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The solar radiation climate of Athens: Variations and tendencies in the period 1992–2017, the brightening era

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ABSTRACT

Solar radiation at the surface of the Earth undergoes short- and long-term variations mostly influenced by changes in atmospheric composition and cloud cover. These two factors characterise the solar radiation climate at a place. This study deals with the solar radiation climate over Athens focusing on the variations and trends of the global and diffuse horizontal irradiances recorded at the Actinometric Station of the National Observatory of Athens. The analysis shows that the global radiation over Athens in the period 1992–2017 presents a maximum in July and in May, June around noon under all and clear skies. For the diffuse component, this occurs in spring and in May (noontime) under all- and clear-sky conditions. The global radiation trends are positive (+0.41%/decade and +2.36%/decade for all and clear skies, respectively), while its diffuse counterpart shows negative trends (−6.93%/decade and −9.27%/decade for similar sky conditions, respectively) in the period 1992–2017. These findings confirm the recovery in the solar radiation levels over Athens in the recent 25 years.

1. Introduction

Solar radiation reaching the surface of the Earth is the primary source for life as it controls various fields, such as atmospheric environment (e.g., Giesen et al., 2008), terrestrial ecosystems (e.g., Asaf et al., 2013), and terrestrial climate (e.g., Bojinski et al., 2014). SSR is the most abundant renewable energy resource for Earth; therefore, its exploitation for solar energy applications started intensively twenty years ago mainly for PV installations (Kambezidis, 2016). Variations in SSR are caused by changes in the atmospheric constituents (Forster et al., 2007), variations in the cloud cover (Haywood and Boucher, 2000), as well as the variability in the Sun-Earth geometry (Milankovitch theory). The latter issue is related to the past history of the climate of the Earth and is not dealt with in the present study. Therefore, clouds and atmospheric aerosols are two factors that play a significant role in establishing the SSR climate at a site. They are statistically varying (in space and time), thus causing an analogous statistical variability in SSR (e.g., Diabate et al., 2004).

In view of the above SSR undergoes variations at scales from seasonal to decadal (e.g., Wild, 2009). The short-term (intra-annual or seasonal) variations in the solar radiation levels are mainly attributed to the rotation of the Earth around the Sun; the long-term (decadal) variations are mostly attributed to changes in atmospheric composition, since solar radiation at the top-of-the-atmosphere experiences very small changes (Fröhlich and Lean, 1998). In this context, global dimming/brightening refers to a decrease/increase in SSR that has serious implications in the Earth's climate, among which are the evaporation rates and the hydrological cycle. Changes in water vapour affect atmospheric transmittance, and, in turn, SSR (Haywood et al., 2011). Furthermore, changes in the diurnal temperature range may be associated with trends in solar radiation and sunshine duration (Besselaar et al., 2015), since a decline in the daily maximum temperatures was observed at many places during the period from 1950 to 1980 (Wild et al., 2007).

The decadal variation in SSR over North America and Europe shows a global dimming in the period of 1960–1980s, and afterward a recovery (global brightening) of $\sim +0.15$ Wm^{-2} y^{-1} to $+0.24$ Wm^{-2} y^{-1} between 1990s and 2000s (Norris and Wild, 2007; Wild, 2009). However, solar dimming continues to exist over India and Southeast Asia (Badarinath et al., 2010; Kambezidis et al., 2015). The studies investigating the global dimming/brightening phenomenon are mostly based on long-term analyses of SSR measurements over parts of Europe, North America and Asia or alternatively on an analysis of the parameters associated with SSR, model simulations for future predictions (e.g., Haywood et al., 2011), combined measurements and models (e.g., Ruckstuhl and Norris, 2009), and exploitation of satellite data (e.g., Hinkelman et al., 2009). Very few studies cover several years beyond the 2000s (e.g., Sanchez-Lorenzo et al., 2015). The Mediterranean (a climatologically-sensitive area as a cross-road of atmospheric aerosols) has been investigated only by Kambezidis et al. (2016) in the period

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Nomenclature

Greek symbols

α_r	extinction coefficient (dimensionless)
γ	solar elevation (radians)
Δ	sky brightness (dimensionless)
ε	sky clearness (dimensionless)

Latin symbols

COD	cloud optical depth (dimensionless)
CR	cloud ratio (dimensionless)
D	trend indicator (dimensionless)
D_e	diffuse horizontal irradiance (Wm^{-2})
$D_{e,sci}$	clear-sky diffuse horizontal irradiance (Wm^{-2})
F	nebulosity index (dimensionless)
G_e	global horizontal irradiance (Wm^{-2})
$G_{e,o}$	solar constant (Wm^{-2})
$G_{e,extra}$	extra-terrestrial global horizontal irradiance (Wm^{-2})
JD	day number ($JD = 1$ for 1 January, $JD = 365$ for 31 December and $JD = 366$ for 31 December in leap years)
K_t	clearness index (dimensionless)
K_d	cloudiness index (dimensionless)
LST	local standard time (h)
m	relative optical mass (dimensionless)
$P_{e,sci}$	theoretical direct horizontal irradiance (Wm^{-2})
s	slope of trend (dimensionless)
S	Sun-Earth distance correction factor (dimensionless)
T_L	Linke turbidity factor (dimensionless)

