Conference Proceedings

EuroSun 2016
Palma de Mallorca (Spain), 11–14 October 2016

Influence of air pollutants on spectral regions from ultraviolet to visible solar radiation

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Abstract

The dependencies of spectral regions of incident solar radiation in ultraviolet and visible spectra on concentrations of air pollutants were studied. We used two different approaches to conduct linear model analyses. First, linear models with different meteorological factors as explanatory variables were made for the entire data set without division according to solar elevation angle. These models showed no apparent influence of air pollutants on incident solar radiation but did reveal an effect of air pollutants on incident solar radiation in combination with relative air humidity. Secondly, after eliminating the major effect of solar elevation angle, linear models showed a spectrally dependent influence of dust particles PM_{10} and NO_x and increasing effects of the other air pollutants on at least one of the studied spectral regions. Dust particles PM_{10} caused a significant reduction in almost all spectral regions. We found that air pollutants affect the spectral composition of incident solar radiation, but it is difficult to identify the direct and indirect impacts of air pollutants on solar radiation in its different spectral regions.

Keywords: *linear regression, pollutants, solar elevation angle, solar radiation*

1. Introduction

Air pollutants created during anthropogenic activities are important compounds in the atmosphere's boundary layer. In addition to their impact on human health (e.g. Pedersen et al., 2006; Sram et al., 2013), they contribute to changes in incident solar radiation, particularly in its intensity, proportions of direct and diffuse radiation (Rooba, 2009), and spectral composition (Jacovides et al., 1997). The absorption and scattering caused by air pollutants are the main physical mechanisms which influence incident solar radiation (Charlson et al., 1992). Absorption of solar radiation is mainly by ozone, water vapour, and compounds of nitrogen and/or carbon (Thuillier et al., 2003). Black and brown carbon particles are the main effective absorbents of ultraviolet and visible solar radiation, and subsequent thermal radiation emission can induce cloud evaporation (Moosmüller et al., 2009) and thus increase the penetration of solar radiation to the Earth's surface. Radiation scattering, especially in the spectral range from 550 to 700 nm, causes an increase in diffuse radiation (Jacovides et al., 1997). These effects have a strongly regional character because of the prevailing influence of local sources of air pollution, pollutant properties, and removal mechanisms (Esteve et al., 2014). The spatial variability of air pollutants is the primary cause of different irradiances in urban versus rural areas when the sky is clear (Jacovides et al., 1997). Various air pollutants selectively affect different spectral regions of solar radiation. For example, UVB radiation is mainly absorbed by ozone (O_3) and sulphur dioxide (SO_2). UVA radiation is absorbed by nitrogen dioxide (NO_2), which has no influence on the transmission of UVB (World Meteorological Organization, 2011). Air pollution has been found to have a significant influence on both ultraviolet and visible regions of the solar spectrum, decreasing in longer wavelengths in urban areas (under cloudless conditions the attenuation of visible radiation reaches 18% in very polluted air; Jacovides et al., 1997). This effect is most important at low latitudes and during summer months (Zhou & Savijärvi, 2014.

doi:10.18086/eurosun.2016.09.06 Available at http://proceedings.ises.org

In this contribution, we used two different approaches to describe the influence of air pollution and other meteorological parameters on the intensity and spectral composition of incident ultraviolet (UV) and visible (VIS) solar radiation. The influence of particular air pollutants on individual spectral regions of UV and VIS spectra is not well known. We first analysed the influence of other meteorological factors, and secondly we studied the influence of individual air pollutants on particular spectral regions of incident solar radiation. We hypothesized that air pollutants significantly influence incident solar radiation and that air pollutants reduce short-wave spectral regions (UVB, UVA, blue radiation) more so than longer-wave spectral regions (green and red radiations) of incident solar radiation (according to Jacovides et al., 1997).

