

DIMMING/BRIGHTENING IN ATHENS: TRENDS IN SUNSHINE DURATION, CLOUD COVER AND REFERENCE EVAPOTRANSPIRATION

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ABSTRACT

Evidence of global dimming/brightening is mainly based upon few measurements of solar radiation. A need for more research supported and extended with the use of other climatic variables, such as sunshine duration (SD), recorded for a longer time period and successfully used as a proxy for solar radiation over the past 80 years, has already been urged. Thus, in this study, residual SD series computed after removal of the cloudiness-related variability, from daily sunshine duration and cloudiness data measured at the National Observatory of Athens are used for highlighting global dimming or brightening periods in Athens, during the period 1951-2001. Furthermore, the consistency of trends in radiation records and their implications for the hydrological cycle and especially the trends in reference evapotranspiration are examined, during the period 1951-2001. The analysis focuses on the seasonal decadal variations, determines and explains the causes of the seasonal trends from the inter-annual and decadal variability of the SD during the last half past century, with a special emphasis in detecting possible subperiods in Athens. The signs of trends in the modeled annual and seasonal reference evapotranspiration are estimated, according to the indicated global dimming/brightening periods.

1 INTRODUCTION

Solar radiation incident at the Earth's surface is the ultimate energy source for life on the planet, and largely determines the climatic conditions. The amount of solar energy reaching the surface is a major component of the surface energy balance and governs a large number of diverse surface processes, such as evaporation and associated hydrological components. Observational and modelling studies emerging in the past two decades suggest that global solar radiation is not necessarily constant on decadal time scales, but shows substantial variations. A widespread reduction of global solar

radiation between the 1950s and early 1980s (global dimming) and the reversal of this trend thereafter (global brightening) have been analysed in numerous studies for various regions of the world as summarized by Wild (2009).

Although causes of these phenomena are not fully understood currently changes in the transmissivity of the Earth's atmosphere due to changes in concentrations and optical properties of aerosols as consequence of anthropogenic emissions are considered the most likely causes (Stanhill and Cohen 2001; Wild et al. 2005, 2007, 2009). A possible connection between the decreasing global solar radiation trends and changes in aerosols has firstly pointed by Stanhill and Moreshet (1992). Recently, an increasing number of studies suggest that changes in aerosol concentrations have contributed to the observed dimming and the subsequent brightening around the globe (Wild et al. 2005; Streets et al. 2006; Ohmura 2006; Ruckstuhl et al. 2008; Ohvri et al. 2009; Vautard et al. 2009; Hatzianastassiou et al. 2009). Especially in Europe, a significant part of the brightening is reported as related to the reduction of local aerosol amounts due to air-quality control measures and stringent measures taken all over Europe and the de-industrialization in eastern European countries.

Since cloudiness is the largest modulator of global solar radiation, it has also been suggested that the dimming period may be linked to a detected increase in total cloud cover since the second half of the 20th century over many regions in the world (Dai et al. 1999). In contrast, a decrease in cloud cover over land, from visual observations and remote sensing (Rossow and Duenas 2004; Warren et al. 2007), has been reported since the late 1970s or the early 1980s. This cloudiness change can be reasonably related to the brightening period (Wild et al. 2005). However, it must be noted that during the dimming period there were areas with decreasing cloudiness (Kaiser 2000; Maugeri et al. 2001; Auer et al. 2007), and also areas lacking cloud cover trends but with decreases in global solar radiation (Stanhill and Moreshet 1992; Stanhill and Cohen 2001; Qian et al. 2006). Also, different studies have detected changes in global solar radiation under clear skies (Abakumova et al. 1996; Wild et al. 2005; Ruckstuhl et al. 2008) and cloudy skies (Liepert 2002), due to variations in atmospheric transparency linked to changes in anthropogenic aerosols. Some researchers suggest that the dimming and brightening over Europe becomes even more pronounced after the effects of changes in cloud amounts were removed (Norris and Wild 2007; Sanchez-Lorenzo et al. 2009). This indicates that aerosol effects may have caused the observed changes in solar radiation over Europe (Norris and Wild 2007; 2009). Apart of the aerosols of anthropogenic origin, aerosol from natural sources could potentially also influence global solar radiation variations, such as volcanic sulfur aerosols (Streets et al. 2009). Volcanic aerosols have a particularly large influence on solar radiation for a few years after the major volcanic eruptions. Another factor which is recently connected with the changes in solar radiation is the impact of atmospheric circulation pattern such as North Atlantic Oscillation (Sanchez-Lorenzo et al. 2008, 2009; Chiacchio and Wild 2010).

