Aerosol layering in free troposphere, its impact on modification of the UV irradiation over industrial site in southern Poland

Institute of Geophysics
Polish Academy of Sciences

Aleksander Pietruczuk, Janusz Krzyścin, Artur Szkop , and Alnilam Fernandes
Institute of Geophysics Polish Academy of Sciences, Warsaw, Poland (alek@igf.edu.pl)

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In this study, we discuss the morphology of atmospheric aerosol layers in the free troposphere, i.e. above Planetary Boundary Layer (PBL), and their impact on the surface UV radiation. It is well known that aerosols attenuate solar radiation. However, only columnar characteristics of aerosols (e.g. optical depth, single scattering albedo, asymmetry factor) are usually used to determine the aerosols' impact on solar radiation reaching the Earth's surface. We would like to experimentally know to what extent aerosols layering above PBL affects UVB (290-315 nm) radiation measured at the ground level. Our interests are focused on short wavelength UV as it has a significant impact on human health.

The aerosols and UV radiation measurements were carried out at Raciborz Observatory (Fig. A1), which is a part of the Institute of Geophysics, Polish Academy of Sciences, observation network, for the period of January 1, 2017 – December 30, 2019. Raciborz is a town in southern Poland, close to the Czechia border (Fig. A2). This area is affected by local urban and industrial pollutions from the area of Silesia in South-Western Poland and North-Eastern Czechia. Remote locations of aerosols may also play an important role in UV radiation modification.

The observatory in Raciborz is equipped with CHM-15k Nimbus ceilometer (Fig.A3), which is used for identification of the aerosols layers, triple Sun-Sky-Lunar CIMEL sunphotometer (for determination of basic columnar characteristics of aerosols), and Kipp & Zonen UVS-E-T biometer measuring the intensity of the erythemally weighted solar radiation responsible for the appearance of skin redness causing skin cancer.

Ceilometers are effective instruments to study atmospheric profiles. They are primarily designed to study the cloud base height, but they are also widely used to study aerosol optical properties in vertical profiles (e.g. aerosol backscatter or extinction coefficients) or just atmospheric aerosol layering. In this work, we utilized statistical models of the free tropospheric aerosol layering impact on the surface UV, to explain differences between the measured and the modeled UV radiation at Raciborz. Figs. B1-B3 show examples of vertical profiles of the backscatter coefficient, which allow identifying layered structure of the atmospheric aerosols above PBL.

We introduce the following classification of the aerosols layers: attached to the top of PBL, residuals of the well-mixed aerosols previously trapped within PBL, and advected above PBL. In the observing period from 1st January 2017, to 30th September 2019 (1003 days), there were 931 profiles (92.8%) obtained regardless of the weather conditions. The layered aerosols' structure was found in 57.5% of the cases. Sometimes a heavy layer of low-level clouds disallowed for identification of aerosols in layers above the clouds. Fig.C1 shows monthly variations of frequency of days with the layers, and frequencies of appearance of three classes of the layered aerosols (summed 3-class frequencies is equal to 100%). Aerosol layers have the highest frequency in August (i.e. about 80% days with at least one layer) and the lowest in November (about 10% days). Frequencies of the class with the layer attached to the PBL top and the class of advected aerosols above PBL are almost equal throughout the year, ~40-50% of all the cases with layered aerosols. The layer with the residual aerosols is much less frequent ~10%.

Monthly statistics (mean and standard deviation) of characteristics of the aerosol layers are shown in Figs. C2-C3 and Figs.D1-D2. The following characteristics of the layer are considered: number of the layers per day, depth (the difference between the top and bottom of the layer), lifetime, the radiation attenuation factor equal to the layer depth (in km) multiplied by its mean backscattered light intensity. The backscattered light intensity changes from 0 to 4 for aerosols, 6-8 for cirrus, and ~ 10 for cirrus. The layer depth is lower in winter (0.5-0.7 km) and higher in summer (~ 1.25 km). A similar pattern is found for the radiation attenuation factor, i.e. ~1.5 (in winter) and 3.5 (in summer), as the mean value of the backscattered light intensity is almost constant (~3) throughout the year. The number of the layers per day (between 2 and 4) and the lifetime (around 8 hours) do not show seasonal variability.

