Changes of aerosol radiative effect on clear sky solar radiation over Europe

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Abstract

The objective of the study consists in quantifying the trends of aerosols radiative effect on clear sky solar radiation using empirical and physical modelling approaches.

The magnitude of aerosol radiative effect and its trends are quantified over Europe using direct and indirect approaches. The direct approach combines modelled aerosol radiative effect with trends from satellite derived aerosol optical thickness data; the indirect approach is based on the separation of clear-sky radiation from direct solar radiation measurements and on delimitation of aerosol effect in its trends.

The radiative effect of aerosols on clear sky solar radiation is -0.32 W/m^2/decade an order of magnitude higher than the radiative effect of water vapour. The interannual variation is between +1.0 and -1.5 W/m^2/decade and shows a slightly positive trend in summertime. The results are presented for the four radiative regions of Europe indicating negative changes in the central, north-eastern and south-eastern regions and showing increase in the southern and northern regions. It is argued that that change of solar radiation is controlled considerably by the aerosol content in the southern part of Europe. The effect of aerosols on clear sky radiation should be taken into account in the improvements of future solar radiation projections.

Keywords: aerosols radiative effect, water vapour, clear sky radiation, surface solar radiation trend

1. Introduction

Aerosols modify the radiation flux of Earth`s atmosphere through direct, indirect and semi-direct effects, thereby defining the entire energy balance of the climate system. Aerosol particles absorb and scatter the incoming shortwave radiation reducing the surface solar radiation. From these two processes absorption is dominant and is determined by the aerosol chemical composition and size distribution. This is considered the direct effect of aerosols.

The presence of aerosols have significant role in cloud formation processes (condensation nuclei), thus aerosols indirectly also affect the shortwave energy flux. Trough this indirect effects aerosols change the optical properties and the lifetime of the clouds [20]. By increasing the particle size of aerosols which act as condensation nuclei the cloud droplet formation decreases logarithmically [5]. As a consequence, the small particles getting to greater distances from the aerosol source contribute more to cloud formation than larger particles near by the pollution [21].

However, the aerosols heat the upper layers through absorption, thus stabilizing them. The heating prevents further cloud formation, or could have cloud dissipation effect. This is considered the semi-direct effect of aerosols. As a result, in the highly contaminated areas that surface solar radiation reduction trough aerosol direct effect may occurs in parallel with decrease in cloudiness. It can be concluded that the aerosol indirect effect become important mainly in remote areas, while the direct and semi-direct effect dominates in the highly contaminated areas.

All long-term changes in aerosol content in the atmosphere will trigger changes in solar radiation flux. For this reason quantification the magnitude of the radiative effect of aerosols become more and more relevant in climate studies enhancing the solar radiation projection. However this kind of assessments has high uncertainty in the literature [8], mainly due to the following reasons:

1. the complex refractive indices of aerosols with different composition and size/shape at given wavelength is not known;
2. the vertical profile of particle shape and size distribution is not known;
3. the concentration of aerosol in the atmosphere has strong local character, and the direct and indirect aerosol measurements are very sporadic.

Measurements of concentration and physical/chemical properties of aerosols are available only from the early 80`s onwards. Regarding pervious period the effect of aerosols on surface solar radiation can be analysed only by indirect methods. On the one hand these consist in separation of surface solar radiation into direct and diffuse components, or in extraction of the cloud effect from the solar radiation flux (clear sky radiation). There are studies arguing that the change of direct radiation follows the surface solar radiation trends [30], but the diffuse radiation does not always show the expected opposite changes, namely increasing diffuse part trough clouds in parallel with solar radiation reduction and conversely [11]. The changes with the same sign (either increasing or decreasing) in solar and diffuse radiation are caused by the significant scattering of aerosol particles in cloud-free atmosphere. In the same time there are studies assessing cloud-free radiation changes based on high time resolution radiation and cloudiness data. These studies show no trends [13] or positive trends [32, 22, 16] in clear sky solar radiation for European stations. The similar trends in surface solar radiation and clear sky radiation indicate the fact that the general decrease of surface solar radiation until 1990s (global dimming) and an increase thereafter (global brightening) is determined by the changing of aerosol content of the atmosphere [12, 31, 32].

On the other hand further studies are elaborated in order to indirectly quantify the aerosol radiative effect. These refer to the analysis of surface solar radiation changes in parallel with the processes strong related to aerosol emissions as volcanic eruption [18, 6], fossil fuels and sulphur emission [25, 27], urbanization [1], atmospheric transmission [17], and sunshine duration [24].

