfaces is higher in the snowless period, that may compensate the effects of lower urban aerosols' SSA. Analysing the UV radiation in the Mexico City metropolitan area, Castro et al. (2001) found the urban albedo of 0.12 over asphalt and grey surface cement sites. This is four times larger than the commonly used albedo of 0.03 over grass. Parisi et al. (2004) found that over some non-shaded parts 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.

Using the value of the erythemal radiation amplification factor due to aerosols of 0.15, which is defined for AOD at 550 nm (Krzyścin and Puchalski, 1998), it could be estimated that 10% AOD 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 difference (~6%) of the erythemal irradiance under cloudless sky conditions due to the urban pollution effect. It seems possible that higher absorption of UV irradiance, i.e. smaller SSA by the anthropogenic aerosols, is a factor that may be responsible for larger attenuation of the surface UVR in Warsaw.

We performed RTM simulations with the observed TO_3 and AOD values over Warsaw to fully compensate (by absorbing aerosols) the UV increase due to changes in albedo from 0.03 to 0.12. $\text{SSA}=0.86$ and 0.85 , for $\text{SZA}=60^\circ$ and 30° , respectively, are found for the city site, i.e., 0.06 and 0.07 less than the value previously used in our RTM simulations for rural aerosols. Such estimate looks probable, as the Warsaw observing site is among the most polluted parts of the city because of abnormal vehicle emissions in the nearby main city roads.

Fountoulakis et al. (2016) discussed factors important for the UV spectral variability in Thessaloniki. They pointed out that the cloudless-sky UV-A irradiances could be sensitive not only to AOD changes but also to SSA changes. Kazadzis et al. (2009b) analyzing Chubarova et al. (2011) found that UV-A irradiance increase in Thessaloniki for the period 1998- 2006 cannot be explained only by the AOD changes, but also by the changes of SSA over the area, due to the improvement of the air quality there. Chubarova et al. (2011) analysing results by CIMEL sun photometers located in Moscow and in Zvenigorod (less polluted site) found that the 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 radiation was 0.02-0.03 smaller than that obtained over from the clean site. It is worth mentioning that there is a lack of the direct retrieval to obtain SSA from UV spectral measurements. An indirect method for BS has been proposed (by 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 when AOD at 340 nm was less than 0.3. 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 ~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. Kazadzis et al. (2009b) found that UV-A irradiance increase in the Thessaloniki for the period 1998–2006 cannot be explained only by the AOD changes, but also by the changes of SSA over the area, due to improvement of the air quality there.

For all sky conditions the attenuation of the surface UV radiation in Warsaw is only slightly higher than that found during cloudless sky conditions, i.e. ~8% for erythemal doses and 5% for UV-A1 doses, which is ~2% greater than found for the cloudless sky case. Cloud-The cloud effects should be more pronounced during the warm period of the year, where the city heat island may generate stronger convection than that existing in the cold period of the year. 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 compared to rural sites in Kanto region. Moreover, urban heat islands lead to more thunderstorm initiation episodes (e.g. Shepherd, 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 the number of droplets, causing larger cloud optical thickness (COT) and finally higher 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 – 14 September. We expect expected to find a higher ratio for that period according to the classical theory stated above. However, the ratio is only slightly lower, i.e. $1.06 \pm 0.17(1\sigma)$, for the erythemal doses, and $1.0506 \pm 0.16(1\sigma)$ for UV-A (324 nm) doses. It, and part of this difference is the effect of different SZAs between the sites. This may suggest that contrary to the expectation, COT is smaller over the urban areas. Jin et al. (2005) discussed aerosol-cloud relationship over New York and Houston. They found that thick urban aerosols correspond to low COT there. Thus, it seems possible that even higher increased cloudiness over urban areas does not necessarily mean higher increased attenuation of solar radiation, because the urban aerosols modify since modification of the cloud structure compensating and properties by the urban aerosols may lead to the effect of increased cloud cover the reformation of clouds which attenuate the solar radiation less effectively.

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 (Krzyścin 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 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 suburbs of the city. Thus 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 and clouds over Warsaw cannot be treated as do not provide an effective shield against excessive human exposure UVR.