The ceilometer observations of the backscattered light are combined with the concurrent measurements of the columnar properties of the aerosols by the CIMEL sunphotometer (CS) that belongs to the AERONET global network. The series of erythemal dose rates by the Kipp & Zonen UVS-E-T biometer during cloudless conditions in the period June-September 2019 are compared with the corresponding modeled ones derived from the radiative transfer model (Tropospheric Ultraviolet-Visible (TUV), Madronich and Flocke, 1997) simulations with the following input values: satellite (OMI) total ozone, the CS columnar characteristics of the aerosols (aerosols optical depth at 340 nm, Angstrom Coefficient for the 340-440nm range, single scattering albedo & total asymmetry factor at 440nm from the AERONET aerosol inversion (version 3) algorithm.

Fig.E1 shows the scatter plot of the measured 15–minute averaged erythemally weighted irradiances (from the Kipp & Zonen UVS-E-T biometer every minute observations under cloudless conditions) versus the averaged TUV modeled values using at least 3 CS observations within this period. In total, there were XXX observation/model pairs for comparison. There is a perfect agreement between the observed and the modeled 15-minute means of the erythemal irradiances. The model, which is based on the satellite ozone and columnar characteristics of aerosols, explains 99,7% of the variance of the observed irradiances. The model/observation differences are within ±5% range for almost 90% of the cases. The mean and median of the model/observation ratio of the erythemal irradiances are equal to 1.00 (Fig.E2). Thus, it seems that additional data concerning the aerosols layering could improve only slightly output of the TUV model. The version of the TUV model including vertical profiles of the aerosol extinction, single scattering, and asymmetry factor will require precise in situ observations of aerosols properties (by balloon sounding) or the aerosol data from meteorological/ climate reanalyses (e.g. MERRA-2) probably having large uncertainties.

Next, we find out how the model/observation ratio, which is based on 15-minute means of the modeled and observed erythemal irradiances, is sensitive to changes in characteristics of the aerosols layers in the free troposphere (above PBL). Two regression models are implemented (and compared): Stepwise regression and Random Forest. The former model finds out optimal linear regression on important (and statistically significant) explaining variables. The latter model combines many decision trees into a single regression model. The following potential regressors (i.e. variables with the expected impact on the model's output - the model/observation ratio) are arbitrarily selected: number of the aerosol layers, mean value of the layer base height, mean value of the layer top height, number of the PBL top attached layers (no.1 of the aerosol layering cluster), number of the residual aerosols layers (no.2 of the cluster), cumulative aerosol layer depth (sum of layers' depths found in a 15-minute period), cumulative radiation amplification coefficient (sum over all layers found in the 15-minute period for the variable - depth of the layer x backscattering ratio). The cumulative values are needed as sometimes there are many layers over the site in the 15-minute period.

Fig.F1 and Fig.F2 show the scatter plots of the observed ratio (between 15-minute means of erythemal irradiances by TUV model and those measured by the biometer) versus the ratio modeled using Random Forest and Stepwise regression, respectively. Random Forest performs much better as it explains ~52% variance of the ratio whereas Stepwise regression only 18%. Evidently, the linear regression using the selected regressors is not able to account for all sophisticated processes responsible for the UV transmissions to the ground (e.g. multiple scattering of solar light between the aerosols layers). Random Forest approach could reveal the impact of the aerosol layering on the surface UV and estimates that the ratio changes in the range ± 5% (from 0.95 to 1.05 see Fig.F1). It means that sometimes TUV model based on the columnar properties of aerosols underestimate (or overestimate) the surface UV. Here, only a simple parameterization of the vertical profile of the aerosols extinction is proposed. Other important aerosol properties (e.g. size distribution, single scattering coefficient, asymmetry factor) are not included in the calculations. It seems that the next step will fill this gap and we hope that the aerosol reanalysis data (Merra -2?) will provide valuable aerosols profile data to be used in the surface UV modeling.

Madronich, S., and S. Flocke (1997), The role of solar radiation in atmospheric chemistry, in Reactions and Processes,Handb. Environ. Chem.,vol. 2, part L, edited by P. Boule, pp. 1–26, Springer, New York.

