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Solar dimming and brightening over Thessaloniki, Greece, and Beijing, China

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ABSTRACT

This work presents evidence that ultraviolet (UV)-A solar irradiances show increasing trends at Thessaloniki, Greece, where air quality has been improving because of air pollution abatement strategies. In contrast, over Beijing, China, where air quality measures were taken later, solar brightening was delayed. It is shown that until the early 1990s, UV-A irradiances over Thessaloniki show a downward trend of –0.5% yr^{-1}, which reverses sign and becomes positive in the last decade (+0.8% yr^{-1}). This brightening is related to a decreasing trend in local aerosol amounts. Both the negative rate of change (dimming) and the positive rate of change (brightening) are amplified in the UV-A solar irradiances, compared with the total solar irradiance, by a factor of 2.6. Satellite derived short-wave radiation over Beijing showed negative changes of –0.4% (1984–1991) and –0.1% yr^{-1} during 1994–2006. The negative trend in solar radiation continued even during 2000–2006. Satellite-derived aerosol optical depth (AOD) increased by +1.0% yr^{-1} during 2000–2006, in agreement with in situ measurements of increasing AOD. Therefore, a statistically significant change from dimming to brightening in Beijing could not be seen in the last decade, but it is expected to occur in the near future.

1. Introduction

In the past decade, a reduction of total solar irradiance reaching ground level under cloudless conditions, called 'global dimming', was attributed to increases of anthropogenic aerosols, the phenomenon varying from region to region (Stanhill and Cohen, 2001; Stanhill and Moreshet, 1992; Liepert, 2002; Romanou et al., 2007). Further studies have shown that over Europe and North America, the negative tendencies in downwelling shortwave (SW) solar radiation have reversed sign in the 1990s, possibly as a result of improvement in air quality, a phenomenon which was named 'global brightening' (Wild et al., 2005; Romanou et al., 2007). These results, which can have significant climatological consequences (IPCC, 2007), were derived using the SW solar irradiance. Until now, no study has included estimates based on ultraviolet (UV)-A irradiances, which are much more sensitive to aerosols, a major factor affecting the downwelling solar radiation, which correlates well with anthropogenic activities (Papayannis et al., 1998; Zerefos et al., 1998; Zerefos et al., 2000; Balis et al., 2003; Gerasopoulos et al., 2003; Fotiadi et al., 2006; Gerasopoulos et al., 2006; Gerasopoulos et al., 2007; Kalivitis et al., 2007).

In this work, we test the hypothesis that over regions where stringent air quality abatement efforts have started before 20 yr or so, global brightening is expected to have started already. In contrast, over regions where air quality measures were taken later, the reversal from dimming to brightening is expected to be seen later. Two urban sites have been chosen for comparison, namely the regions over Thessaloniki (41°N, 23°E) and over Beijing (40°N, 116°E), which are representative of regions with high aerosol load. Northern Greece has been selected because it is well known to be located at the crossroads of aerosols and various pollutants pathways originating in central and Eastern Europe (Lelieveld et al., 2002; Zerefos et al., 2002). Thessaloniki, the major city in northern Greece, lies along the exit of air pollutants from Europe, in the path of the prevailing long-range transport (LRT) trajectories, as we move from central and eastern Europe to the Mediterranean (Zerefos et. al., 2002). On the other hand, northern China is a region of rapid growth, which exceeds the pollution growth rates found in Europe and other parts of the world (Chan and Yao, 2008). Moreover, environmental legislation was implemented in Europe about a decade

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earlier than in China, that is, since the 1980s (EC, 1980; 1989 and for China, see, for example, http://www.gov.cn/xwfb/2008-02/27/content_903668.htm). Finally, quality assured aerosol optical depth (AOD) and solar radiation data are available for both sites under comparison (Zerefos, 2002; Xia et al., 2006).

2. Data

2.1. Ground based data

2.1.1. Solar irradiance and other measurements at Thessaloniki.. The UV irradiance has been monitored continuously at the Aristotle University of Thessaloniki, Greece (40.6°N, 22.9°E) with an Eppley Ultraviolet Radiometer (290–385 nm) (The Eppley Laboratory INC., Newport, Rhode Island, USA) since 1983. The instrument is located on the roof of the Physics Department, and it is calibrated regularly by means of a standard radiometer of the same type. In the present work, we used measurements of mean daily UV solar irradiance at the surface under clear skies. Clear-sky days were characterized by the duration of sunshine, which should exceed 80% of its calculated daily maximum. A second radiometer of type EKO MS-210A (315– 400 nm) (EKO Instruments Co. Ltd., N. Tatum Boulevard, Phoenix, USA) located on the same roof started operating in the autumn of 1998. Comparison of the clear-sky measurements with the two instruments, for a common period in operation, showed excellent statistical agreement ($r = 0.996$, number of observations = 460, significance level >99%). To correspond to the UV-A range, the measurements of the Eppley radiometer were modified to simulate the measurements of the EKO instrument, using the regression equation that resulted from their highly significant correlation.

