Causes of dimming/brightening in Greece and implications on reference evapotranspiration

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Abstract: Many studies continue to investigate, in a changing climate, the decadal changes of surface solar radiation (SSR) known as Global Dimming/Brightening phenomenon (GDB) and its underlying causes. Contributing to the ongoing debate on whether GDB is global or just local phenomenon, this study analyses the temporal changes of Sunshine Duration (SD) measurements (as a proxy of SSR), for various areas in Greece, during the period 1968 to 2012. In addition to the temporal changes in aerosol concentrations and cloud cover (CL), changes in precipitable water (PW) and the effect of urbanization are also investigated as possible causes of GDB. Anomaly CL and PW series examined according to their time evolution are subsequently used to remove the CL effect and detect causes of GDB linked to atmospheric aerosols. Moreover, the population density index is used to quantify the impact of urbanization on GDB. The consistency of SSR trends with the trends of reference evapotranspiration (ET) and their impact on changes in the hydrological cycle has hardly been studied until now. In order to investigate the implication of GDB in ET changes, anomaly ET series, are estimated by the Reference Evapotranspiration Model for Complex Terrains (REMCT), which has already been tested and locally calibrated in Greece, for the same time period. The results show that the ET temporal changes rather follow the SD ones, indicating the GDB effect in the ET changes in Greece.

Key words: Global Dimming/Brightening phenomenon, Sunshine Duration, population density index, Reference Evapotranspiration Model for Complex Terrains

1. INTRODUCTION

Many researchers have confirmed GDB phenomenon, namely the widely observed decline of SSR (Dimming) between 1950s and 1980s and its subsequent recovery until around 2000, (Brightening) in many parts of the world (e.g. Stanhill and Cohen, 2001; Wild, 2009), while mixed trends are shown afterwards (Wild, 2009, 2016). Possible causes of GDB are associated with temporal changes in aerosol or and CL (Stanhill and Cohen, 2001; Wild, 2009). Changes in concentrations and optical properties of aerosols due to the direct/indirect aerosol effect are considered as the most likely factor explaining SSR variations (e.g. Wild, 2009, 2016). Water vapour also influences SSR and although the magnitude of its impact is reported as substantially small, should not be ignored (Ohmura, 2009; Wild, 2009).

Some studies have argued that GDB is dominated by the large air polluted urban sites and thus, is more of a local rather than a global phenomenon. In addition, the possible impact of urbanization on GDB has recently come to the light (Wang et al., 2014; Imamovic et al., 2016; Tanaka et al., 2016). In order to infer the influence of urbanization on SSR, many studies have used population density data, as proxies of air pollution level (Alpert and Kishcha 2008; Stanhill and Cohen, 2009).

Changes in SSR affecting the energy available at the surface to drive evaporation are considered as a potential impact of GDB on the water cycle (Wild and Liepert, 2010). Evaporation paradox, the decrease of pan evaporation (Epan) under global warming, has been explained by the decreasing SSR during dimming phase (Stanhill and Cohen, 2001; Roderick at al., 2009). Moreover, the decrease from 1950s and the recently reported increase after mid-1980s of Epan (Ogolo, 2011) or ET (Papaioannou et al., 2011; Zhao et al., 2015) mainly follow the SSR trends, underlying the impact of GDB on changes in the hydrological cycle, but further investigation is needed.
As a first objective, this study aims to contribute to the recent debate on whether the observed SSR changes are global or just local phenomenon, by detecting GDB phenomenon in Greece, using SD measurements as a proxy of SSR during the period 1968-2012. The second objective is to detect possible causes of GDB during the same period. Besides investigating changes in aerosols or cloud cover, effects of PW changes and the impact of urbanization (taking into account population density indices) especially during dimming period, are also examined. The third objective is to investigate GDB impact on ET. The consistency of SD trends with the trends of ET estimates by the REMCT model or measurements of Epan at a non-urbanized site are tested.

2. DATA AND METHODS

2.1 Data sets

Daily measurements of SD and CL, obtained from the National Meteorological Service for 13 stations (evenly distributed across the country, Figure 1) are used for analysing long-term changes in SSR and detect the GDB phenomenon in Greece, during the period 1968-2012. Daily SD is considered as a 'proxy' of SSR (Stanhill and Cohen, 2005) and daily CL is used for removing the cloud cover-related variability from the SD measurements. Additionally, column integrated water-vapour (PW) daily NCEP/NCAR reanalysis products extracted for the pixel in which the 13 stations are located, are also employed for detecting causes of GDB linked mainly to changes in water-vapour.

Municipality population data, obtained from the Hellenic Statistical Authority (http://www.statistics.gr/el/statistics/pop) are used for indicating any effect of urbanization on SD.

Monthly values of precipitation, mean and maximum air temperature for the 13 stations are used for estimating monthly ET from REMCT model (Diodato and Belloccchi, 2007), for the period 1968-2012. Daily Epan measurements of Agia Barbara station obtained from the Institute of Land Reclamation of Crete are also used for investigating the GDB impact on evaporation in a non-urbanized area.
The years 2005, 2006, 2007 and 2008 are excluded from the analysis, due to a gap in the quality control of the data supplied by the National Meteorological Service.