2. Material and methods

Two identical systems of sensors for solar radiation measurements were situated in the botanical gardens of the University of Ostrava (49°49.64873' N, 18°19.56197' E). Data from the first system were used for analysis. Data from the second system were used as a control of measurement reliability. Both systems consist of UVA and UVB sensors (Skye, UK), sensors measuring at wavelength intervals 400–700 nm (VIS), 510–700 nm, and 600–700 nm, and a sensor for global radiation (EMS Brno, Czech Republic). Spectral regions of VIS were calculated from the following interval measurements: blue (400–510 nm), green (510–600 nm), and red (600–700 nm). The systems also contain sensors for measuring air temperature and relative air humidity (EMS 33R, EMS Brno). Air pollution (hourly concentrations of PM_{10}, NO, NO_2, NO_x, SO_2, O_3, and CO) and hourly values for air pressure were taken from the website www.ims-msk.cz (provider: Public Health Institute Ostrava; their own data). Hourly values for visibility were taken from the website https://www.wunderground.com/history/airport/LKMT/2013/5/8/DailyHistory.html?req_city=NA&req_state=NA&req_statename=NA (meteorological data from airports). Data were divided according to weather into three categories – cloudy, partly cloudy, and sunny days. Only data for sunny days were used for analyses in order to eliminate the influence of clouds, which is difficult to define.

We used two different approaches to data analysis by linear regression. First, we analysed the influence of meteorological factors and air pollution on the spectral composition of incident solar radiation. We used solar elevation angle (SA), relative air humidity (Hum), air pressure (AirPress), and visibility (Vis) as meteorological factors and air pollutants (PCpol) as one variable using the first principal component equation $-0.33\ PM_{10} - 0.38\ NO - 0.41\ NO_2 - 0.44\ NO_x - 0.36\ SO_2 + 0.32\ O_3 - 0.39\ CO$ because of very high correlation among concentrations of individual air pollutants. We created a total of 15 linear models for each measured spectral region of incident solar radiation using different explanatory variables and their combinations (Tab. 1). We compared the coefficients of determination (R^2) for the final linear models. The main aim was to determine those factors which contributed significantly to improving the correspondence of the linear models with the measured data. We hypothesized a significant influence of air pollutants on incident solar radiation. These linear models were made for data in 2014, 2015, and the first half of 2016. In total, we used 615 hourly measurements from 179 days.

Secondly, we analysed the relationship between the intensity of incident solar radiation (UVA, UVB, blue, green, and red radiations) and concentrations of air pollutants (PM_{10}, NO, NO_2, NO_x, SO_2, tropospheric O_3, and CO). Each linear model had only two explanatory variables – solar elevation angle and one air pollutant (because of highly correlated concentrations of air pollutants; Tab. 2). In order to reduce the effect of varying solar elevation angle on solar irradiance, data obtained for the period when the solar elevation angle was within intervals 15–25° and 25–35° were analysed separately. These intervals were chosen according to the maximum solar elevation angle during winter months. If we were to use data with a greater solar elevation angle, we would lose winter data which are important because the highest concentrations of some air pollutants occur during winter. We compared the significances of each air pollutant's influence according to the p-values from the linear models. The main aim was to determine whether particular air pollutants influenced the spectral regions of incident solar radiation during different radiation conditions (given by two intervals of solar elevation angle). We hypothesized a significant reduction of incident solar radiation due to air pollutants. These linear models were made for data in 2014 and 2015. In total, we used 313 hourly measurements from 63 days.

The statistical analyses were performed in the R statistical environment version 3.3.0 (R Core Team, 2016).

3. Results and discussion

First, we studied linear models for spectral regions of incident solar radiation made using different combinations of explanatory variables. Solar elevation angle and relative air humidity were revealed as the most important explanatory variables (Tab. 1). The linear model with only solar elevation angle as the explanatory variable accounted for 62.53% of variability in UV radiation and 57.56% of variability in VIS radiation. Relative air humidity was the only explanatory variable to show an opposite effect – it explained variability in VIS radiation (36.55%) better than variability in UV radiation (29.33%; Fig. 1). The linear model with solar elevation angle and relative air humidity as explanatory variables exhibited the best explained variability among all models (71.72% for UV radiation, 72.00% for VIS radiation). The addition of other variables did not improve the linear models in a significant way. The addition of air pollutants to the linear model with solar elevation angle and relative air humidity as explanatory variables increased the explained variability of linear models by 0.74% for UV and by 1.04% for VIS radiation (Tab. 1, Fig. 1). However, the addition of air pollutants to the linear model with only solar elevation angle as the explanatory variable increased the explained variability of linear models imperceptibly (0.035% for UV and 0.057% for VIS radiation). These results demonstrate that the influence of air pollutants is important in combination with relative air humidity.