Based on direct measurement as aerosol optical thickness (AOT) the aerosol radiative effect on clear sky radiation can be directly calculated. Ruckstuhl [22] shows that the direct radiative effect of aerosols is approximately five times larger than the indirect aerosol and other cloud effects in the period of 1981-2005. Hatzianastassiou et al. [7] quantified the aerosol direct effect using satellite derived AOT data of Ozone Monitoring Programme (Ozone Monitoring Instrument, OMI) for the mid and high latitudes of Northern Hemisphere showing a decrease trend during the period of 1984 to 2001. Papadimas [19] modelled the natural and anthropogenic aerosol direct radiative forcing in the Mediterranean region using also satellite derived aerosol data (MODIS Terra). Rosenfeld [21] in his works highlights the fact that the increased aerosol concentration in remote areas intensifies cumuliform cloud formation, and in this way the rainfall increases in that region. As the consequence can affirm that aerosols modify the solar radiation flux not only at places with intense human activities, but the effects can be detected in the isolated parts of the world too justified by surface data [26, 31, 3, 23], and by satellite observations [10, 14].

Beyond to quantifying of aerosol radiative effect on clear sky solar radiation for all Europe the objective of the study consists in determining the trends of these radiative effects using empirical and physical modelling approaches.

2. Data and methods

The daily and monthly ground-based surface solar radiation data are available from the World Radiation Data Centre (WRDC) representing the European continent by 66 stations (Fig. 1) for the period of 1975-2006 (trend analyse) and 1983-2005 (indirect approach).

The aerosols measurements are coming from the NASA EOS-AURA OMI (Ozone Monitoring Instrument) project and include aerosol optical thickness data at 500 nm (AOT_{500}) [28]. This data are derived from the near UV spectral band measurements of Nimbus 7 and Earth Probe satellites with a spatial resolution of 1x1 degrees. Because of the coarse spatial resolution these datasets can only take into account the large-scale aerosol dispersion processes such as desert sand, or biomass burning. The monthly data represent the period of 1980-2001.

The quantification of the radiation effect of water vapour and aerosols have been elaborated using the Mesoscale Atmospheric Global Irradiance Code (MAGIC) [15]. The radiation values of MAGIC code are calculated by the libRadtran radiative transfer model. For cloud-free radiation the model assumes plane atmosphere and uses the modified Lambert-Beer function for each wavelengths. The optical depth for different inclination angels is taking into account by introducing a correction factor. The Code stores the input parameters defined for each point (aerosol optical depth, single-scattering coefficient, asymmetry parameter, water vapour, ozone, albedo) in Look Up Tables (LUT). This method allows a faster retrieval of values. In the first run the solar radiation values have been determined in clear sky condition including KINEE/MPI/Aerocom aerosol data [9], ERA-INTERIM integrated water vapour data [2], and albedo from SARB/CERES (http://www-surf.larc.nasa.gov/surf/pages/bbalb.html). In the next run the analyzed parameter (water vapour or aerosols) are ignored in order to quantify its radiative effect.

Regional patters based on multiannual variability of WRDC surface solar radiation data have been determined by K-mean clustering. Base on this analyse four radiative regions are delimited over Europe (Fig. 1), and the radiative effect of aerosols on clear sky radiation are presented in each cases.

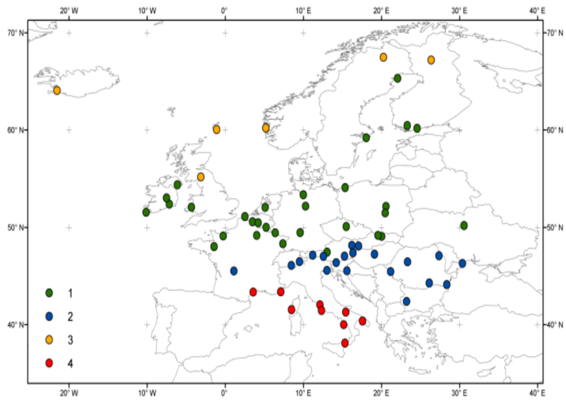

Fig. 1 Radiative regions over Europe: 1 – Central and North-East Europe, 2 – South-East Europe, 3 – Northern Europe, 4 – Southern Europe (Mediterranean)

3. Changes in aerosol radiative effect on clear sky radiation

In this study the magnitude of aerosol radiative effect and its trends is going to be quantified over Europe using direct and indirect approaches. The direct approach combines modelled aerosol effect on clear sky radiation with trends from satellite derived AOT data; the indirect approach is based on the separation of clear-sky radiation from ground-based solar radiation measurements and delimitates the aerosol effect in the trends.