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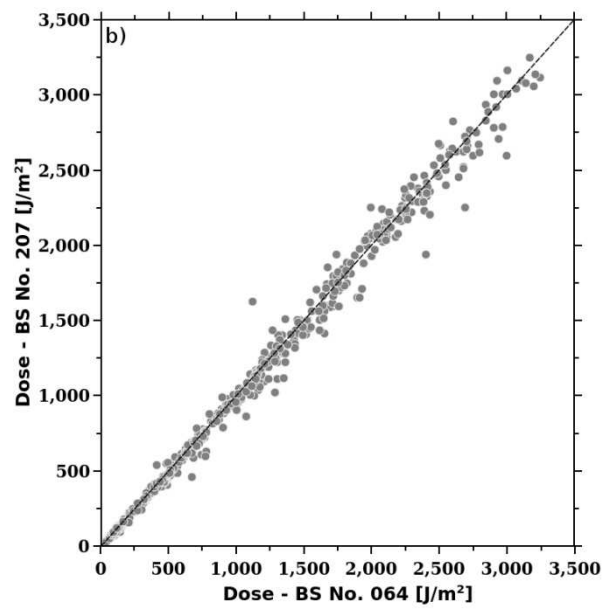
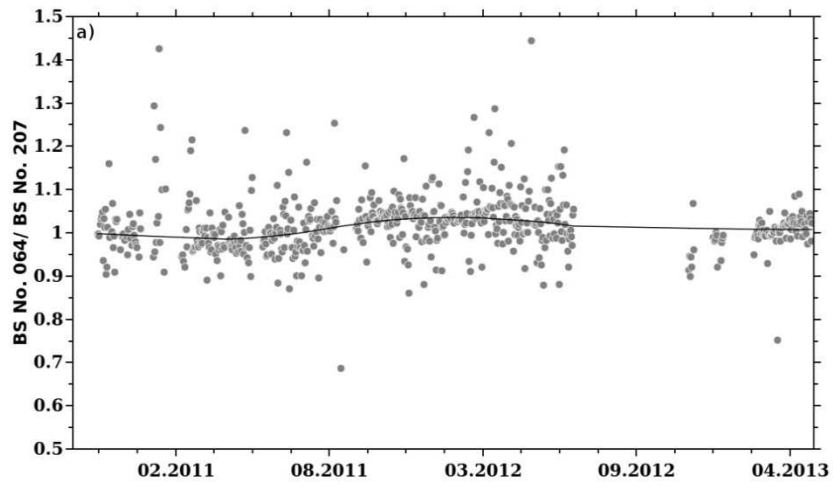
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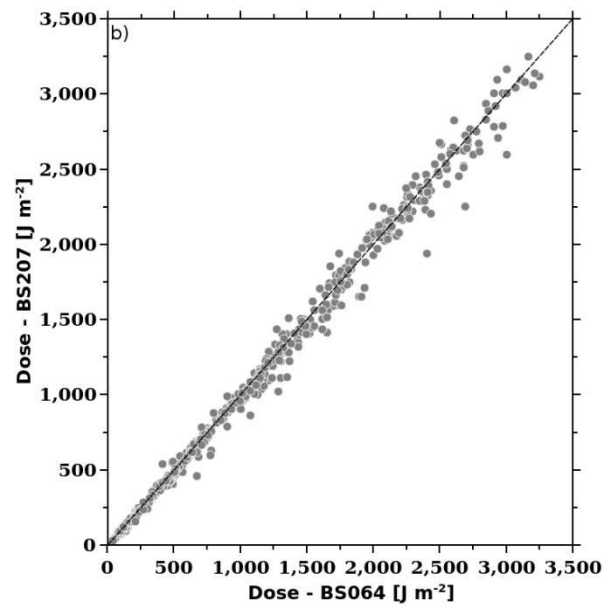
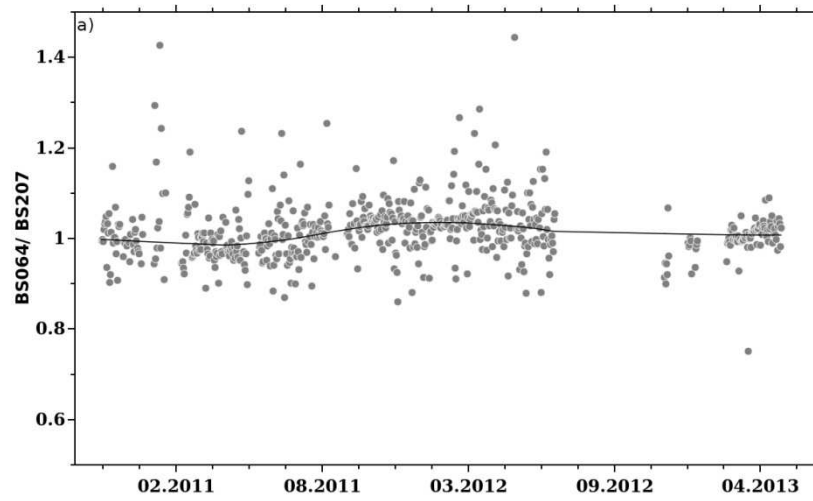
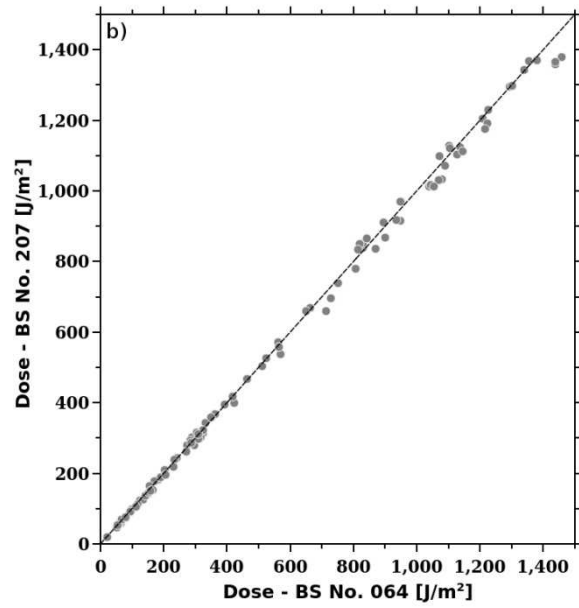
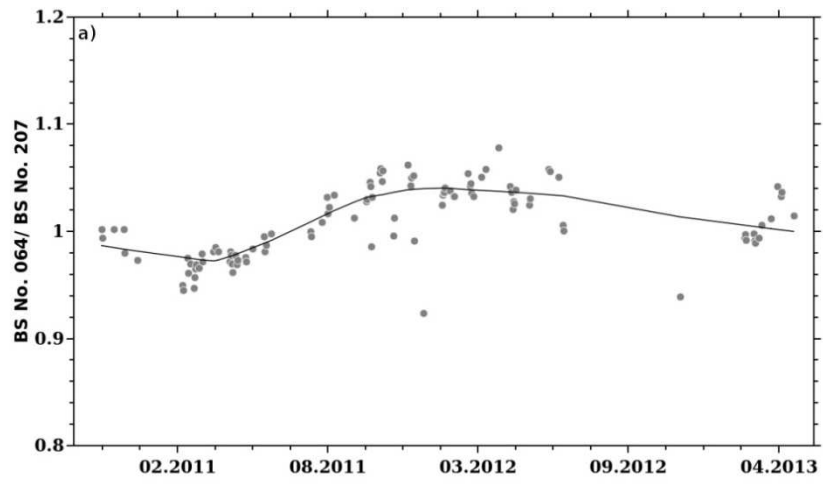


Figure 1a: The ratio between erythemal 6h (noon \pm 3 hr) doses measured by the Brewer Spectrophotometer No. 64 and No. 207 while working simultaneously at Belsk (all-sky conditions). The solid curve ~~represent~~represents the smoothed data by LOWESS filter.