Conclusions:

1) The surface UV radiation measured by standard biometer (Kipp & Zonen) under clear-sky conditions is sensitive to the aerosol layering above Planetary Boundary Layer
2) The ceilometer measurements of the atmospheric backscatter coefficient allow to construct proxies to identify the aerosol layering impact on surface radiation.
3) Aerosols layering over the industrial site in Poland, Racibórz, has seasonal variability
4) Random Forest is a perspective tool to study the effects of aerosols layering on surface radiation

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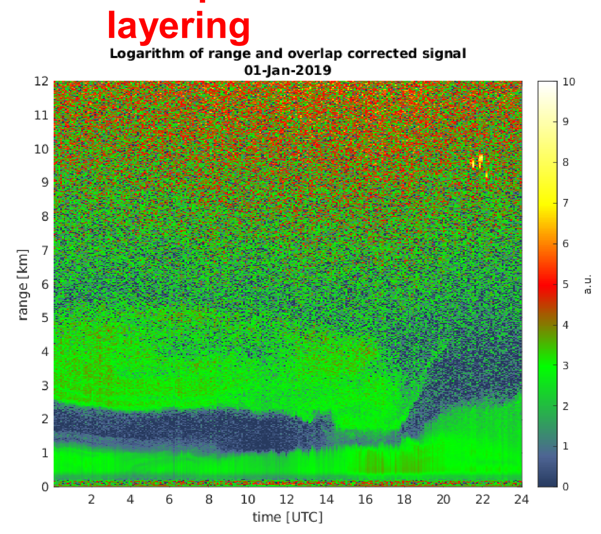
A1. View of Raciborz station