The SW solar irradiance at the Aristotle University Campus has been monitored by two pyranometers, an Eppley Precision Pyranometer (The Eppley Laboratory INC., Newport, Rhode Island, USA) (EP) and a Kipp & Zonen CM-11 (Kipp & Zonen, Delft, The Netherlands) (KZ). The former instrument has been monitoring SW solar irradiance since 1980, whereas the latter started operating in the spring of 1992. Comparison of the daily measurements of the two instruments under all sky conditions for the period 1993–1995 revealed an excellent correlation between the two data sets ($r = 0.999$, 1078 pairs, significance level >99%) and a small bias of ~3.4%, which was attributed to the slightly different spectral ranges of the instruments (Meleti et al., 2008). The two data sets have been homogenized with the use of the calculated best fit, and a uniform time-series of total solar irradiance over Thessaloniki has been constructed (Meleti et al., 2008). In this study, we made use of the EP irradiance data for the period 1984–1994 and of the KZ irradiance data for the period 1995–2006 for clear-sky conditions as characterized above.

The AOD data set was derived from the direct-beam measurements conducted with a single monochromator spectrophotometer (Brewer MKII), located on the roof of the Physics Department at the University of Thessaloniki. The instrument is designed to take direct sun measurements at five nominal wavelengths, namely 306.3, 310.1, 313.5, 316.8 and 320.0 nm, which are also used to obtain the total column ozone. The method to retrieve the AOD data from these measurements is based on the Langley extrapolation method to derive the relative calibration of the solar irradiance (Marenco et al., 2002; Groebner and Meleti, 2004). To minimize the ozone effect, the time-series of the AOD at 320 nm was selected. Although the AOD refers to the UV part of the solar spectrum, its correlation with the AOD in the visible band is high (Meleti and Cappelani, 2000). The mean daily AOD under clear skies was calculated, depending on the availability of data. The data set covers the period September 1984–September 2006, and the mean value of the AOD for the whole period was found to be 0.45 ± 0.17 (1σ).

Measurements of total sulphur dioxide (SO_2) column have been routinely conducted at the Laboratory of Atmospheric Physics since March 1982, from which the longest available time-series of columnar SO_2 under near-clear skies is available. These data are obtained as part of the standard algorithm to retrieve columnar ozone measurements from the single Brewer spectrophotometer (Bais et al., 1993). Both columnar and surface SO_2 measurements for the centre of Thessaloniki city indicate that the gas concentration have been decreasing since the 1990s due to the European Union's (EU) sulphur control policies and the economic crisis in Eastern Europe in the 1990s, where industrial activity slumped and several inefficient plants were closed or modernized, East German brown coal power plants had to close and, if reopened in 1994, had to follow strict German legislation. Furthermore, the two United Nations Long-Range Transboundary Air Pollution Sulphur Protocols played an important role in reducing air-borne load of sulphur compounds (UN LRTAP, 1984, 1985). At Thessaloniki, the estimated rate of decrease for the mean monthly SO_2 total column is about 0.02 m atm cm[1] yr^{-1} for the period between March 1982 and March 2007.

2.1.2. Ground-level measurements of aerosol optical depth at 550 nm over Beijing and Thessaloniki (AERONET).. Aerosol optical depth level 2 (quality assured) data for both Thessaloniki and Beijing have been downloaded from the Aerosol Robotic Network (AERONET) data archive (http://aeronet.gsfc.nasa.gov; Holben et al., 1998). The Beijing site is located at the Institute of Atmospheric Physics (IAP), in the densely populated urban area of Beijing. A sun photometer (Cimel Electronique, France) is operating on the roof of the IAP building since 2001 (39.98°N, 116.38°E and 30 m above the ground). The data include daily and monthly averages of AOD at various wavelengths together with the Ångström parameter. In this study, we made use of the monthly mean AOD at 550 nm from July 2002 to July 2007, which was retrieved from the AERONET measurements at 440 nm and 675 nm using the corresponding (440 to 675 nm) Ångström exponent 'a'.