Figure 1b: ~~The~~Scatter plot of doses measured by ~~the~~ Brewer ~~spectrophotometers~~spectrophotometers No. 207 ~~versus those~~ measured by the Brewer ~~spectrophotometer~~spectrophotometer and No. 64.



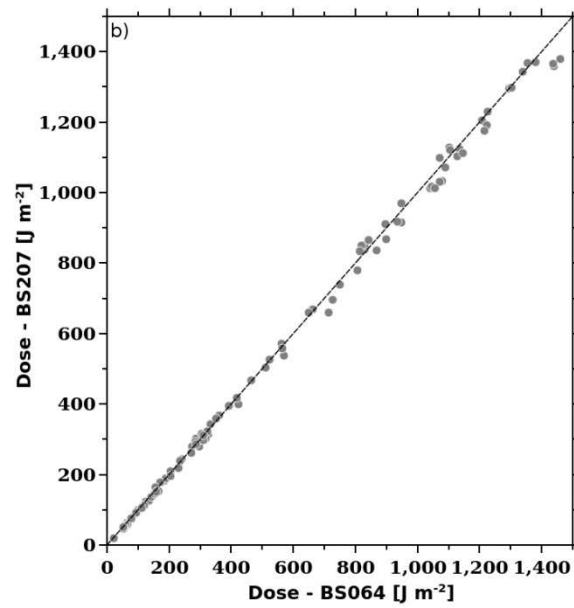
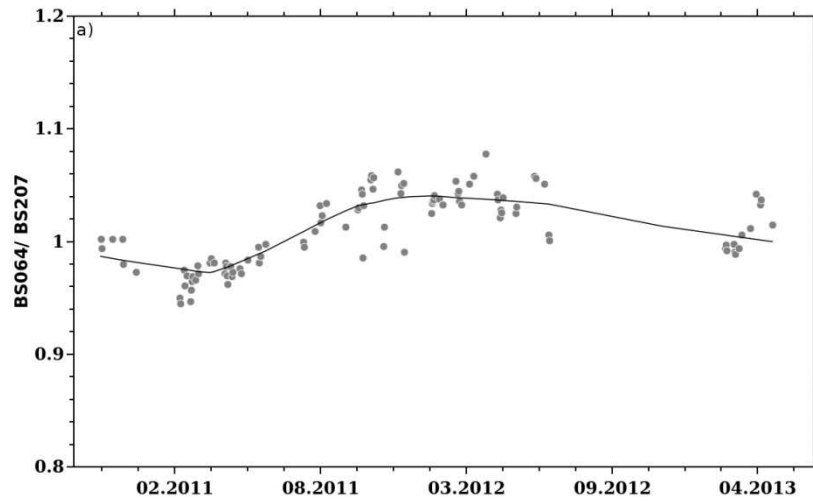


Figure 2a: ~~The same~~ Same as Fig.1a but for cloudless-sky conditions and 3h doses calculated for the period before noon (noon-3.5h, noon-0.5h).

5 | Figure 2b: ~~The same~~ Same as Fig.1b but for cloudless-sky conditions and 3h doses calculated for the period before noon (noon-3.5h, noon-0.5h).