2.2 Methods

2.2.1 Causes of GDB

In order to address the question of whether GDB is local or a larger scale phenomenon, the 13 stations are separated into two groups: urban and rural. Municipalities and communes of Greece are characterized as urban when having 10000 or more inhabitants in the largest population center (http://unstats.un.org/unsd/demographic/sconcerns/densurb/Defintion_of%20Urban.pdf) and as rural or semirural, when the population is less than 2000 or between 2000 and 9999, respectively (https://www.statistics.gr/documents/20181/1210503/methodological_note_census_coverage_survey_final.pdf).

For detecting GDB and its possible causes, anomalies of annual SD and CL or PW values for each station are computed, as relative deviations from the corresponding 1971-2000 mean, during 1968-2012. Annual mean series are calculated by averaging the 13 stations considered ‘as a whole’. In order to remove the cloud effect and detect causes of GDB linked to atmospheric aerosols, the residuals SD time series are calculated from the linear regressions of SD and CL anomalies for each station.

Population data are assumed as a proxy for anthropogenic activity, especially during the dimming period, which is characterized by limited air quality regulations. For quantifying the possible impact of urbanization on SD changes, the population density (PD) index, already used in several studies (e.g. Imamovic et al., 2016; Tanaka et al., 2016) is calculated as:

\[ PD = \frac{TP}{LA} \]  \hspace{1cm} (1)

where, TP is the total population and LA is the land area of each municipality (km²).

2.2.2 Impact of GDB on ET changes

In order to investigate the effects of GDB in ET, annual ET anomaly values are estimated, as relative deviations from their corresponding 1971-2000 mean, for the 13 stations, for the period 1968-2012. REMCT model is selected for estimating ET in Greece, since its model parameters for various groups of stations have been locally calibrated and it has been independently validated from available Epan measurements (Papaoannou et al., 2011). Especially, the model has been also verified in the urban area of Athens (Kitsara et al., 2013). The REMCT model estimates ET as:

\[ ET_{DB} = \frac{R_s}{\lambda} \cdot \cdot \cdot (T + 17.8) \cdot \cdot \cdot (\sqrt{T_{\max} - ref(T_{\min})} \cdot f(w) \cdot Rd) \cdot f(c_{\lim}) \]  \hspace{1cm} (2)

where \( R_s \) is the mean monthly extraterrestrial solar radiation (MJ m² d⁻¹), \( \lambda \) is the latent heat of vaporization (MJ kg⁻¹), T or \( T_{\max} \) is the mean monthly or the mean monthly maximum air temperature (°C) respectively, Rd is the number of rainy days in a month (month⁻¹), ref(T_min) is a reference minimum air temperature (°C) and f(clim) and f(w) are semi-empirical functions.

Since Epan measurements incorporate the influence of radiation, atmospheric humidity and wind speed, trends of annual Epan measured at the non-urbanized area of Agia Barbara are also computed, for the period 1970-2007.

The analysis is furthermore accomplished by applying the best fits, from first order to third order, to the yearly time series of the mentioned SD or PW or residual SD or ET anomalies or Epan values.
3. RESULTS

3.1 Causes of GDB

In order to detect GDB and its causes, annual SD and residual SD or PW anomaly series, either for all stations (as averaged from the 13 stations) or for the selected urban (Iraklio) or rural (Methoni) station are shown in Figure 2 as a, b or c, respectively. Annual SD anomaly series for all stations (black bold line) show a negative trend up to minimum at the early 1980s (dimming period), a recovery until early 2000 (brightening period) and a stabilization phase until the end of the considered period (Figure 2a). Temporal changes of SD anomaly series, selected to represent urban or rural areas (noted with red or green bold line, respectively) have shown the same dimming/brightening periods. The evolution of annual CL anomaly series for all stations has been found as decreasing until late1980s, followed by an increase until 2012 not explaining the obvious decrease/increase in SD. Thus, the residual SD series are obtained from the linear regressions of SD and CL anomalies and their time evolution is presented either for all stations, considered as averages from the 13 stations, (bold black line) or for the selected urban (red bold line) or rural (green bold line) station in Figure 2b. The residual SD series for all stations show a clear decrease from the beginning of the study period up to early 1980s with a subsequent recovery until mid-2000 and a phase of stabilization thereafter. The residual SD anomaly series for urban or rural sites, although similar in shape, as compared to the evolution of the residuals SD series for all stations, indicate the reversal from dimming to brightening a little bit earlier, around 1980. A clear decrease in residual SD series is detected between 1991 and 1992 especially at the urban station, probably due to Pinatubo volcanic eruption (June 1991). Additionally, the effect of water-vapour changes in GDB is examined and the time evolutions of PW anomalies for all stations (or urban or rural station), are shown in Figure 2c (black or red or green bold line, respectively). PW anomalies decreasing from 1968 up to early 1980s (or 1980), remaining stable until mid-2000s (or 2000, respectively) and rather decreasing thereafter cannot explain SD variation.