3.1 Direct approach

The direct approach includes two steps in order to determine the changes in aerosol radiation effect on clear sky radiation. In the first step the magnitude of aerosol radiative effect is calculated in cloud free conditions using the MAGIC code. In the next step a linear function is determined between the aerosol radiative effect and its corresponding AOT values. Based on this function a radiative effect value can be assigned to each AOT value from the satellite derived OMI dataset. In this way a new dataset of aerosol radiative effect is created and the multiannual changes can be detected using linear trend analyse.

3.1.1 Modelling radiative effect of aerosols on clear sky radiation

The absolute values of aerosol radiation effect are determined by the MAGIC radiation code. In the first run clear sky radiation values are calculated integrating KINEE/MPI/Aerocom aerosol and ERA-INTERIM water vapour multiannual monthly means. In the next run the clear sky radiation values are also calculated ignoring aerosol data (adjusted to 0) from the algorithm. In this way the clear sky radiation values from the second run contain the radiation extinction cased only by water vapour. Both runs were carried out for each months of the year, taking into account the varying astrological factors. The difference between the aerosol-included and aerosol-free clear sky radiation value is equal to the absolute aerosol radiative effect in W/m^2, indicating the changes in solar radiation if the given aerosol content is present in the atmosphere. Fig. 2 shows the spatial distribution of annual aerosol radiative effect in W/m^2 over Europe calculated by MAGIC radiation code. High values are representing the central part of the continent and in the Mediterranean Basin.

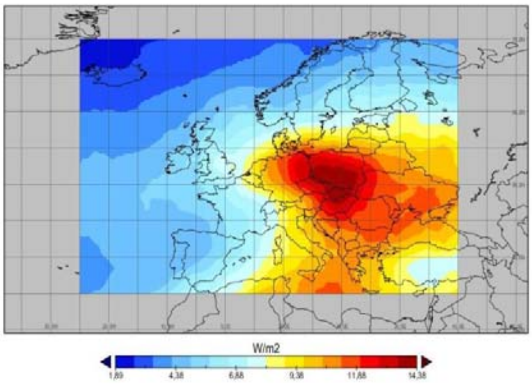

Fig. 2 Regional differences in aerosol radiative effect (W/m^2) in Europe determined by MAGIC radiation code

The interannual variation of aerosol radiative forcing is also calculated (Fig. 3), the higher radiative effect means higher aerosol concentrations in the warm period of the year, which results decrease in surface solar radiation.

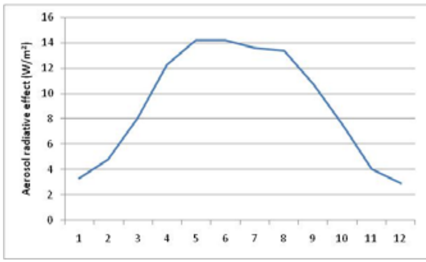

Fig. 3 The interannual variation of aerosol radiative forcing in Europe determined by MAGIC radiation code

3.1.2 Trend analyze of aerosol radiative effect

In order to assess the multiannual changes of aerosol radiative effect OMI AOT_{500} satellite data are used available for the period of 1980-2001(except 1993-1996).

A linear function fitting is elaborated between the aerosol concentration (AOT) built in the MAGIC code and its aerosol radiative effect in the case of the 50 European stations (Fig.1). To take into account the different inclination angle of the Sun the stations are grouped in 6 bands along the geographical latitudes as the following: between latitudes of 38.25 and 43.75 having 9 stations, between latitudes of 44.24 and 48.25 having 14 stations, between latitudes of 48.25 and 51.25 having 11 stations, between latitudes of 52 and 55.25 having 9 stations; between latitudes of 60.25 and 60.75 having 4 stations, and between latitudes of 64.25 and 67.25 having 3 stations. Fig. 4 shows the linear relationship between the AOT values and corresponding aerosol radiative effect in the southern band in March and July. This function is calculated for each station and for each month.