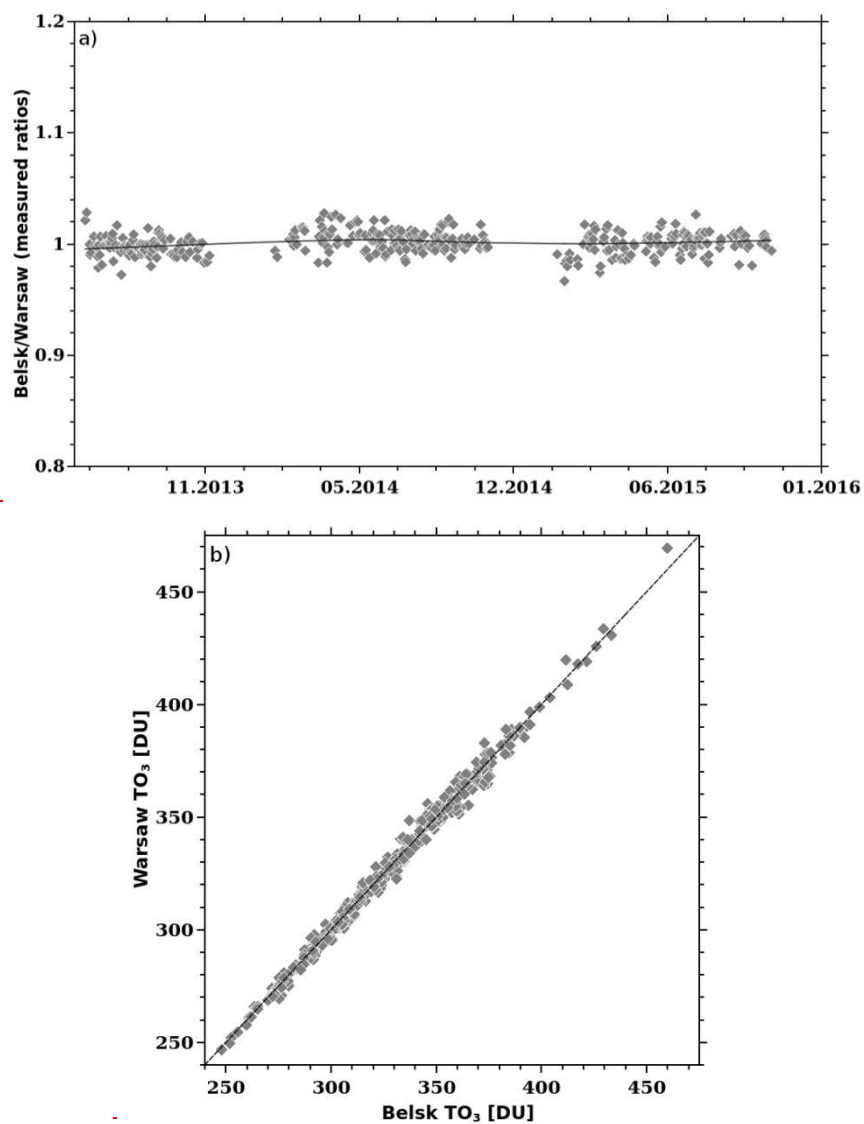
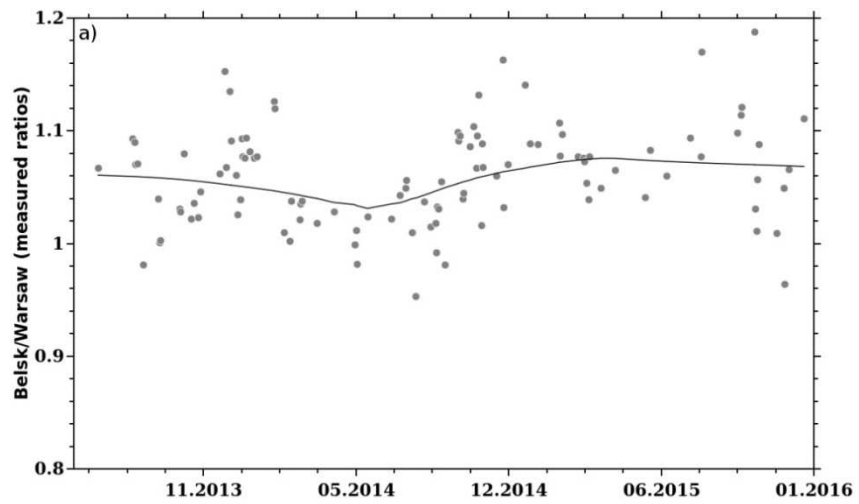
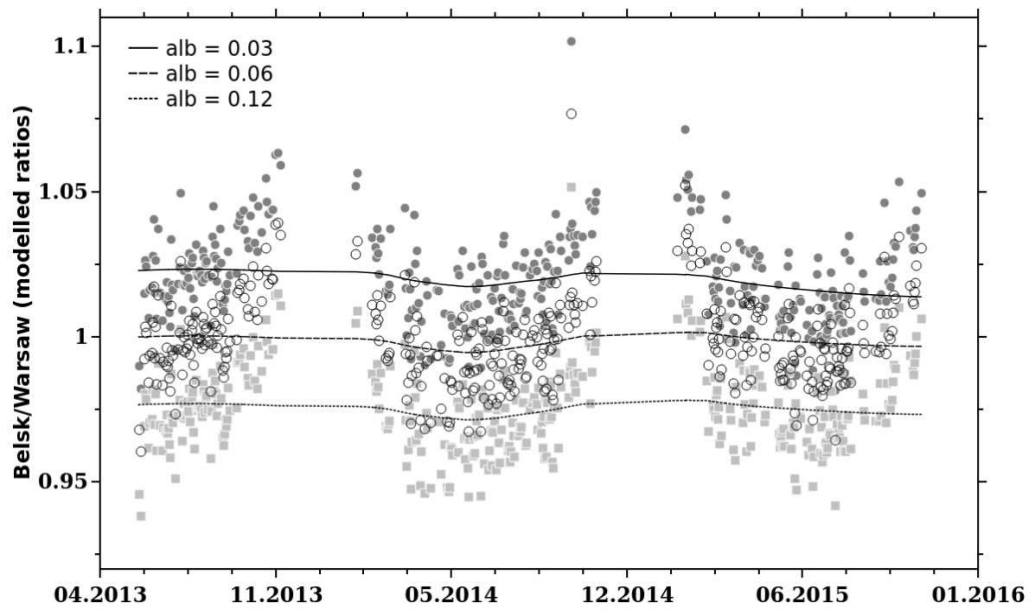


Figure 3a: The ratio between total ozone values measured by the Brewer Spectrophotometer No.64 and No.207 while working simultaneously at Belsk and in Warsaw for the period May 2013-December 2015. The solid curve represent the smoothed data by LOWESS filter.

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.