[1] 1 m atm cm equals 2.8×10^{-5} kg m^{-2} of SO_2

Similarly the AERONET measurements at Thessaloniki cover the period from September 2005 to May 2007. The AERONET station at Thessaloniki is collocated at the same site with the previously described spectrophotometric measurements site at the Laboratory of Atmospheric Physics of the University of Thessaloniki.

2.2. Satellite data

2.2.1. Radiation fluxes at the surface (ISCCP-FD). A 23-year (1984–2006) satellite radiative flux data set has been used in the present study (http://isccp.giss.nasa.gov/projects/flux.html). It includes full and clear sky upwelling and downwelling, total short- ($SW = 0.2 < \lambda < 5\ \mu m$) and total long-wave ($LW = 5 < \lambda < 200\ \mu m$) radiative fluxes at the surface and at four levels in the atmosphere, reported every 3 h on an equal-area projection grid of 2.5° latitude/longitude at the equator (Zhang et al., 2004 and references therein).

Short- and long-wave radiative flux profiles were calculated using the cloud and surface properties derived by the International Satellite Cloud Climatology Project (ISCCP)-D1 data set. The analysis takes into account cloud cover, optical thickness and top temperature/pressure along with surface visible reflectivity and skin temperature, atmospheric temperature and humidity profiles from the TIROS Operational Vertical Sounder (TOVS). The analysis also considered ozone from Total Ozone Mapping Spectrometer (TOMS), near-surface air temperature diurnal cycle amplitudes and phases from surface weather reports and the first NCEP reanalysis. Also, different climatology of cloud-particle size and vertical layer distributions, as well as time and space varying climatology of tropospheric and stratospheric aerosols and the NASA-GISS model emmissivities have been used (Hansen et al., 2007).

All these data sets were projected onto a common, global, equal-area grid (equivalent to 2.5° latitude–longitude intervals at the equator) and inserted into the NASA-GISS GCM radiative transfer model (Hansen et al, 2007). The results provide physically consistent surface and top-of-atmosphere radiative fluxes, which have been used to show changes that are attributed to natural variability such as interannual changes in cloud cover, especially in the tropics, El Nino events and anthropogenic changes in climate forcing due to greenhouse gases and aerosols (Romanou et al, 2007). To minimize the impact of the Mount Pinatubo eruption on the satellite retrievals, data taken between August 1991 and June 1994 were not used in our analysis.

Uncertainties of the fluxes at the surface are not only caused by data contamination by Mt. Pinatubo. On a global scale, they are estimated to be about 10–15 W m^{-2} above normal, and regionally they may reach higher values (Zhang et al., 2004). As shown by Xia et al. (2006), ISCCP-FD underestimated surface irradiance in eastern China. The difference between monthly surface observations and ISCCP-FD can reach 30–40 W m^{-2} in some cases. The observed biases are caused by undersampling of cloud variations, measurement errors in atmospheric and surface temperatures and water vapour vertical profiles, as well as biases in the aerosol climatology used in the retrieval algorithm. The average biases of ISCCP-FD satellite fluxes relative to the SW and LW values measured by the Baseline Surface Radiation Network (BSRN) are +5.8 and –0.8 W m^{-2}, respectively. The correlation between the satellite and the measured SW radiative fluxes is the lowest (0.89) in the tropical zone (15°S–15°N), particularly in situations affected by heavy aerosol events.

2.2.2. Aerosol optical depth at 550 nm (MODIS/Terra). Aerosol products from the Moderate-resolution Imaging Spectroradiometer sensor aboard the Terra satellite (MODIS/Terra) were employed to analyse the temporal and spatial variability of aerosols over Thessaloniki and some other sites in the Southern Balkan region (Koukouli et al., 2007). Daily overpass data for the study areas were analysed at a spatial resolution of 50 × 50 km. In this study, we use daily level-2 collection 005 MODIS/Terra AOD at 550 nm, from July 2000 to July 2008. This 8-year data set was analysed to evaluate the aerosol seasonal, intraseasonal and geographical variability over Thessaloniki and Beijing. Details on the MODIS aerosol products and their extensive validation with the AERONET measurements can be found, for example, in Ichoku et al. (2002), Chu et al. (2003) and Remer et al. (2005), whereas those specifically dealing with collection 005 can be found in Levy et al. (2007) for the globe and in Li et al. (2007b) for China (including Beijing).