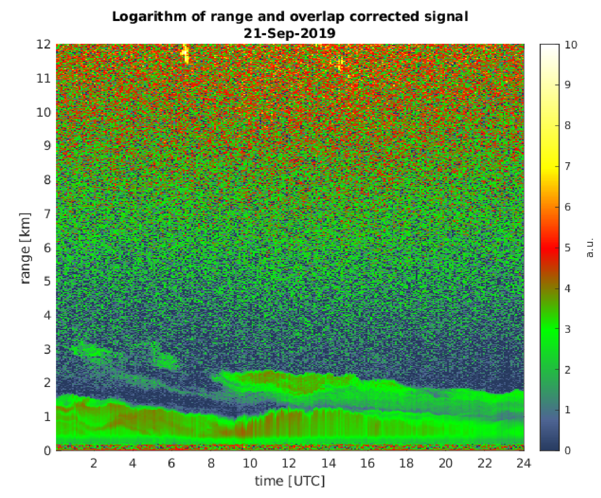
A2. Location of Raciborz station

A3. CHM-15K Ceilometer

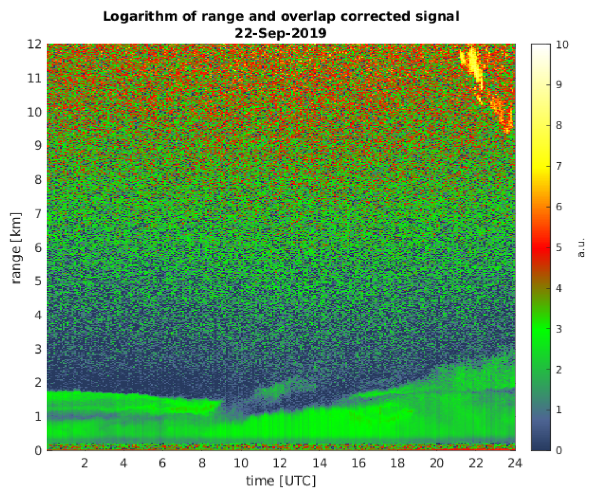
B1. Example 1 of the aerosols layering



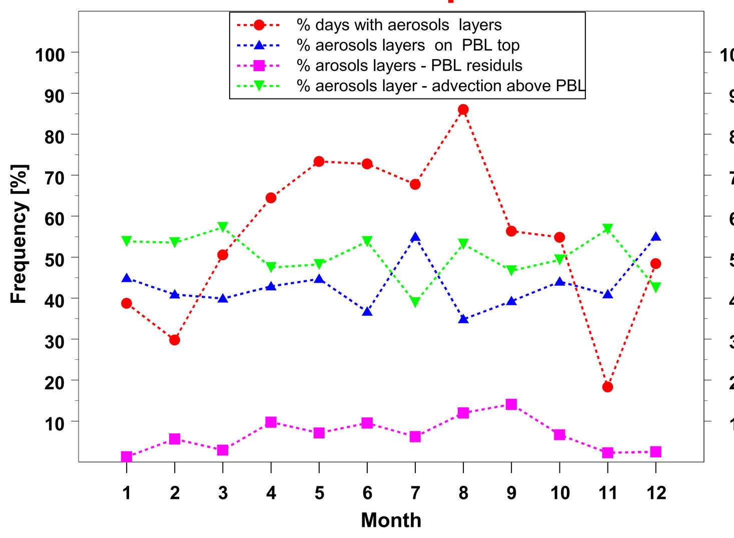
B2. Example 2 of the aerosols layering



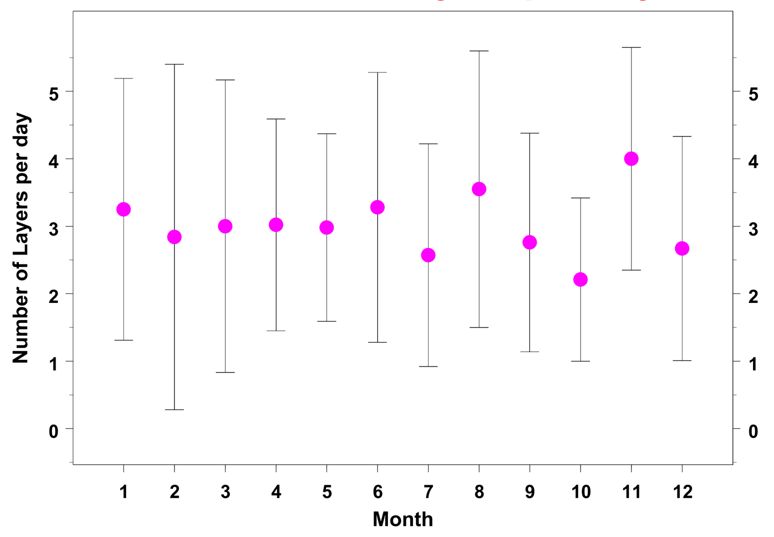
B3. Example 3 of the aerosols layering



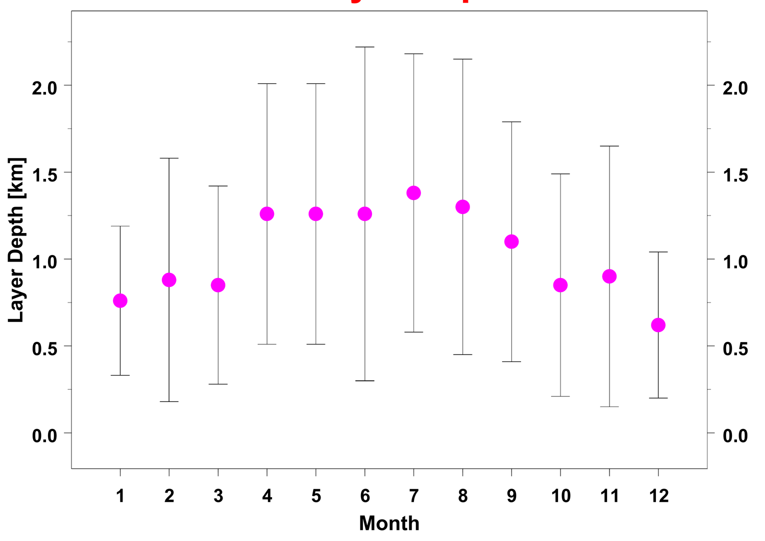
C1. Seasonal pattern of the aerosols cluster frequencies