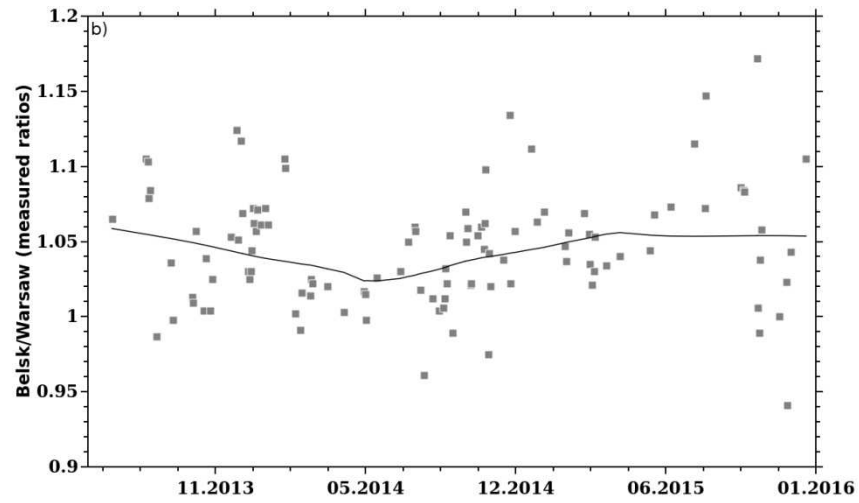
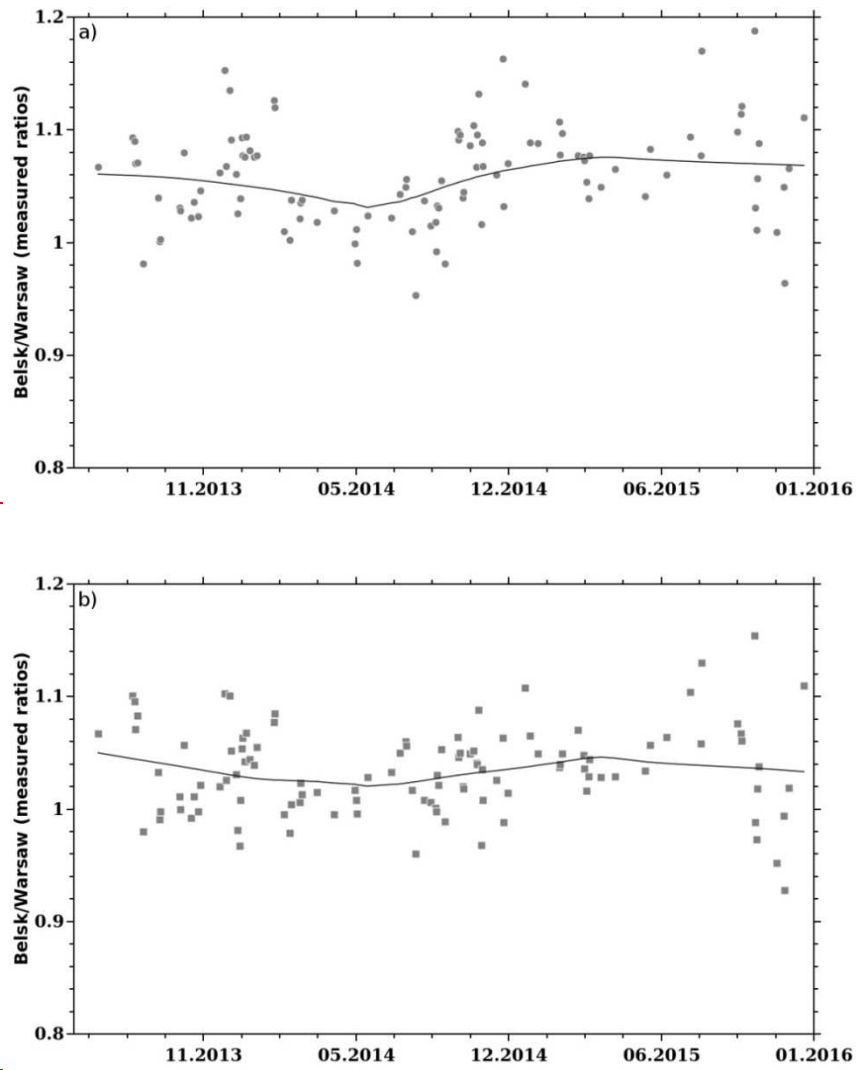
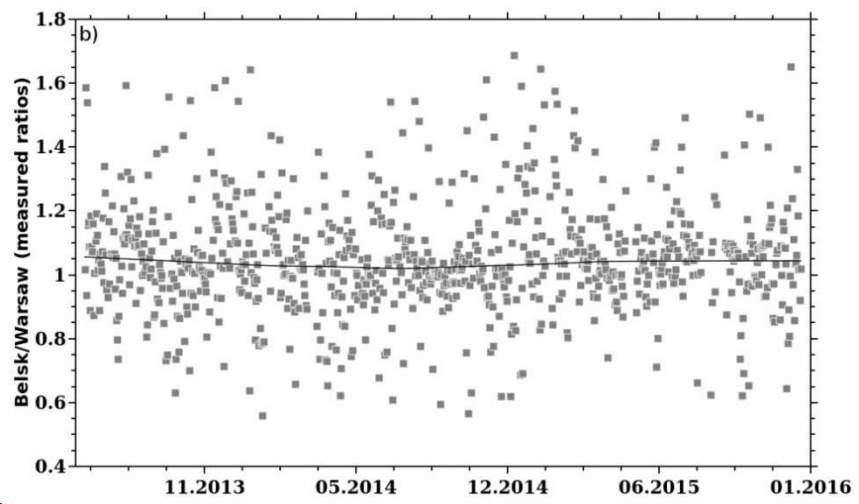
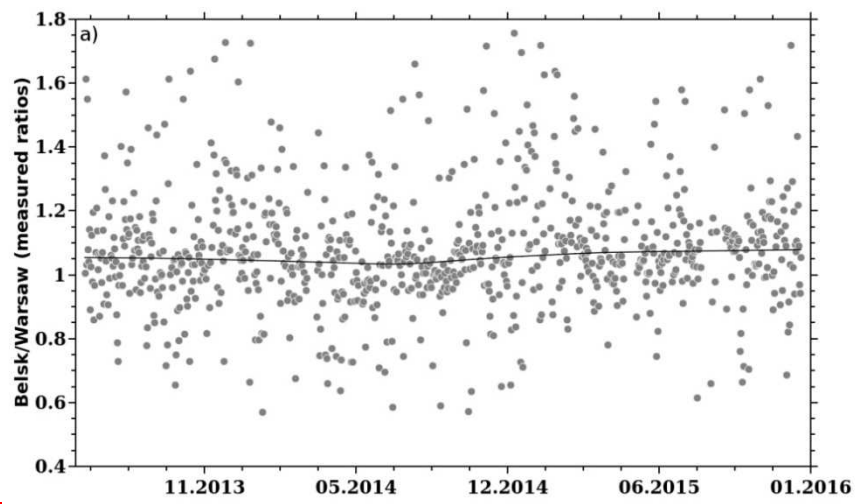


Figure 34: The Belsk/Warsaw ratio between partially daily 6 hr doses (local noon \pm 3h) calculated by FastRT model with following input values: total column amount of ozone measured by the Brewer spectrophotometer, SSA=0.92, AOD=0.32 at 340 nm, surface albedo 0.03 at Belsk and {0.03, 0.06, 0.12} in Warsaw. The solid curve represent the smoothed data by LOWESS filter.