Evidence of global dimming is thus far based mainly upon few measurements of solar radiation. Thus, a need for more accurate measurements and research extended on longer series of records has been urged (Stanhill and Cohen, 2005). A number of valuable proxy parameters for the decadal changes in solar radiation have been put forward in the literature. Multidecadal records of sunshine duration, pan

evaporation and diurnal temperature range measurements despite their individual drawbacks, may allow an extension of the spatial and temporal information on the evolution of solar radiation. Sunshine duration may serve as useful proxy for solar radiation, as pointed out, by *Stanhill and Cohen* (2005). SD variations in various regions have been analyzed in numerous studies, as for example summarized by *Sanchez-Lorenzo et al.* (2007). SD time evolution has been reported with a decrease since the 1950s until the mid-1980s, and a recovery thereafter (*Sanchez-Lorenzo et al.* 2007, *Abakumova et al.* 2008, *Sanchez-Lorenzo et al.* 2008, *Stanhill and Cohen* 2008, *Liley* 2009, *Sanchez-Lorenzo et al.* 2009), in line with studies investigating changes in surface solar radiation. *Sanchez-Lorenzo et al.* (2009) as well, using long-term SD data for the Iberian Peninsula found the dimming and subsequent brightening periods even in records that only contained SD of cloud-free days, indicating the contribution of changes in aerosol concentrations to these trends.

Solar radiation is a major driver of evaporation especially in energy limited environments. Contrary to the expectation that a warmer climate will increase evaporation, many studies have reported decreasing or increasing pan evaporation over the past 50 years or so, for many places of the world with widely different climates as summarized by *Papaioannou et al.* (2011). The interpretation mainly of negative trend has been controversial. At first it was thought as indication of a general negative trend in terrestrial evaporation in those areas, which seemed incompatible with the reported general increases in global precipitation in the same period. *Brutsaert and Parlange* (1998), suggested that this may indicate increasing terrestrial evaporation, due to the complementary relationship between potential and actual evaporation. On the other hand in some studies (*Cohen et al.* 2002; *Roderick and Farquhar* 2002; *Ohmura and Wild* 2002; *Liu et al.* 2004; *Wild et al.* 2004), this was attributed in decreasing solar irradiance (global dimming) giving evidence of decreasing landscape evaporation. *Brutsaert* (2006) has shown that both effects (global dimming and the complementary relationship) can be combined. Recently, *Teuling et al.* (2009) have shown that both scenarios of decreasing actual evapotranspiration with decreasing pan evaporation in regions with ample supply of water and of increasing evapotranspiration with decreasing pan evaporation can be encompassed. Several studies have examined the trends in potential or reference evapotranspiration as well, in order to investigate the changes to latent heat (the energy equivalent to evaporation) over land. The Penman-Monteith formulation (*Monteith*, 1981; *Allen et al.* 1998) has been widely used. Like the trends in pan evaporation, trends in reference evapotranspiration have been reported negative for some regions and positive for other ones. The new 'reference evapotranspiration model for complex terrains' (REMCT), developed by *Diodato and Bellocchi* (2007) and calibrated for Greece by *Papaioannou et al.* (2011) has been used to indicate that reference evapotranspiration over Greece during the period 1950-2001 decreases or increases following the global dimming/brightening periods.

Few studies so far have focused on the seasonal decadal variations in global solar radiation. Thus in this study daily sunshine duration (as a proxy of global solar radiation) and cloud cover, measured at National Observatory of Athens are used (at different temporal resolutions) for detecting possible dimming/brightening subperiods. The evolution of sunshine duration and cloud cover anomalies (during the period 1951-2001) is used for obtaining "residuals" SD series (after removing the linear associated

cloudiness variability) for highlighting the global dimming or brightening periods in Athens. The overall contribution of cloud cover to changes in SD in different seasons is examined. The seasons with the strongest decrease/increase are evaluated and the causes of the seasonal trends from the interannual and decadal variability of sunshine duration are determined. Additionally the consistency of trends in radiation and cloudiness records and their implications for the hydrological cycle and especially the trends in reference evapotranspiration are examined, during the same period. The locally calibrated (Papaioanou et al. 2011) ‘reference evapotranspiration model for complex terrains’ (REMCT), developed by Diodato and Bellocchi (2007), is used for estimating trends of reference evapotranspiration in Athens. The signs of trends in the modeled annual and seasonal reference evapotranspiration are estimated, according to the indicated global dimming/brightening periods.