2.3. DISORT model data

Using MODIS AOD monthly data, we have calculated the clear-sky downwelling SW radiation (0.3–4 μm) and daily UV-A irradiances (325–400 nm) for Thessaloniki and Beijing. We made use of the LIBRADTRAN atmospheric radiative transfer software package (Mayer and Kylling, 2005). The SW solar radiation was calculated using the two-stream radiative transfer solver SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer; Ricchiazzi and Yang, 1998). For the UV-A solar radiation data, we made use of the pseudo-spherical approximation (SDISORT) by Dahlback and Stamnes (1991). In this study, we have used, at both sites, the same values for the aerosol optical properties and surface reflectivity. Also, use was made of the same Air Force Geophysics Laboratory (AFGL) mid-latitude winter and summer profiles for ozone, temperature and air pressure (Anderson et al., 1986) and the same extraterrestrial solar flux by Kurucz (1994). Aerosol optical depth wavelength dependence was taken into account using MODIS AOD at 550 nm and a constant Ångström exponent 'a' (=1.4).

3. Results and discussion

Several air pollutants harmful to human health have been targeted by EU directives, international Conventions and their subsequent protocols such as the Convention on Long-Range

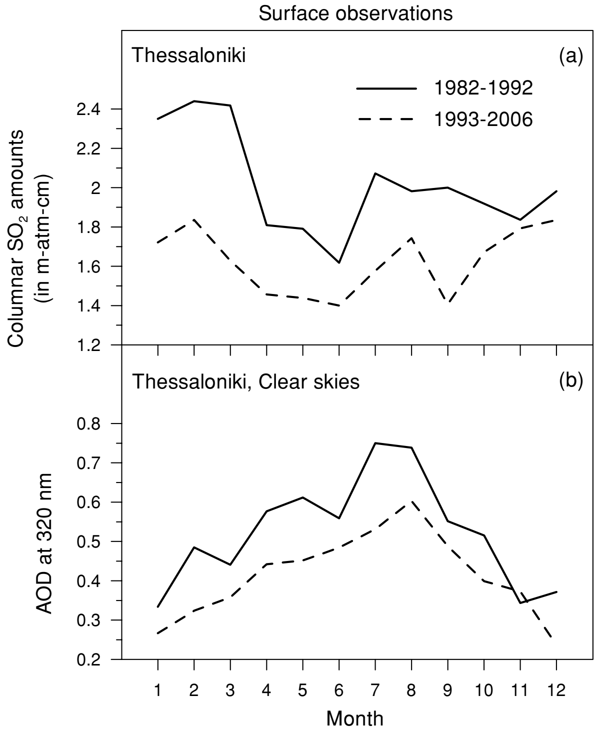

Fig. 1. (a) Seasonal variation of columnar SO_2 amounts from 1982–1992 to 1993–2006, as measured by a Brewer monochromator at Thessaloniki (SE Europe). (b) Same as (a) but for AOD at 320 nm.

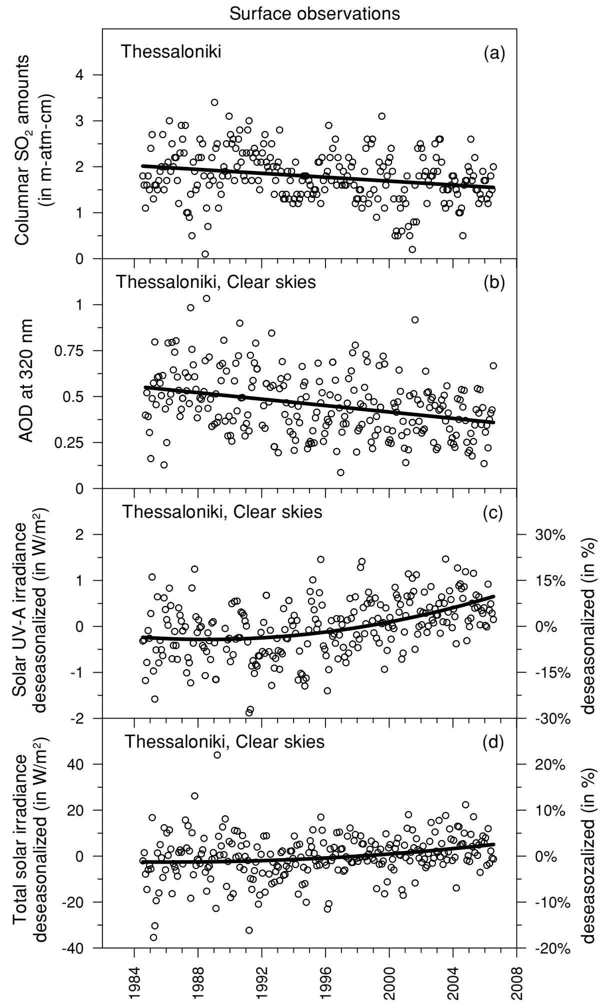

Fig. 2. (a) Time-series of mean monthly SO_2 amounts over Thessaloniki, Greece (40.6°N, 22.9°E), as measured by a Brewer monochromator. (b) Same as (a) but for AOD at 320 nm. (c) Same as (a) but for Eppley–EKO de-seasonalized solar UV-A irradiance measurements. (d) Same as (a) but for Eppley–Kipp–Zonen de-seasonalized total solar irradiance.