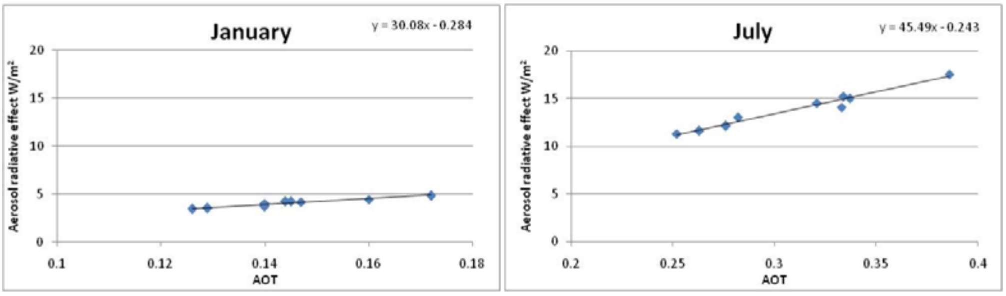

Fig. 4 Linear relationship between AOT values and corresponding aerosol radiative effect in the southern part of Europe in March and July

Based on the linear function determined for each station in Europe a radiative effect values can be assigned to each monthly AOT_{500} values available from the OMI satellite measurements (the AOT_{500} values of the station are equal with the value of the 1x1 degrees resolution pixel containing the given station). In the next step the linear trend analyzes of the newly created aerosol radiative effect datasets are elaborated. The results are presented in the Fig. 5, (green curve). Implicitly negative changes in aerosol radiative effect induces positive change in solar radiation, and conversely. The multiannual change of aerosol radiative effect over Europe is -0.61 W/m^2/decades.

3.2 Indirect approach

Beside of direct approach the change in aerosol radiative effect is calculated based on ground-base clear sky radiation trends. This approach is used as a verification of the method applied in earlier stage, mainly for the linear function fitting between aerosol radiative effect and measured data. The starting point of this approach is to elaborate the trends of clear sky radiation controlled by the effect of aerosols and water vapour. If we subtract the water vapour effect also calculated by MAGIC radiation code from this trend, the magnitude of aerosol radiative effect will be obtained. In this case it is assumed that the two effects don not amplify and do not cancel each other, and their arithmetic sum gives the change in clear sky radiation trend.

3.2.1 Clear sky radiation trends

The separation of cloudy and cloud-free situations from the surface solar radiation dataset requires high temporal resolution (hourly) cloudiness and radiation data. For long period only daily data are available in WRDC database for the entire continent. In the same time the delimitation of cloud free situations based on synoptic cloudiness measurement were not feasible because the very few cases of days without clouds in all observation times. For this reason, the following indirect method was used. In the case of each station the monthly clear sky radiation has been determined using the MAGIC radiation code. This value includes the radiation extinction of clean atmosphere as well as the radiative effect of aerosols and water vapour. Then the modelled clear sky radiation values are compared with the ground-base daily solar radiation measurements from WRDC dataset. All empirical values greater than 90% of the modelled value are denoted as radiation in cloud free situation. This method allows the presence of same cloud cover, but it is argued that in the case of cloudiness less then 3 okta the radiative effect of clouds is negligible [29]. In this way the cloud free situations are delimited from the daily WRDC solar radiation data. Table 1 shows the multiannual changes of monthly clear sky solar radiation for the 50 European in the period of 1983-2005. In winter and spring the positive changes are dominating, except December and April, summer and autumn is characterised by negative trends, except November. The multiannual trend shows a slightly increase in clear sky radiation with 0.01 W/m^2/decades.

Table 1. Trends of WRDC surface clear sky solar radiation, trends of water vapour radiative effect based MAGIC radiation code and ERA-INTERIM database and trends of aerosol radiative effect by extracting for Europe in the period of 1983-2005

	Jan.	Febr.	March	April	May	June	July	August	Sept.	Okt.	Nov.	Dec.	Year
Trends of clear sky solar radiation (WRDC) W/m^2/decades	0,73	0,97	1,67	-0,88	0,71	-1,11	-0,79	-0,30	-0,39	-0,57	0,12	-0,01	0,01
Trends in water vapor radiative effect on clear sky radiation W/m^2/decades	-0,04	0,01	-0,17	0,03	-0,16	0,13	0,04	0,21	0,04	0,05	0,14	-0,06	0,02
Trends in aerosol radiative effect on clear sky radiation W/m^2/decades	**-0,69**	**-0,97**	**-1,50**	**0,85**	**-0,55**	**0,98**	**0,75**	**0,09**	**0,35**	**0,53**	**-0,27**	**0,07**	**-0,03**