2 DATA AND METHODS

2.1 Data sets

Daily Sunshine Duration measured at the National Observatory of Athens (37°58' N, 23°43' E), by Campbell-Stokes heliographs, is used as a proxy for exploring changes in solar radiation in Athens, during the period 1951-2001. Daily measurements of cloudiness (CL) are furthermore used for removing the cloudiness-related variability from the SD measurements, during the same period. The daily series of CL are obtained from the averages of 3-daily observations taken at 8, 14 and 20 LST. Monthly values of mean- (T) and maximum- ($T_{\max}$) air temperature, precipitation (PR) and number of rainy days (Rd) available for the period 1951-2001 are used to obtain monthly reference evapotranspiration by REMCT (Diodato and Bellocchi 2007) as calibrated by Papaioanou et al. (2011). Daily measurements of dry- and wet bulb- temperature, wind velocity and sunshine hours obtained from the National Observatory of Athens (NOA), during the period 1990-2001, are used for estimating reference evapotranspiration by Penman-Monteith equation (Monteith, 1981).

2.2 Methods

2.2.1 Reference Evapotranspiration

The ‘reference evapotranspiration model for complex terrains’, based on monthly rainfall occurrence and air temperature (Diodato and Bellocchi, 2007), is selected for estimating trends of reference evapotranspiration in Athens, since temperature and rainfall attributes are available for longer time periods. REMCT includes also, the effect of climate and site elevation and incorporates a monthly function of minimum air temperature, conditioned by the precipitation status to account for seasonal shifts. Monthly values of reference evapotranspiration (ET_{DIOBEL}) based on REMCT, are estimated by the following nonlinear equation:

$$ET_{DIOBEL} = \frac{R_{so}}{\lambda} \cdot (T + 17.8) \cdot (\sqrt{T_{\max} - ref(T_{\min})} - f(w) \cdot Rd) \cdot f(c \lim) \quad (1)$$

where, R_{so} is the mean monthly extraterrestrial solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), λ is the latent heat of vaporization (MJ kg^{-1}), T is the mean monthly air temperature ($^{\circ}\text{C}$), $T_{\max}$ is the mean monthly maximum air temperature ($^{\circ}\text{C}$), R_d is the number of rainy days in a month (month^{-1}), $\text{ref}(T_{\min})$ is a reference minimum air temperature ($^{\circ}\text{C}$), $f(\text{clim})$ and $f(w)$ are semi-empirical functions (month), modulating the rate at which the energetic forcing, involved in the evapotranspirative processes (principally the term under square root in equation 1), is approached as air temperatures and rainy days change. The reference minimum air temperature is determined as:

$$\text{ref}(T_{\min}) = a[1 - \alpha \cos(2\pi \frac{m-b}{c})] \quad (2)$$

Where, m is the month, a , α , b and c are empirical parameters equal to: -2.64 ($^{\circ}\text{C}$), 1.79 , 6.5 and 12.0 , respectively. The two semi-empirical functions are determined as:

$$f(\text{clim}) = d - e \cdot (\sqrt{(g - E) \cdot \frac{P}{1000}} - h \cdot E) \quad \text{and} \quad (3)$$