Transboundary Air Pollution (CLRTAP; Geneva, 1979). Although ratification and implementation of a large number of EU directives, together with the observed de-industrialization in eastern European counties, have improved air quality in large areas of Europe, this is not necessarily the case in other parts of the world where pollution abatement measures were taken later. This does not mean that all developing countries have taken stringent measures, neither that all developing countries are polluting. For example, there is now ample evidence that southeast (SE) Europe experienced its highest regional values of locally produced and transported SO_2 during the 1980s (Eisinger and Burrows, 1998; Zerefos et al., 2000; Lelieveld et al., 2002; Zerefos et al., 2002), which have lowered in the 1990s (Zerefos et al., 2000). Figure 1a shows an example of the seasonal variation of columnar SO_2 amounts at Thessaloniki downwind from major sources of SO_2 in central and Eastern Europe. Due to control measures taken in the 1980s (EC, 1980, 1989), the winter peak apparent in the 1982–1992 data has decreased over the period 1993–2006 by about 40%. The summer peak, mainly from LRT, has also decreased by about 20%. Aerosol optical depth data at 320 nm (Fig. 1b) show similar decrease in the 1990s and 2000s, of the order of 25%.

Indeed, the long-term change in columnar SO_2 over Thessaloniki is negative at rates of about –0.02 m atm cm (or –1.1%) yr^{-1}, and it is statistically significant at confidence level greater than 99% (Fig. 2a). A highly significant negative trend is also found for AOD at 320 nm (about –2.0% yr^{-1}, Fig. 2b). Kazadzis et al. (2007) found negative trends in AOD in Thessaloniki for the period 1997–2005, which paralleled the decreasing trends of the local particulate matter (PM_{10}) aerosol concentrations. This result was tested here by calculating the correlation coefficient between the de-seasonalized time-series of UV-A and AOD at 320 nm, which is found to be highly significant ($r \approx$ –0.6, 1611 clear-sky days, confidence level >99.9%).

We have analysed the long-term variability of solar UV-A irradiance at Thessaloniki from 1984 to 2006, after removing the seasonal cycle, by subtracting the long-term monthly mean from each individual monthly value. Figure 2c shows the time-series of the de-seasonalized solar UV-A irradiances from July 1984 to

July 2006 in watts per square meter (W m^{-2}) and for clear sky conditions. The solid black curve shows a polynomial fit, which has been applied to the data. As can be seen from Fig. 2c, the negative trend in the solar UV-A irradiance in the 1980s reverses its sign and becomes positive in the 1990s and the 2000s. This is also true when total solar irradiance is examined (Fig. 2d). This change represents evidence of solar dimming at Thessaloniki, until the end of the 1980s and of brightening since the beginning of the 1990s. A significant part of the brightening is related to the reduction of local aerosol amounts after the year 1990, as a result of the cleaning of the lower atmosphere at Thessaloniki due to air-quality control measures and stringent measures taken all over Europe and the de-industrialization in eastern European countries (EC, 1980, 1989, 1996; Basbas et al., 2004). These trends are also in agreement with analyses at several European stations, based on UV-A carefully maintained and detailed records (Chubarova and Nezval', 2000; Zerefos, 2002; Wild et al., 2005). Noteworthy at this point is the result that both the negative (dimming) and the positive rates of change (brightening) are amplified in the UV-A solar irradiances compared with the total solar irradiance.

In contrast to Thessaloniki, where solar irradiance appears to increase after 1990, Beijing is a region where stricter pollution regulation started in the late 1990s (http://www.gov.cn/xwfb/2008-02/27/content_903668.htm), and therefore solar brightening is expected to have started much later than over Thessaloniki. For instance, Gao et al. (2008) have shown that SO_2 concentrations over Beijing were increasing from 1981 to 1998, and since about the year 2000, they started showing a declining tendency. Also Hao and Wang (2005) have shown that significant improvements in air quality in China have been achieved during the early–21st-century. However, with reinvigorated economic growth and continued expansion of the transportation system, some of those gains have been lost in the last few years (Streets et al., 2008).