5 **Figure 5: The Belsk/Warsaw ratio between the partially: The Belsk/Warsaw ratio between the partial daily 3h doses (noon-3.5h, noon-0.5h) measured during cloudless-sky conditions existing over both sites for erythemal doses (a) and UV-A1A (324nm) doses (b). Solid curves represent the smoothed data by LOWESS filter.**



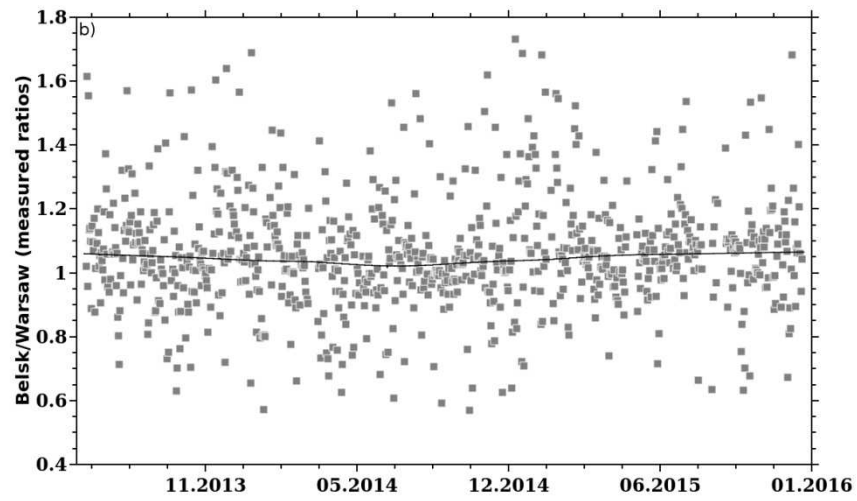
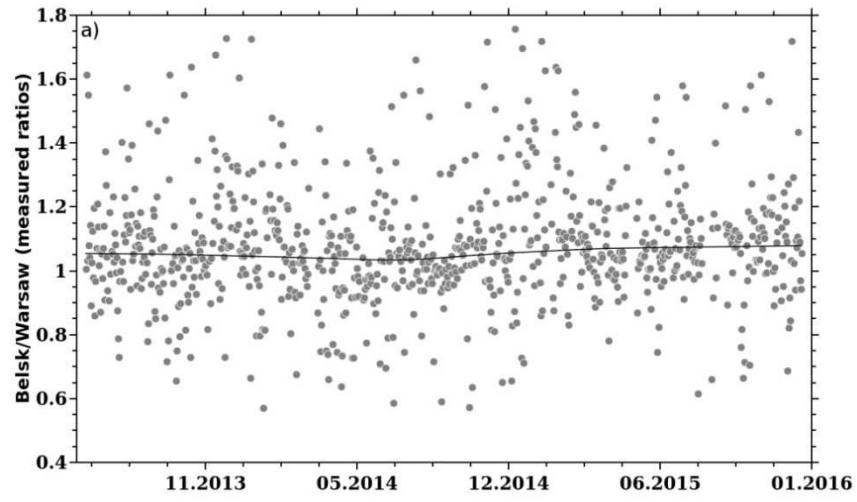
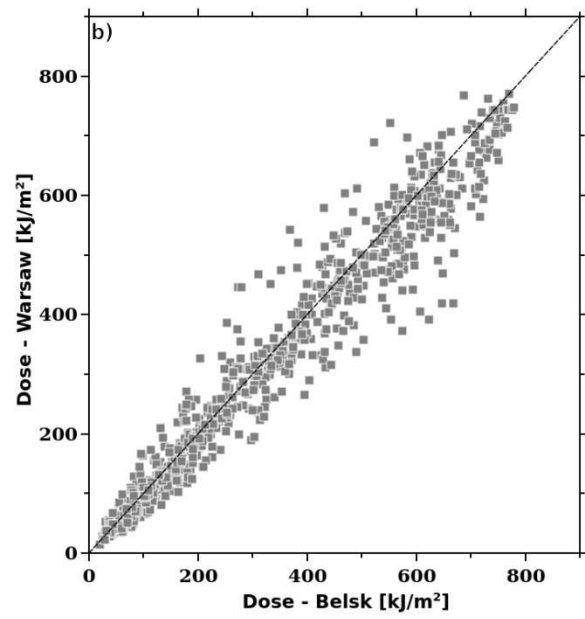
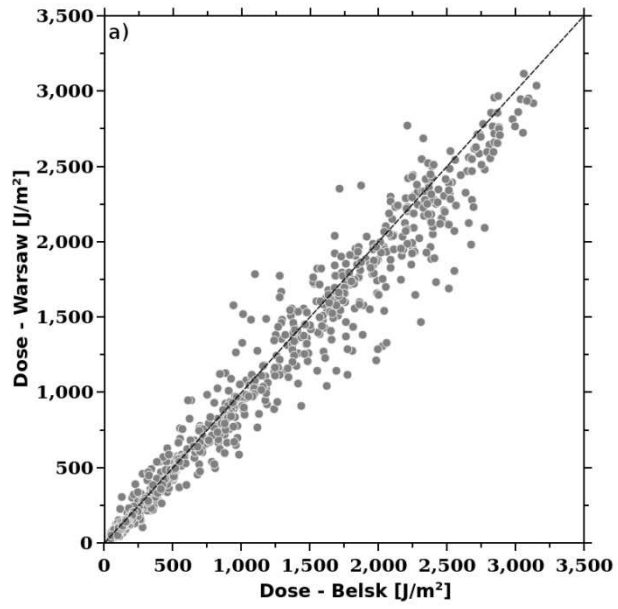


Figure 46: The same as Fig.5 but for the near noon partiallypartial daily dose (noon-3h, noon+3h) for all-sky conditions. Solid curves represent the smoothed data by LOWESS filter.