$$f(w) = k + q \cdot (T_{(a)\max} - 10)^3 \quad (4)$$

where $T_{(a)\max}$ is the long-term yearly mean daily maximum temperature ($^{\circ}\text{C}$), E is the site's elevation, (m), P is the long-term mean annual precipitation (m), d , e , g , h , k and q are empirical parameters equal to 0.00247 , 0.000000831 (m^{-1}), 2000 (m), 0.1 (m^{-1}), 0.0397 ($^{\circ}\text{C}^{0.5} \text{month}^{-1}$) and 0.000079228 ($^{\circ}\text{C}^{-3}$). The parameter g [in $f(\text{clim})$ function], set equal to 2000 m, is the upper elevation for REMCT to be applied. REMCT has been applied in Greece, after developing a methodology for calibrating the model parameters for various groups of stations (Papaioannou et al. 2011). NOA is considered as belonging to group 3 (Table 2 in Papaioannou et al. 2011). The recalculated REMCT parameters used in this study are $d=2.158\text{E}-03$, $e=4.600\text{E}-07 \text{ m}^{-1}$, $h=4.236\text{E}-01 \text{ m}^{-1}$, $k=2.619\text{E}-02 \text{ }^{\circ}\text{C}^{0.5} \text{month}^{-1}$, $q=3.880\text{E}-05 \text{ }^{\circ}\text{C}^{-3}$. The obtained $\text{ET}_{\text{DIOBEL}}$ values are compared with monthly Penman-Monteith estimates ($\text{ET}_{\text{PENMON}}$).

The daily $\text{ET}_{\text{PENMON}}$ used to estimate potential evapotranspiration from hypothetical reference grass with an assumed height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23 (Allen et al., 1998) is expressed as:

$$\text{ET}_{\text{PENMON}} = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \quad (5)$$

Where, Δ is the slope of saturated vapor pressure in relation to air temperature ($\text{kPa } ^{\circ}\text{C}^{-1}$), γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$), R_n is the net radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), G is the soil heat flux density ($\text{MJ m}^{-2} \text{d}^{-1}$), $(e_s - e_a)$ is the vapor pressure deficit (kPa), T is the mean daily air temperature at 2 m above ground level ($^{\circ}\text{C}$), u_2 is the wind speed at 2 m above ground level (m s^{-1}). Daily values of G or R_n (based on sunshine hours) are estimated according to Allen et al. (1998).

2.2.2 Trends in Sunshine Duration, Cloud Cover and Reference Evapotranspiration

Since SD records integrate insolation during all daylight hours, the mean CL defined from the referred 3 observations per day seem adequate for comparisons with the SD series. Thus, the annual and seasonal anomalies of SD and CL calculated as relative deviations from their corresponding 1971-2001 mean (Sanchez-Lorenzo et al.,

2009) are estimated during the period 1951-2001. The mean annual and seasonal evolutions of both variables are compared. In order to remove the cloud effect and detect a dimming or brightening signal linked to other factors, and similarly to other authors (Wild et al. 2005; Norris and Wild 2007; Sanchez-Lorenzo et al. 2009) the residual SD time series are obtained from the linear regressions of SD and CL anomalies.

Investigating the consistency of trends in radiation and reference evapotranspiration, the trends of locally calibrated ET_{DIOBEL} estimates or their anomalies are also examined on annual and seasonal basis according to dimming/brightening periods in Athens.

The analysis is furthermore accomplished by applying the best fits, from first order to third order, to all yearly and seasonal time series of anomalies, following the technique referred by Chiacchio and Wild (2010).

The trends in all considered time series are examined as statistically significant, by the nonparametric Mann-Kendall test, recommended by the World Meteorological Organization (Sneyers 1990). Having established their significance, the magnitude of the time trends for the highlighted dimming or brightening periods in Greece is determined, using standard parametric regression methods.

3 RESULTS

3.1 Reference Evapotranspiration

Since temperature and rainfall attributes are available for a long time period in NOA the new reference evapotranspiration model for complex terrains, developed by Diodato and Bellocchi (2007), is selected for estimating reference evapotranspiration in Athens. The model is applied with locally calibrated parameter values (Papaioannou et al. 2011) for obtaining monthly ET_{DIOBEL} values. The calibrated ET_{DIOBEL} estimates are validated by the results of linear regressions with monthly ET_{PENMON} estimates for the period 1990-2001. The correlation between all monthly ET_{DIOBEL} and ET_{PENMON} estimates, is presented in figure 1. The results from their linear regression show a very good agreement (R^2 equals to 0.977, at 95% significant level and the slope is equal to 0.938).