Figure 3 shows the time-series of AOD at 550 nm in clear skies retrieved from the MODIS instrument during the period 2000–2008, over the two sites under study (Thessaloniki and Beijing), together with the AERONET AOD measurements. From that figure, it appears that although both series of AOD (in the visible part of the spectrum) initially had similar mean values (about 0.5 for Beijing and 0.3 for Thessaloniki), at the end of the record, their difference became twice as large (0.6 for Beijing and 0.2 for Thessaloniki). Aerosol optical depth being decreasing over Thessaloniki at rates of –4.5% yr^{-1} and increasing over Beijing by about 1.0% yr^{-1} between 2000 and 2008. The surface based AERONET AOD measurements over Beijing show similar trends with those retrieved from the satellite (+0.8% yr^{-1}). We note here that the MODIS collection 005 and the AERONET AODs over Beijing are well correlated to each other ($r \approx +0.77$, confidence level >99%). This has been shown also by Li et al. (2007a,b) for the Beijing Forest station, whose data were used in the present work.

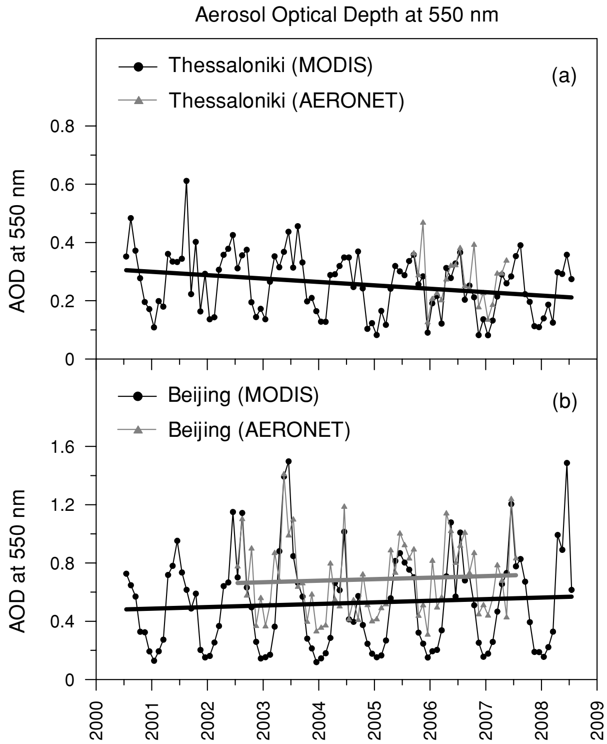

Fig. 3. (a) Time-series of AOD at 550 nm at Thessaloniki from MODIS (circles) and AERONET data (triangles). (b) Same as (a) but for Beijing.

These contrasting trends between AOD at the two sites under study are also evident in satellite retrievals of clear-sky downwelling solar radiation. Figure 4 shows the de-seasonalized time-series of clear-sky downwelling solar radiation from ISCCP-FD together with the de-seasonalized AOD from MODIS over Thessaloniki (Fig. 4a) and Beijing (Fig. 4b). Data taken between August 1991 and June 1994 were not used in our analysis to avoid the naturally perturbed period caused by the Mt. Pinatubo eruption. Trends in solar radiation have been calculated for two periods: (1) the period (1984–1991) before the Mt. Pinatubo eruption and (2) the period (1994–2006) after the Mt. Pinatubo eruption, and they are shown in Table 1.

As can be seen from Fig. 4a, the satellite-derived, downwelling SW solar radiation over Thessaloniki is showing an irradiance decrease (dimming) till the end of the 1980s, which levels off in the 1990s and the 2000s. The corresponding AOD at 550 nm is showing a decreasing tendency since 2000 as a result of improving air quality in Europe as discussed before. It is noted that these findings (in the SW band) are consistent with the findings from the ground-based measurements taken in the UV-A part of the spectrum (Fig. 2). In addition, we stress here the fact that trends in the UV-A solar irradiance are an amplification of changes seen in the SW band (by a factor of 2.6).