3.2.2 Trend analyze of aerosol radiative effect

As it is mentioned in the 3.2.1 section the trends of WRDC clear sky radiation is controlled by the radiative effect of aerosol and water vapour. In order to determine the aerosol role in these trends, the radiative effect of water vapour should be extract. The radiative effect of water vapour on clear sky radiation was calculated in the same way as presented in the sections 3.1.1 and 3.1.2 for aerosols, namely the absolute radiative effect of water vapour is calculated as the difference between the water vapour-included and water vapour-free clear sky radiation values modelled by MAGIG radiation code. In the next step the linear function fitting is also elaborated between the radiative effect and the corresponding integrated water vapour values build in the code. In the last step based on linear functions water vapour radiative effect is assigned to each monthly data of ERA-INTERIM integrated water vapour dataset in the period of 1983-2005. The obtained trends of water vapour radiative effect are presented in Table 1, showing that these changes are an order of magnitude smaller than the changes in the case of clear sky radiation.

As the consequence the role of aerosol radiative effect on clear sky radiation trends can be calculated by substracting the trends of water vapour radiative affect from the clear sky radiation trends. The results are presented in Table 1 and in Fig. 5 (blue curve). The multiannual change of aerosol radiative effect based on this approach is -0.03 W/m^2/decades. Fig 5 also presents the magnitude of aerosol radiative effect trend calculated by the direct approach. The magnitude and the interannual variation of the aerosol radiative effect trends calculated in the two approaches are fitting well. In the first part of the year a negative trend is detected indicating decrease aerosol content thus increase in solar radiation (see Table 1), the second part of the year show slightly positive changes but with smaller magnitudes.

Averaging the results of the two approaches (Fig. 5, red curve) the overall annual trend of aerosol radiative effect on clear sky radiation over Europe is -0.32 W/m^2/decades.

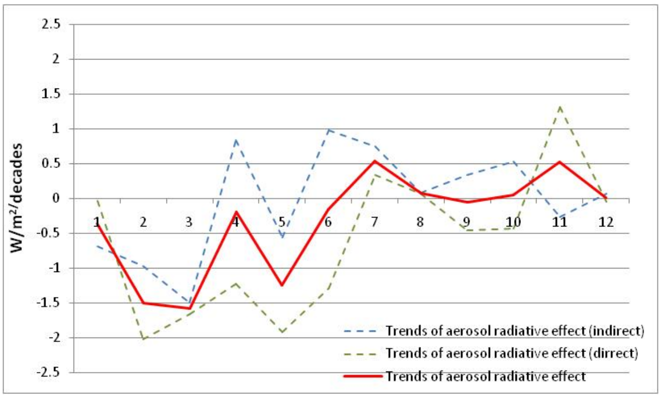

Fig. 5 Multiannual changes of aerosol radiative forcing defined by direct and indirect approaches and the average of the two approaches (red curve) over Europe in the period of 1985-2005

4. Regional patterns of changes in aerosol radiative effect

The magnitude of aerosol radiative effect changes by averaging the results of direct and indirect approaches has been calculated separately for the four radiative regions of Europe. The results are shown in Table 2. In the central, north-eastern and south-eastern part of the continent a decrease in aerosol radiative effect trends are detected indicating clearer atmosphere in the last decades. In the same time the northern and southern regions show increase in aerosol radiative effect resulting less solar radiation at the surface in cloud-free situations. The highest changes are denoted in the Mediterranean region (annually 1.15 W/m^2/decades) indicating increase in aerosol content (mainly trough large-scale aerosol dispersion processes).

Table 2. Changes of aerosol radiative effect in W/m^2/decades determined by averaging the outputs of direct and indirect approaches in the case of the four radiative regions of Europe (1983-2005)

Regions	Jan-Febr	March-Apr	May-Jun	Jul-Aug	Sept-Okt	Nov-Dec	Year
Central and North-East Europe	-0,99	-1,78	-0,10	0,38	-0,58	-0,42	-0,58
South-East Europe	-0,55	-0,28	-0,89	-0,54	-0,07	-0,10	-0,41
Northern Europe	-1,55	0,32	1,29	1,73	1,24	0,15	0,53
Southern Europe (Mediterranean)	0,31	1,80	1,63	1,18	1,57	0,43	1,15

Table 3. shows the linear trends detected in WRDC ground-base surface solar radiation data (including cloudy situations as well) for the four radiative zones of Europe. Taking into account the magnitudes of the solar radiation changes, the positive decadal changes of Central and North-East Europe are +4.35 ±0.31 W/m^2 and 1.98 ±0.27 W/m^2 in South-East Europe. Negative changes are detected in the southern and northern part of the continent, with values of -3.61 ±0.37 and -2.37 ±0.22 W/m^2 /decade respectively. The magnitudes of relative changes in surface solar radiation (compared to the multiannual averages) are 3.0; 1.64; -2.05 and -2.73%/decade, respectively.