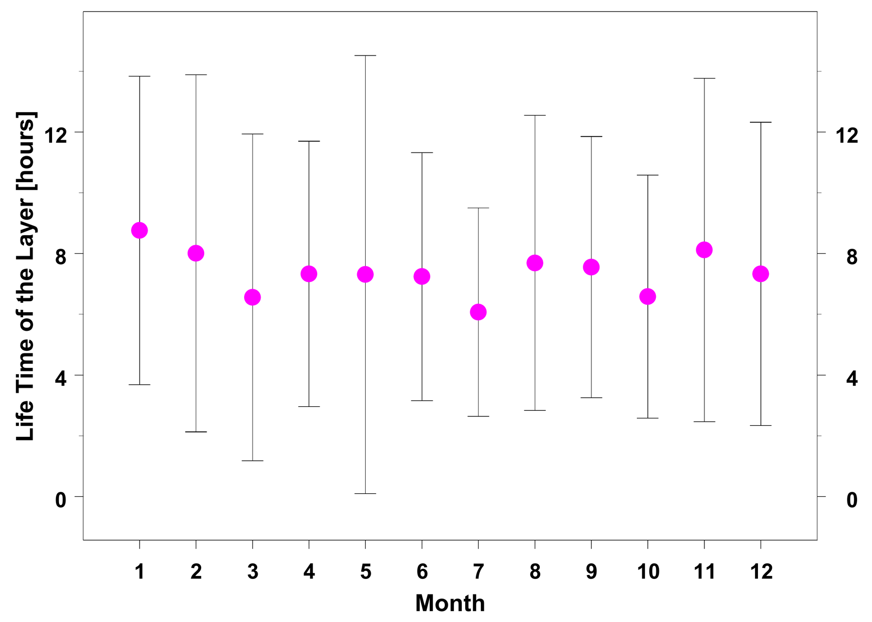
C2. Seasonal pattern of the number of aerosols layers per day



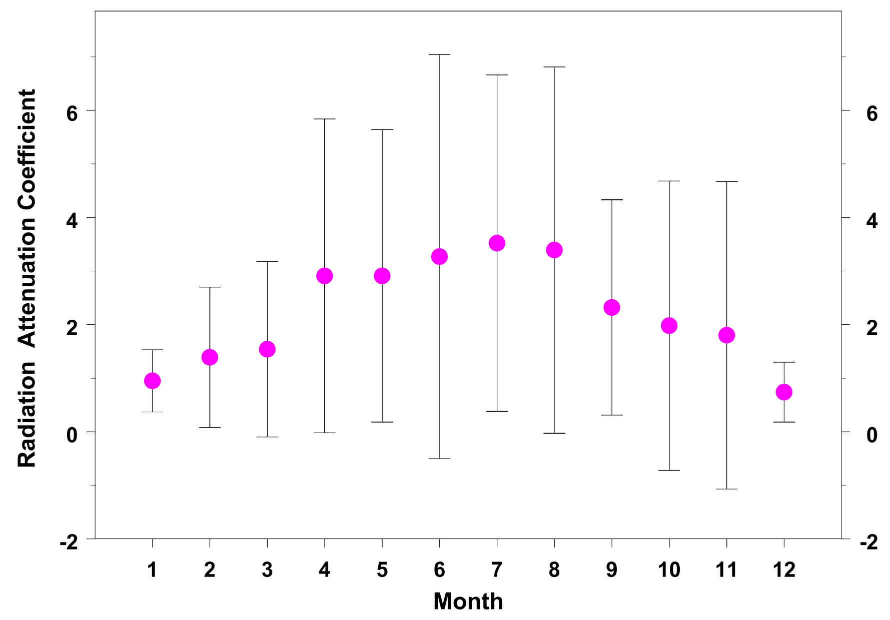
C3. Seasonal pattern of the aerosols layer depth