~~Solid curves represent the smoothed data by LOWESS filter.~~



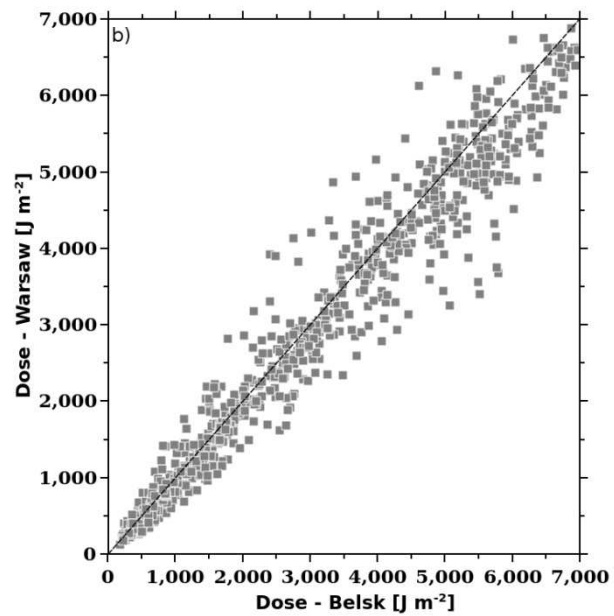
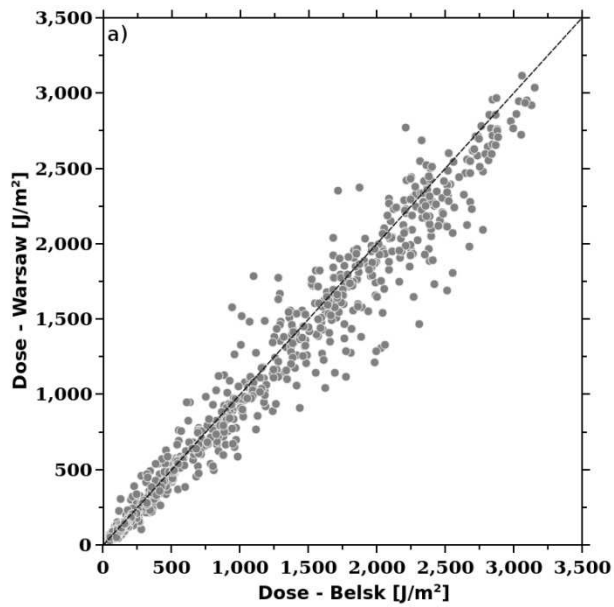
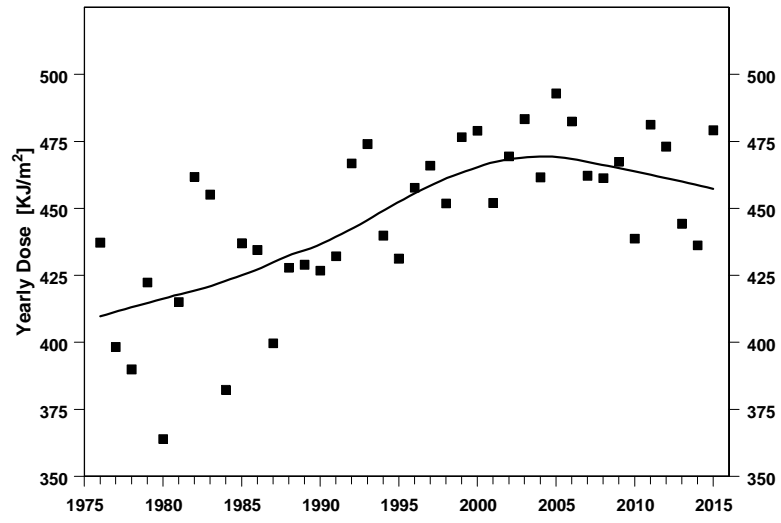
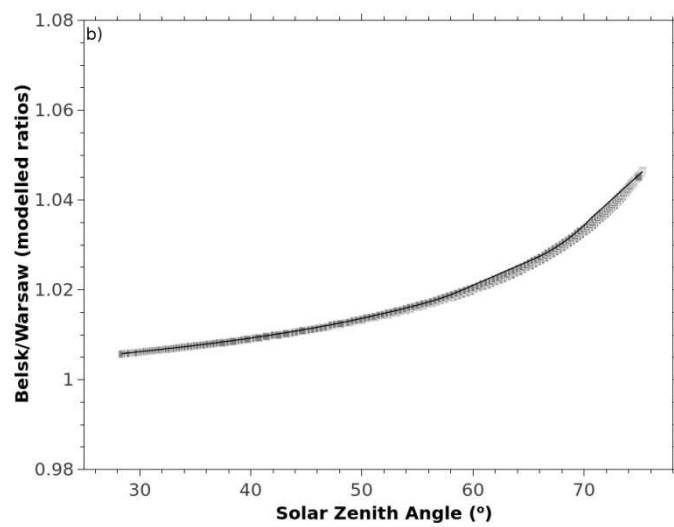
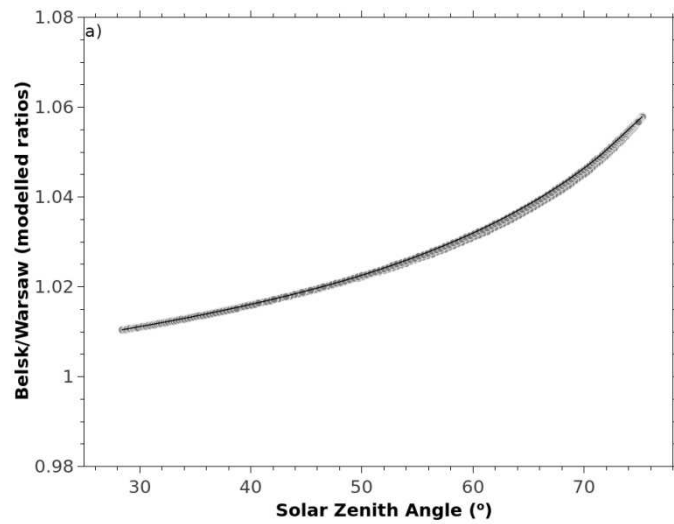


Figure 57: Partially: Scatter plot of partial daily near-noon-doses {(local noon-3h, local noon+3h)} measured in Warsaw versus those at and Belsk: erythemal doses (a) and UV-A1A (324nm) doses (b).