Abbreviations

amsl	above mean sea level
ASNOA	Actinometric Station of the National Observatory of Athens
BSRN	Baseline Solar Radiation Network
CIE	Commission Internationale de l' Eclairage
CLARA	clouds, albedo, and radiation (data set)
GEBA	Global Energy Balance Archive
ITA	innovative trend analysis
M-K	Mann-Kendall statistic
LRA	linear regression analysis
PMOD/WRC	Physical Meteorological Observatory in Davos/World Radiation Centre
PSP	precision spectral pyranometer
SARAH	surface solar radiation data set – Heliostat
SSR	surface solar radiation

1979–2012.

The solar radiation climate at a location provides the levels and trends of the SSR components (global, diffuse, direct) for a long period of time (usually equal to or longer than 10 years). At international level several works have dealt with the solar radiation climate at various locations on Earth (for Barcelona, Spain, Jiménez, 1981; from satellite data, Schmetz, 1989; for Alaska, Dissing and Wendler, 1998; for Central Europe, Petrenz et al., 2007; for Bengaluru, Akshay et al., 2016; for California, Nottrot and Kleissl, 2010, and for Morocco, Mensour et al., 2017). In Greece no such a study has appeared as the country does not possess an organised solar radiation network; the only complete solar platform at the moment is the ASNOA established in 1952.

A recent study by Kazadzis et al. (2018) examined the variation of the global horizontal radiation levels in the period 1954–2012 and tried to construct the SSR time-series in the period 1900–1953 from observations of cloudiness in order to show the early and late global dimming effects over the city of Athens as well as the recovery of SSR in the recent years. Nevertheless, that study does not possess characteristics of a solar radiation climatology for Athens, a lack that is dealt with in the present work. A second characteristic of the present study is the inclusion of the diffuse solar radiation in a solar radiation climatology for the first time worldwide. Indeed, both solar radiation parameters (global and diffuse) are presented here, whereas Kazadzis et al. (2018) analysed the global horizontal irradiance only. A third characteristic of the present study is the application of the ITA method in Greece for the first time; this method was introduced by Şen, (2012) to climatological time-series.

The structure of the paper is as follows. Section 2 presents the data used in the study (i.e., the data collection in Section 2.1, the processing of the data in Section 2.2, the research methodology in Section 2.3). Section 3 presents the results of the study (i.e., the month-hour diagrams in Section 3.1, the SSR variations under all-sky conditions in Section 3.2, the effect of the atmosphere/sky status on SSR in Section 3.3, the SSR variations over Athens under clear-sky conditions in Section 3.4). Section 4 presents the main conclusions of the study. Acknowledgments and References follow.

2. Materials and methods

2.1. Data collection

The ASNOA is a unique solar radiation station in Greece (37.97° N, 22.72° E, 107 m amsl). It is situated on the Hill of Pnyx, very close to the Acropolis of Athens. It started its operation in 1953 by measuring global horizontal radiation. In the progress of time, ASNOA was enriched with other radiometric equipment for measuring additional solar radiation components, e.g., diffuse horizontal radiation. In 1992 ASNOA acquired a research-level daylight station in the frame of a European project. Therefore, the common period of 1992–2017 (26 years) was chosen for the analysis of solar radiation levels at Athens, a Mediterranean site. The analysis of the daylight levels for the same time period will be the subject of a separate work. Another reason for choosing the above-mentioned time period is the observation by researchers (e.g., Sanchez-Lorenzo et al., 2009; Kambezidis et al., 2016) about the recovery of solar radiation levels (global brightening) after 1990 over most parts of Europe and the Mediterranean. The parameters analysed in this work are the global horizontal irradiance, G_e (in Wm^{-2}), and the diffuse horizontal irradiance, D_e (in Wm^{-2}). Both parameters are recorded at ASNOA by a data logger, which is programmed to perform measurements every 20 s; the logger calculates 1-min averages from three 20-s samples and stores them. The 1-min values are processed off-line following a quality-control test as shown in Table 1, where P_e is the direct horizontal irradiance ($P_e = G_e - D_e$, in Wm^{-2}); $G_{e,extra}$ is given by Iqbal (1983):

$$G_{e,extra} = S \cdot G_{e,o} \cdot sin\gamma, \tag{1a}$$

Table 1
Quality-control tests for the 1-min average values of the irradiance parameters at ASNOA (Kambezidis et al., 1994). SSR values not obeying any of the criteria were rejected.

$D_e < 1.1\ G_e$
$G_e < 1.2\ G_{e,extra}$
$D_e < 0.8\ G_{e,extra}$
$P_e < G_{e,extra}$
$G_e \geq 10\ Wm^{-2}$ (lower detection limit of pyranometers)
$\gamma \geq 5°$ (avoidance of the cosine effect on pyranometers)