PDs (as a proxy of local air pollution) are employed for investigating the possible effect of urbanization on the observed SD changes. Figure 1 shows the population per decade at municipality basis for the 13 sites (with urban or rural and semirural sites, noted with red or green color, respectively) and Figure 2d shows the changes in PDs in the 13 municipalities. Red and green lines indicate urban and rural stations, respectively. PDs are obviously increased for the majority of the urban stations, during the first decades of the study (1961-1981) and they are stabilized, during the last decade. In contrast, PDs of the rural areas attain lower values and remain unchanged through the years. The PDs of the selected urban (Iraklio) or rural (Methoni) station are shown in dashed lines in Figure 2d. Large PDs in Iraklio (among the biggest Greek cities) change through the years, while low PDs in Methoni remain almost the same.

3.2 Impact of GDB on ET changes

The impact of GDB on ET is examined by investigating the consistency of SD trends with ET trends. Annual time evolutions of anomalies of ETDB, for all stations (as averaged from 13 sites) or for the selected urban or rural station, for the period 1968-2012 are shown in Figure 3a (black or red or green bold line, respectively). A negative trend up to minimum around the late 1970s, then a recovery until mid-2000 and a slight decrease until the end of the study period is observed. Similar variations of ETDB anomalies are observed for urban or rural stations, except during the period after the mid-2000, when they continue to rise in rural sites but slightly decrease in urban ones.

To enhance the results for the effect of GDB on evaporation, temporal variation of annual Epan measurements from 1970 up to 2007, for the rural area of Agia Barbara (which has a stable population around 2000) and annual SD series from the closest site of Tympaki are presented in Figure 3b. Annual Epan series highlighted the dimming period from 1970 up to early or mid-1980s
and the brightening period thereafter until 2007, in accordance with the results of ET_{DB}. It is indicated that even in the non-urbanized site of Agia Barbara, the GDB is still observed, probably related to the background aerosols.

![Figure 2](image1.png)  
**Figure 2.** Annual time evolution of (a) SD anomaly, (b) residuals estimated from the linear regression between SD anomaly and CL anomaly and (c) PW anomaly for all stations or the selected urban (Iraklio) or rural (Methoni) station, during the period 1968-2012. Changes of population density index in urban (red line) or rural (green line) stations in Greece since 1961 (d).

![Figure 3](image2.png)  
**Figure 3.** Annual time evolution of (a) ET anomalies for all stations or the selected urban (Iraklio) or rural (Methoni) station, during 1968-2012, (b) Epan values in Agia Barbara (1970-2007) or SD anomalies in Tympaki (1974-2004).

4. DISCUSSION AND CONCLUSIONS

Dimming is detected in Greece, from 1968 to early-1980s, while afterwards brightening is observed until mid-2000 and seems to level off thereafter, in general accordance with studies based
on SD trends in Europe (e.g. Manara et al., 2015). Thus, GDB might be regarded, as not a local phenomenon.

PW and CL changes were found as not attributing to the phenomenon. After removing cloud effect, annual residual SD series highlighted the same GDB periods, in urban and rural sites, pinpointing that dimming is mainly linked to aerosols changes (e.g. Norris and Wild, 2007). Furthermore, brightening is consistent with the reduction of local aerosols, due to air-quality control measures taken all over European Union (Streets et al., 2006).

PD indices have shown that any urbanization was mainly occurred, during the dimming period, but SD anomalies decline during the dimming phase in both urban and rural sites. During the brightening phase, SD recovery happened not only in the rural areas, which is supposed to be unaffected from urbanization and local pollution, but also in the urban stations in agreement with results referred by Wang et al. (2014). This suggests that local air pollution did not play a role in causing GDB, in agreement with the findings of Tanaka et al. (2016), for Japan or Imamovic et al. (2016), for Europe.

Annual ET_{DB} anomalies show a negative trend until the late 70s and then a partial recovery until mid -2000s, for all stations or both the selected urban or rural station, being in general coincidence with the annual evolution of SD anomalies and pointing out the GDB effect on ET changes. This is in agreement with similar results reported by Papaioannou et al. (2011), Kitsara et al. (2013), Zhao et al. (2015). The effect of SD trends on ET_{DB} trends is furthermore supported by Epan trends in the rural area of Agia Barbara, following the changes of SD anomalies (obtained from the nearest Tympaki station), underlying that GDB is due to background air pollution transported from long distance polluted areas, through long-range transport (Ramanathan et al., 2007).

This study suggests that the GDB in Greece is not restricted to urban areas but is also detected in rural areas in accordance with other studies (Wang et al., 2014; Imamovic et al., 2016) and probably caused by large scale changes in background aerosols (Tanaka et al., 2016).

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REFERENCES