5 **Figure 68: Yearly means of the Belsk/Warsaw ratio between erythemal dose measured (a) and UV-A (324nm) (b) irradiances calculated by the libRadtran model for 2015 versus SZA at Belsk for the period 1976-2015 at Belsk (squares 10:40 (GMT)). The solid curve denotes the smoothed data by LOWESS filter.**

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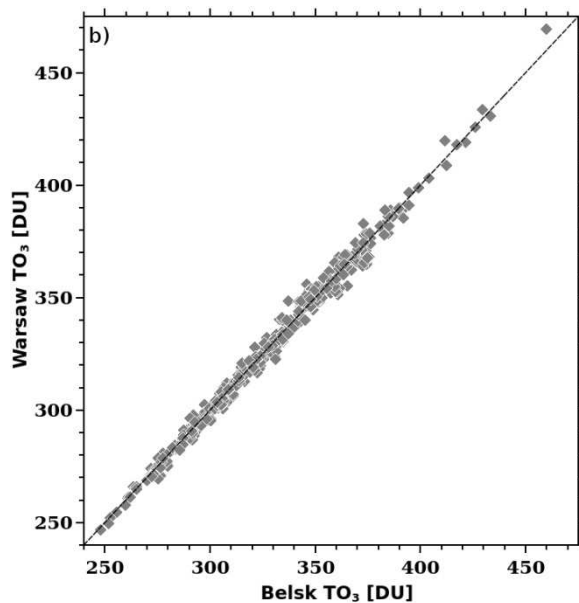
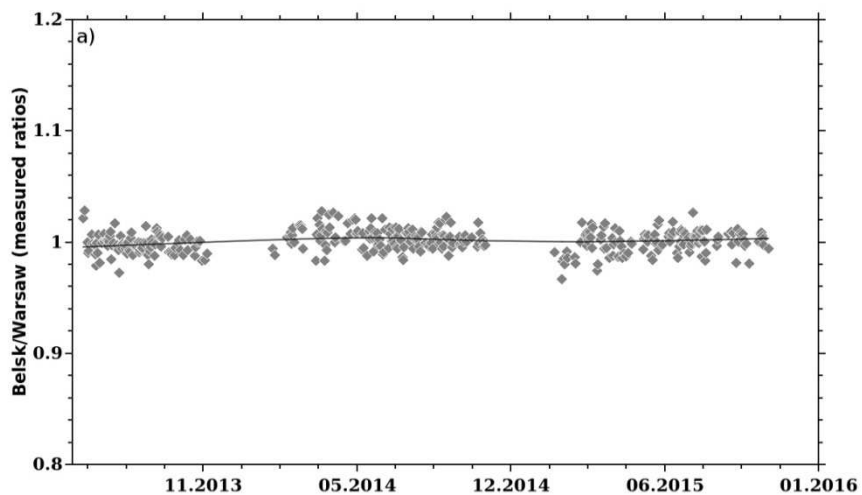


Figure 7a: The ratio between total ozone values measured by the Brewer Spectrophotometer No. 64 and No. 207 while working simultaneously at Belsk and in Warsaw for the period May 2013-December 2015. The solid curve represents the smoothed data by LOWESS filter.

Figure 7b: Scatter plot of total ozone values measured by the Brewer Spectrophotometers No. 207 and No. 064 while working simultaneously at Belsk and in Warsaw from May 2013 to December 2015.

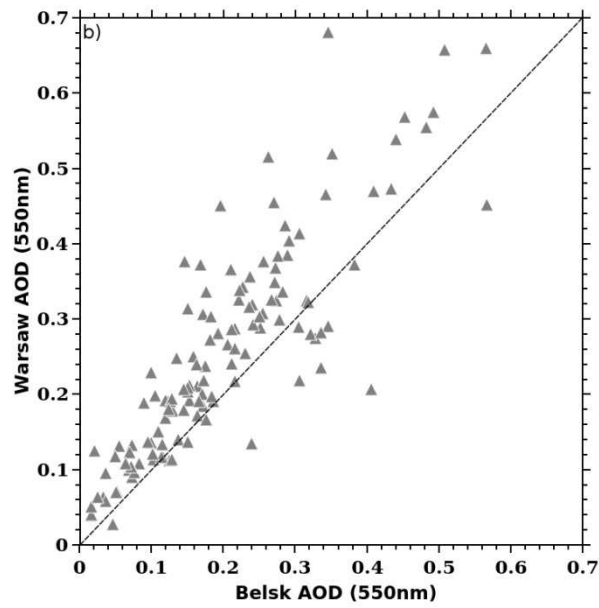
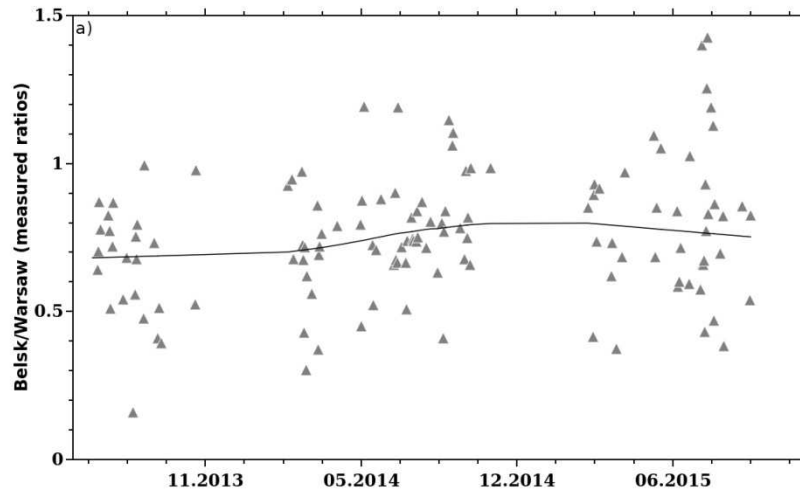


Figure 8a: The ratio between AOD at 550nm measured simultaneously by MODIS over Belsk and Warsaw in the period May 2013-December 2015. The solid curve represents the smoothed data by LOWESS filter.

5 **Figure 8b:** Scatter plot of AOD at 550nm measured by MODIS over Belsk and Warsaw from May 2013 to December 2015.