Tab. 1: Coefficients of determination (in %) for different types of linear models for measured spectral regions. SA = solar elevation angle, Hum = relative air humidity, Vis = visibility, AirPress = air pressure, PCpol = principal component of air pollutants. Bold values are displayed in Fig. 1.

	UVB	UVA	Blue	Green	Red
SA+Hum+Vis+AirPress+PCpol	71.61	73.34	73.16	73.65	72.71
SA+Hum+AirPress+PCpol	71.57	73.31	73.15	73.62	72.70
SA+Hum+Vis+PCpol	71.46	73.10	72.92	73.35	72.31
SA+Hum+PCpol	**71.42**	**73.07**	**72.90**	**73.32**	**72.30**
SA+Hum+Vis+AirPress	71.21	72.69	72.34	72.97	71.70
SA+Hum+AirPress	71.16	72.66	72.32	72.94	71.68
SA+Hum+Vis	71.06	72.46	72.11	72.68	71.31
SA+Hum	**71.01**	**72.42**	**72.08**	**72.64**	**71.29**
SA+Vis	63.90	62.45	58.37	59.62	57.21
SA+AirPress+PCpol	63.61	62.17	58.04	59.34	57.05
SA+AirPress	63.58	62.15	57.99	59.27	57.03
SA+PCpol	63.36	61.77	57.60	58.84	56.41
SA	**63.32**	**61.74**	**57.54**	**58.75**	**56.39**
Hum	**26.97**	**31.68**	**36.69**	**36.01**	**36.94**
AirPress	0.22	0.36	0.40	0.47	0.59

These linear models were created from all data without division into intervals according to solar elevation angle, which is the main factor determining the intensity of incident solar radiation. This fact could be the reason why other meteorological factors showed only a small improvement in linear models and our hypothesis about the significant influence of air pollutants on incident solar radiation was not proven. From these results it is difficult to quantify the exact influence of meteorological factors and air pollutants on incident solar radiation.

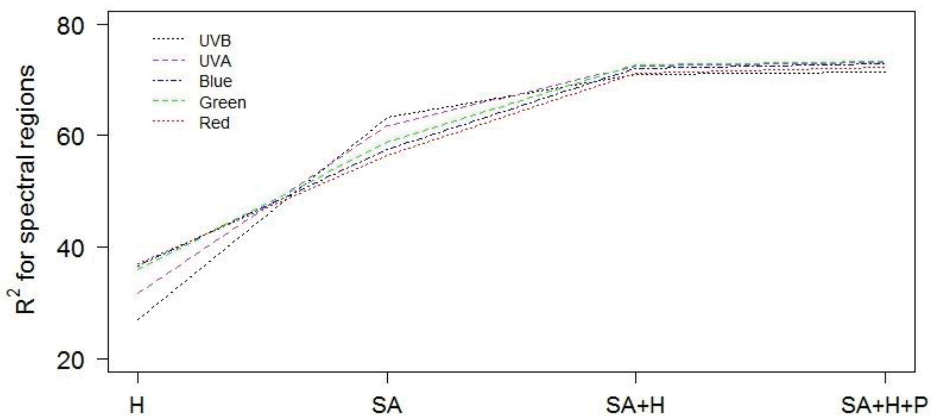

Fig. 1: Coefficients of determination (in %) for selected linear models for measured spectral regions. H = relative air humidity, SA = solar elevation angle, P = principal component of air pollutants. Only linear models with significant improvement of explained variability are shown.

Next, we studied the different influences of particular air pollutants on individual spectral regions of incident solar radiation during varying intervals of solar elevation angle. Each linear model had only two explanatory variables – solar elevation angle and one air pollutant (Tab. 2).

The air pollutant PM_{10} had the most significant reducing effect on all studied spectral bands except for the green band (Tab. 2). This effect was expected because dust particles cause a reduction of incident solar radiation (Rooba, 2009). However, the results surprisingly showed that the influence of PM_{10} on incident solar radiation was spectrally dependent insofar as PM_{10} had no significant influence on green radiation. Nitrogen oxides had a significant negative effect only on the intensities of some spectral bands, particularly blue radiation (Tab. 2). They showed surprisingly positive effects on green radiation at higher solar elevation angles. The effects of NO_x are more significant for visible than ultraviolet radiation. Palancar et al. (2013) reported that NO_2 significantly absorbs UV radiation, but our results did not confirm that.