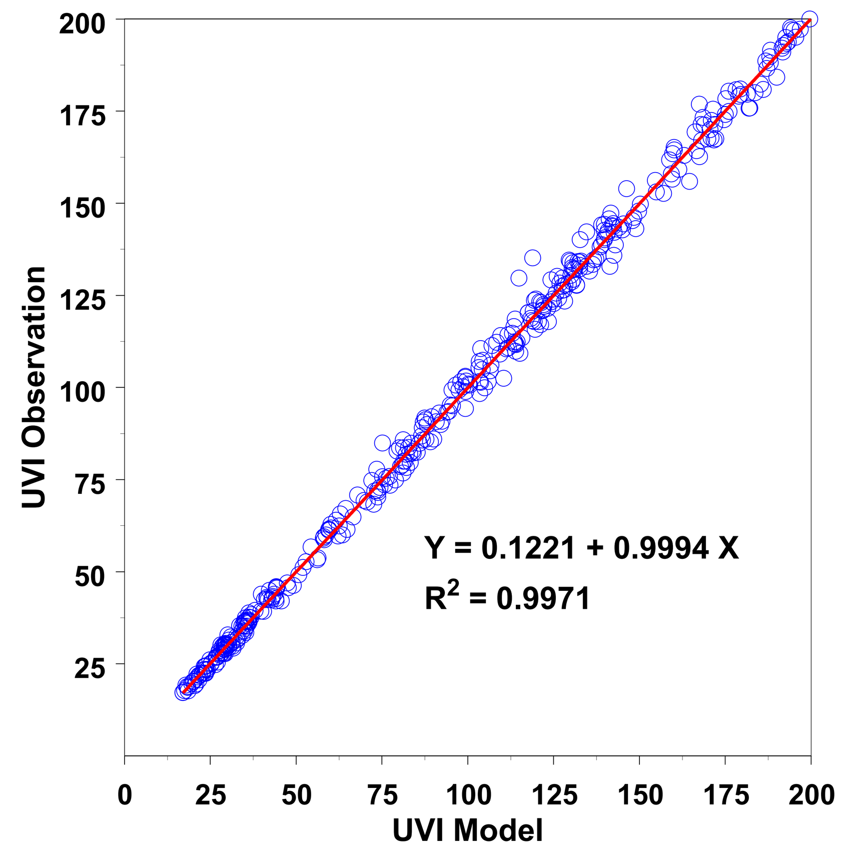
D1. Seasonal pattern of the aerosols layer life time



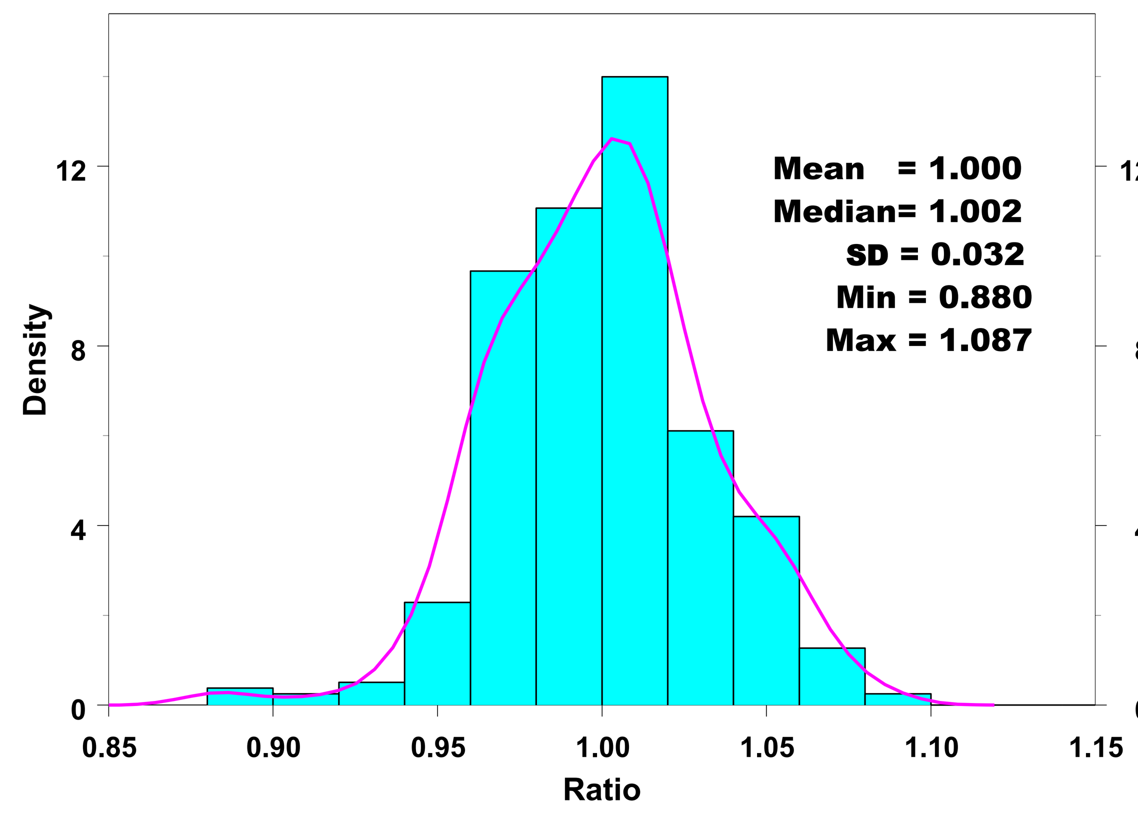
D2. Seasonal pattern of the radiation amplification factor (mean backscattering coefficient x the layer depth)