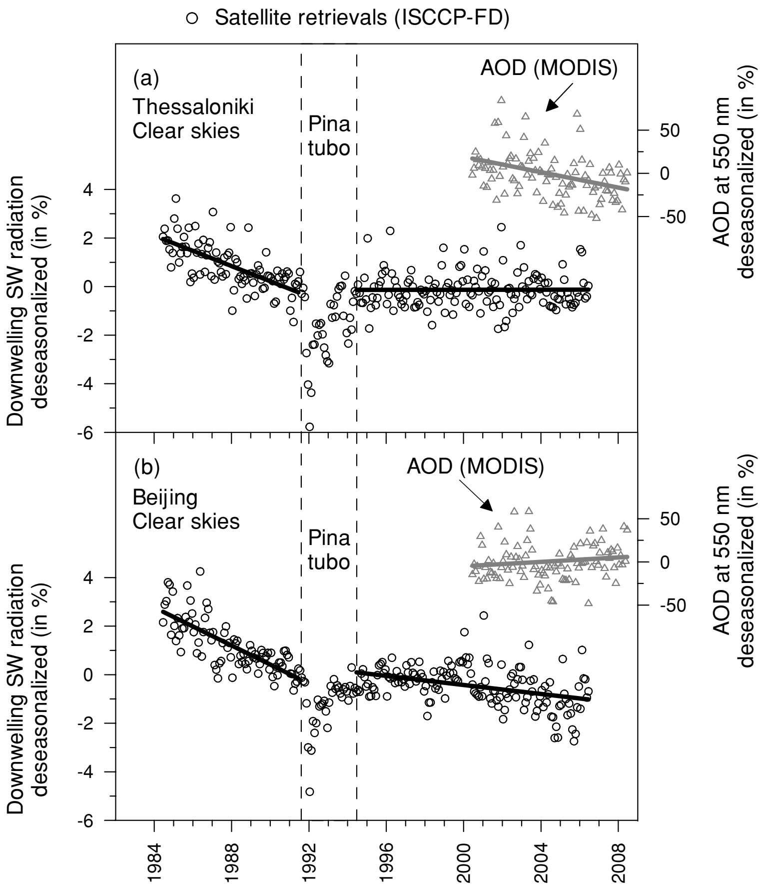

Fig. 4. (a) Time-series of de-seasonalized downwelling clear-sky short-wave radiation (in%) over Thessaloniki from ISCCP-FD satellite retrievals (circles) together with AOD at 550 nm from MODIS (triangles). (b) Same as (a) but for Beijing.

Table 1. Long-term means (in W m^{-2}) and trends (in% yr^{-1}) of clear-sky downwelling solar radiation over Thessaloniki and Beijing based on ISCCP-FD satellite retrievals (in the SW band) and Eppley–EKO ground-based UV-A measurements (only for Thessaloniki)

	1984–1991		1994–2006	
	Mean (W m^{-2})	Trend (% yr^{-1})	Mean (W m^{-2})	Trend (% yr^{-1})
	Total solar irradiance (satellite retrievals)			
Thessaloniki	225 ± 88	–0.3 (>99)	222 ± 86	0.0
Beijing	220 ± 79	–0.4 (>99)	216 ± 77	–0.1 (99)
	UV-A solar irradiance (ground-based data)			
Thessaloniki	8.4 ± 3.8	−0.5	9.0 ± 4.0	+0.8 (>99%)

Note: Values in brackets refer to statistical significance of each trend.

In contrast to Thessaloniki, the results over Beijing are showing decreases in solar radiation throughout the whole period of record (Fig. 4b and Table 1). The negative trends of solar radiation over Beijing are estimated to be about –0.4% yr^{-1} for the period 1984–1991 and about –0.1% yr^{-1} for the period 1994–2006 (Table 1). The negative trend in solar radiation can be seen to continue even between 2000 and 2006. This is in agreement with the observed increasing trend over Beijing in the MODIS-derived AOD between 2000 and 2006 (+1.0% yr^{-1}, Fig. 4b). We note here that the MODIS AOD trend is also in agreement with surface AOD measurements from AERONET data (+0.8% yr^{-1}, Fig. 3b).

To quantify the contribution of aerosol loading changes to the SW and UV-A radiation changes, we have analysed the SW and UV-A solar irradiance trends calculated from the DISORT radiative transfer model, in which use was made of the MODIS AOD monthly data as input. For the region of Thessaloniki, the model reveals increasing trends in solar radiation after 2000, which are estimated to be +0.25% yr^{-1} for the SW radiation and +0.65% yr^{-1} in the UV-A part of the spectrum. Both trends are consistent with the findings from the ground-based measurements over the same period, as can be seen from Fig. 2 (+0.25% for SW and +0.4% for UV-A). The difference between the trends in the SW and the UV-A part of solar irradiance show the effect of the AOD wavelength dependence to the solar radiation trends at different wavelength bands. On the other hand, the model-derived SW and UV-A irradiances show negative trends over Beijing during the period 2000–2006, which agree with the negative trends seen in the ISCCP-FD satellite retrievals. The model-derived trends in Beijing are estimated to be about –0.2% yr^{-1} for the SW radiation. For the same period, ISCCP-FD satellite retrievals are showing a –0.15% change in SW radiation. Finally, over Beijing, UV-A radiation model calculations show reductions in solar UV-A irradiances between 2000 and 2006, of the order of –0.8% yr^{-1}.