Tab. 2: Statistical significances (p-values) of linear models of radiation dependencies on air pollutants. Bold number indicates significant dependence (i.e. p-value < 0.05). Grey colour denotes a positive effect.

Radiation	UVB		UVA		Blue		Green		Red	
Solar angle (°)	15–25	25–35	15–25	25–35	15–25	25–35	15–25	25–35	15–25	25–35
PM_{10}	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**0.010**	0.827	0.987	**0.003**	**< 0.001**
NO	0.067	0.131	**0.044**	0.162	**< 0.001**	0.065	0.516	**0.037**	**0.003**	0.665
NO_2	0.651	0.107	0.956	0.133	**0.004**	**0.001**	0.108	**0.035**	0.243	0.141
NO_x	0.182	0.116	0.217	0.174	**< 0.001**	**0.005**	0.730	**0.014**	**0.015**	0.405
SO_2	**0.007**	0.649	**0.001**	0.805	0.164	0.055	**< 0.001**	0.055	**<0.001**	0.675
O_3	0.245	0.101	0.448	0.167	**0.001**	**< 0.001**	**0.023**	**< 0.001**	0.102	0.610
CO	0.187	0.679	0.057	0.974	0.682	0.157	**0.004**	0.096	0.331	0.945

Sulphur dioxide had a significant positive effect on UVB, UVA, green, and red radiation at lower solar elevation angles (Tab. 2). These results contradicted our expectations. Such positive effects might be caused by multi-scattering of radiation on these molecules or could be connected with other climatic factors which accompany higher SO_2 concentrations. The fact that this effect occurred only during low solar elevation angles can be connected with the higher SO_2 concentration during winter months (there are usually lower SO_2 concentrations when solar elevation angle is higher).

Tropospheric ozone had no significant effects on UV radiation but a significant positive effect on blue radiation and a significant negative effect on green radiation (Tab. 2). These results also contradicted our expectations, based on the general knowledge that ozone absorbs light with a wavelength shorter than 300 nm (e.g. Lu & Khalil, 1996). Although it had been thought that ozone does not absorb light with a wavelength longer than 350 nm (e.g. Kudish and Evseev, 2011), in reality it also absorbs visible light in the Chappius band with absorption peaks at 575 and 603 nm (e.g. Jodpimai et al., 2016). This fact could explain the significant reduction in green radiation, but the absence of effect on UV radiation was rather surprising. Carbon monoxide had a significant effect only in a single case – on green radiation in combination a lower solar elevation angle (Tab. 2). It seems that CO has no special influence on incident solar radiation.

Although studies about the general reduction of solar radiation by anthropogenic aerosol are quite common (e.g. Rooba, 2009; Esteve et al., 2014), detailed analyses are not available. To the best of our knowledge, there are no scientific reports regarding the influence of individual air pollutants on incident solar radiation in the spectral regions we have studied.

4. Conclusions

The results of this study were dependent upon the approach used. Linear models on data which were not divided according to solar elevation angle did not confirm our hypothesis about the significant influence of air pollutants on incident solar radiation. That was due to the dominant effect of solar elevation angle on incident solar radiation. The influence of air pollutants in combination with relative air humidity, however, was noticeable. After eliminating the major effect of solar elevation angle, linear models showed a significant influence of individual air pollutants on particular spectral regions of incident solar radiation. The spectrally dependent influence of PM_{10} and NO_x and positive influence of SO_2 on incident solar radiation were the main findings of this study. It is evident that air pollutants affect the spectral composition of incident solar radiation, but it is difficult to recognize the direct (especially absorption) and indirect impacts of air pollutants on absorption and scattering characteristics of the atmosphere for spectral regions of incident solar radiation with different wavelength ranges.

5. Acknowledgement

This work was financially supported by grants COST CZ LD14005 and SGS06/UVAFM/2016 (specific university research grant) and by EU structural funding Operational Programme Research and Development for Innovation, project no. CZ.1.05/2.1.00/19.0388. We thank to English Editorial Services for English language assistance.

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