It can be argued that the spatial distribution of the surface solar radiation trends corresponds in sign (opposite sigh) with the changes of aerosol radiative effect. The positive surface solar radiation trend in parallel with the negative trend of the aerosol radiative effect in Central, North-east and South-East Europe indicate a considerably decrease of aerosol content in this regions during the last decades mentioned in the literature as well [31, 32]. In the northern part of the continent a negative trend is found in surface solar radiation in parallel with the slight increase of positive aerosol radiative effect (0,53 W/m^2 /decade). In this region the decrease of solar radiation is mainly explained by the increase of cloudiness confirmed by multiannual synoptic cloudiness observations [4]. In the case of Mediterranean region surface solar radiation declining trend is associated with considerably positive changes in aerosol radiative effect. This result coincides with the modelled outputs of Papadimas [19] for the same region. In the same time the multiannual changes in cloudiness shows also a decrease [4] in this region. In this way can be argued that that change of surface solar radiation is controlled considerably by the aerosol content in the southern part of Europe.

Table 3. Changes in solar radiation in different radiative regions of Europe based on WRDC ground-base surface solar radiation data (1975-2006), the significance level of trends p=0,05

Regions	Stations (number)	The magnitude of the significant linear trend (W/m^2/decade)	Relative trend (%)
Central and North-East Europe	30	1,98 (±0,27)	1,64
South-East Europe	21	4,35 (±0,31)	3,00
Northern Europe	6	-2,37(±0,22)	-2,73
Southern Europe (Mediterranean)	9	-3,61 (±0,37)	-2,05

5. Results and discussion

In the study radiative effects of the aerosols and integrated water vapour on clear sky radiation are computed by radiation transfer model providing an upper estimation of the real effects since in the presence of clouds these effects are somewhat reduced. The multiannual changes of these radiative effects are also calculated using surface and reanalyse datasets.

The magnitude of multiannual changes in aerosol radiative effect over Europe is quantified using direct and indirect approaches and the results are found to be similar. This supports the certainty of the estimates on aerosol effects which is a frequent issue in the scientific literature.

It can be argued that the radiative effect of water vapour on clear sky solar radiation exhibits +0.02 W/m^2/decades being smaller by an order of magnitude from the changes detected in aerosol radiative effect (-0.32 W/m^2/decades). The monthly radiative effects induced by aerosols in the case of clear sky radiation are varying between +0.5 and -1.5 W/m^2/decades over Europe.

The results regarding changes of aerosol radiative effect are interpreted for the four radiative regions of Europe indicating negative changes in Central, North-Eastern and South-Eastern Europe and showing an increase in the southern and northern part of the continent. In the case of Southern Europe the magnitude of aerosol radiative effect changes (1.15 W/m^2/decades) is the same order of magnitude than the multiannual changes of surface solar radiation (-2.05 W/m^2/decades). In the same time the decrease in cloudiness is also detected in this region, thus the variation of solar radiation is caused mainly by the changes of aerosol content. In the northern part of the continent the decrease in solar radiation is explained mainly by the changes of cloudiness with opposite sign.

It should be mentioned that all calculations carried out in this study refer to cloud free conditions. The presence of different cloud layers would require the vertical profile of the aerosol multi-scattering parameters not available from direct measurements. The method could be enhanced in this way. Certainly, the changes of aerosol concentrations has less effect on radiation in all sky situations, mainly in the northern part of the continent showing remarkable cloud amounts. More accurate results could be obtained also by replacing the satellite derived aerosol data with direct measurements with higher spatial resolution.

In the literature the radiative effects of aerosols are mainly based on computation algorithms of deterministic models. The long-term prediction of the surface solar radiation is, however, largely affected the lack of knowledge on future tendencies of these components and the differences of the estimations by the different radiation codes. For this reason the independent validation of MAGIC modelled values by empirical data is considered useful in order to enhance the accuracy of the estimations.

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