4. Summary and conclusions

In this work, we have tested the hypothesis that over regions where stringent air quality abatement efforts have started well before present, global brightening is expected to have started already, replacing the global dimming observed in the 1980s. In contrast, over regions where air quality measures were taken later, the reversal from dimming to brightening is expected to be seen later. To test this hypothesis, two individual sites have been selected for comparison as to the observed trends in solar radiation, namely the region of Thessaloniki in northern Greece (which also possesses the longest clear sky time-series of UV-A solar irradiance) and Beijing in northern China. We have included estimates from ground-based measurements of UV-A and total solar irradiances, which are much more sensitive to aerosols, a major factor affecting the downwelling solar radiation and which correlates well with anthropogenic activities (Zerefos et al., 2002). For the greater Thessaloniki and the greater Beijing regions, use was made of clear sky downwelling solar radiation from ISCCP-FD satellite retrievals (in the SW band).

The results for Thessaloniki show that until the early 1990s, UV-A irradiances were decreasing at a rate of about –0.5% yr^{-1}, and then reversed sign and became positive in the 1990s and the 2000s (+0.8% yr^{-1}). This long-term change presents evidence of solar dimming in Thessaloniki until the end of the 1980s and of brightening since the beginning of the 1990s. This increase (brightening) is related to the observed decreasing trend in local aerosol amounts. Brightening is also evident in the total solar irradiance data. Both the negative rate of change (dimming) and the positive rate of change (brightening) are amplified in the UV-A solar irradiances compared with the total solar irradiance, by a factor of 2.6. The analysis of satellite retrievals (in the SW band) for the same region showed similar changes in aerosol and radiation trends. Aerosol optical depth being decreasing at rates of –4.5% yr^{-1} and downwelling solar irradiance trends had levelled off.

In contrast to Thessaloniki, where generally solar radiation increased during the period 1994–2006, the results for Beijing showed decreases in downwelling SW solar radiation throughout the whole period of record. The negative trends of solar radiation over Beijing were estimated to be about –0.4% yr^{-1} for the period 1984–1991 and about –0.1% yr^{-1} for the period 1994–2006. The negative trend in solar radiation was continued even between 2000 and 2006. Satellite derived AOD increased by +1.0% per year between 2000 and 2006, in agreement with in situ measurements of increasing AOD from AERONET data (+0.8% per year).

A significant part of the brightening over Thessaloniki after 1990 is expected to be related to the reduction of local aerosol amounts after 1990, as a result of European and national initiatives to reduce air pollution. Specifically, legislative acts such as the European Union Framework Council Directive on Ambient Air Quality Assessment and Management (EC, 1996) have delimited certain thresholds for characterizing the quality for the atmospheric environment. This effort was initialized in WHO Air Quality Guidelines for Europe in 1987, with updates in 1996 and 2005 (WHO, 2005). Significant air quality improvements during the late 1980s and 1990s in Thessaloniki were attributed to the EC Directive as well as transportation measures and improvements of the diesel fuel quality (Basbas et al, 2004).

However, in China, similar measures were taken late in the 1990s and coincided with an unprecedented industrial, economic and population growth for China's cities that probably counterbalanced the effects of air pollution abatement strategies (Chan and Yao, 2008). Moreover, as the European experience has indicated, the measures will take more than a decade to start showing observable improvements in regional air quality. After 2000, the largest part of the brightening over Thessaloniki may be attributed to the improvements of air quality ensued by the EC Directives of the 1980s, whereas similar measures were not yet implemented in China until 1996, resulting in the observed dimming over Beijing. Since the 1990s, China's industrial and economic growth as well as the urban population expansion that followed the emergence of several mega-cities, one of which is Beijing and the surrounding region, led to tremendous increase of energy consumption and emissions of air pollutants that further degraded the already low air quality in these areas, resulting in air pollution over China's cities well above the acceptable levels (Chan and Yao, 2008). Although much effort was devoted to alleviating air pollution problems in China's cities, the increasing number of vehicles is counteracting the measures taken to reduce aerosol emissions. Moreover, as experience in EU has shown, legislative measures to reduce air pollution will take about a decade to transform to observable improvements in air quality.

Therefore, a statistically significant change from dimming to brightening in Beijing could not be seen in the last decade, with the data sets studied, but it is expected to occur in the near future. This is because of the new stricter measures taken in China as mentioned above. Finally, the findings in this work indicate the need for high-quality ground-based observations to be used as reliable ground truth.

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