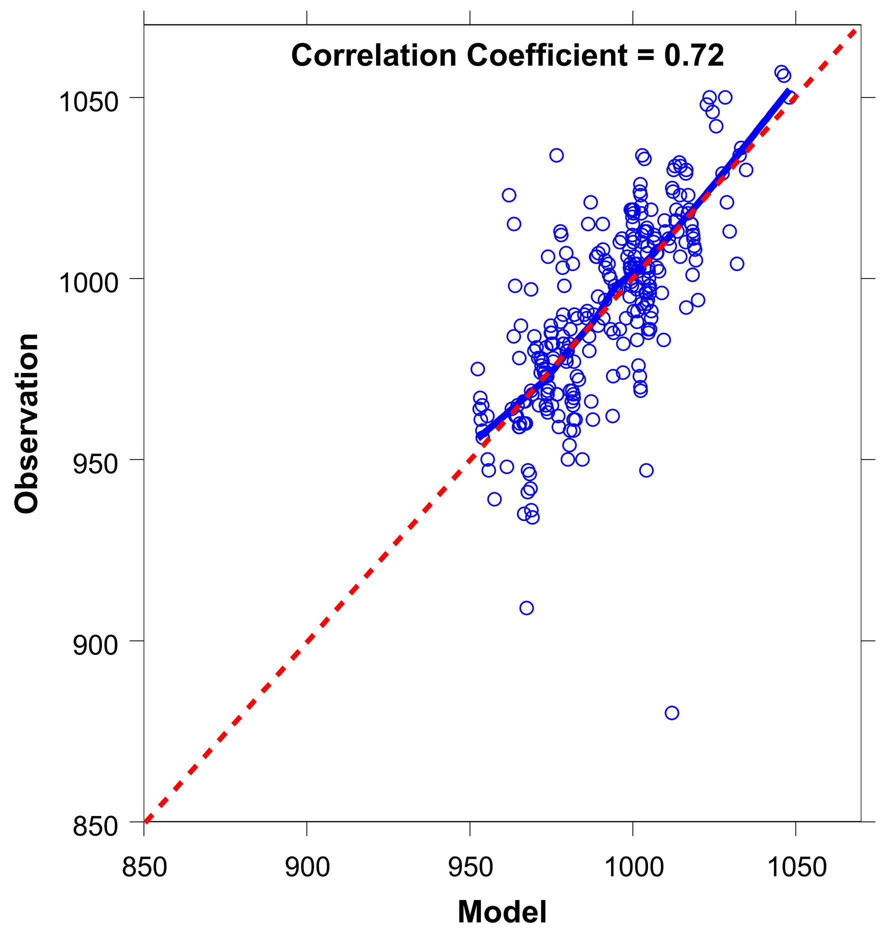
E1. Observed the erythemal irradiance versus those by TUV model based on the satellite total ozone (OMI) and columnar characteristics of aerosols from CIMEL measurements



E2. Histogram of the ratio between the observed and modelled (TUV) irradiances averaged over 15-minute periods (June-September 2019)



F1. The ratio (multiplied by 1000) between the measured erythemal irradiances and those by TUV model versus the ratio derived from Random Forest model using the regressors related to the aerosols layering



F2. The same as Fig.F1 but the stepwise regression model is used instead Random Forest.