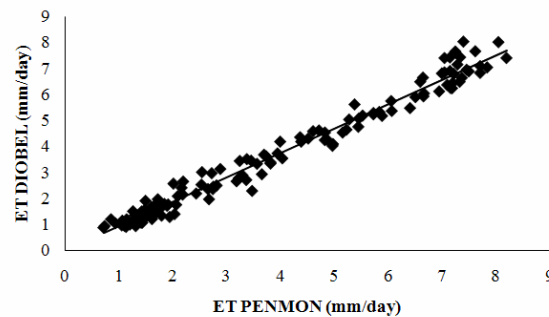


Figure 1 - Monthly Diodato Bellocchi evapotranspiration (ET_{DIOBEL}) as a function of monthly Penman-Montheith evapotranspiration (ET_{PENMON}) for the period 1990-2001. The solid line is the 1:1 line

It is obvious that most points tend to line up around the 1:1 line. These results suggest that ET_{DIOBEL} seems to be a good indicator of reference evapotranspiration for Athens.

3.2 Trends in Sunshine Duration, Cloud Cover and Reference Evapotranspiration

Figure 2 presents the mean annual, Spring and Summer evolution series for SD and CL anomalies (with reversed axis) in NOA.

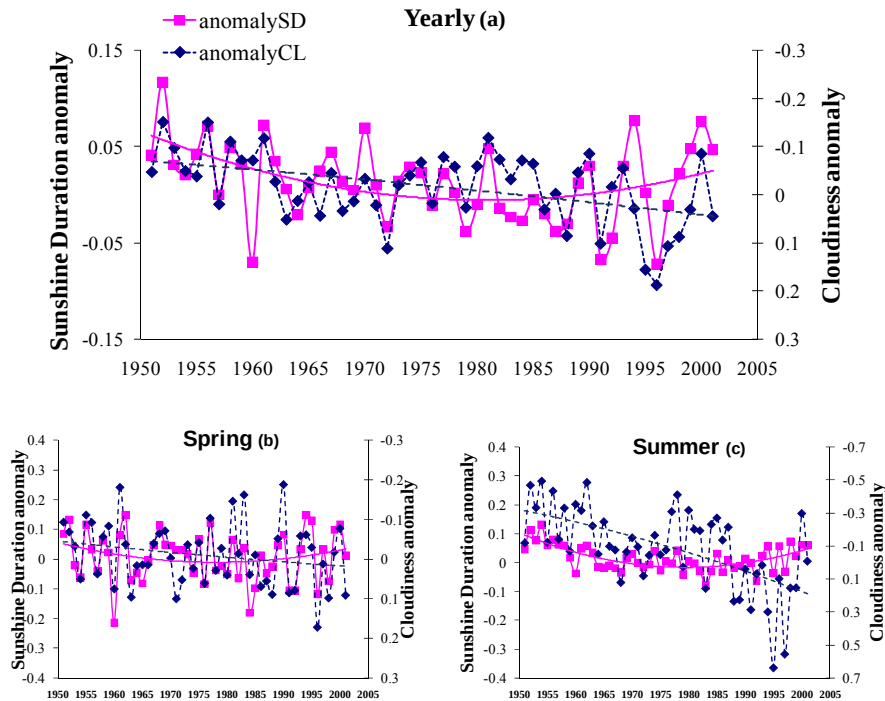


Figure 2 - Annual (a), spring (b), summer(c) time evolution of anomalies of SD and CL during the period 1951-2001.

A clear disagreement between both series from the 1950s to 1980s is detected in annual, Spring and Summer time evolution (a, b, c). Thus, SD shows a clear decrease (dimming) during this subperiod while CL increases. After the 1980s there is a good agreement between both variables since SD increases and CL increases too. During Winter and Autumn the disagreement between the SD and CL anomalies is extended up to 1990s. It must be noticed though that there is still a correlation between the two variables (R equals to -0.52 , -0.67 and -0.47 for annual, Spring and Summer series respectively).

In order to remove the cloud effect and detect a dimming or brightening signal linked to other parameters, the residual SD time series are obtained from the linear

regressions of SD and CL anomalies. The residual SD time series for each season are linearly regressed with the yearly residual SD series. The results from the linear regressions show correlation coefficients higher for Spring and Summer (R is equal to 0.70 and 0.65 respectively), as compared with Winter and Autumn residual series (R is equal to 0.40 and 0.54 respectively). The time evolution of annual residual SD time series for Athens (figure 3a) show a decrease from 1951 to the beginning of the 1980 with a subsequent recovery until 2001.

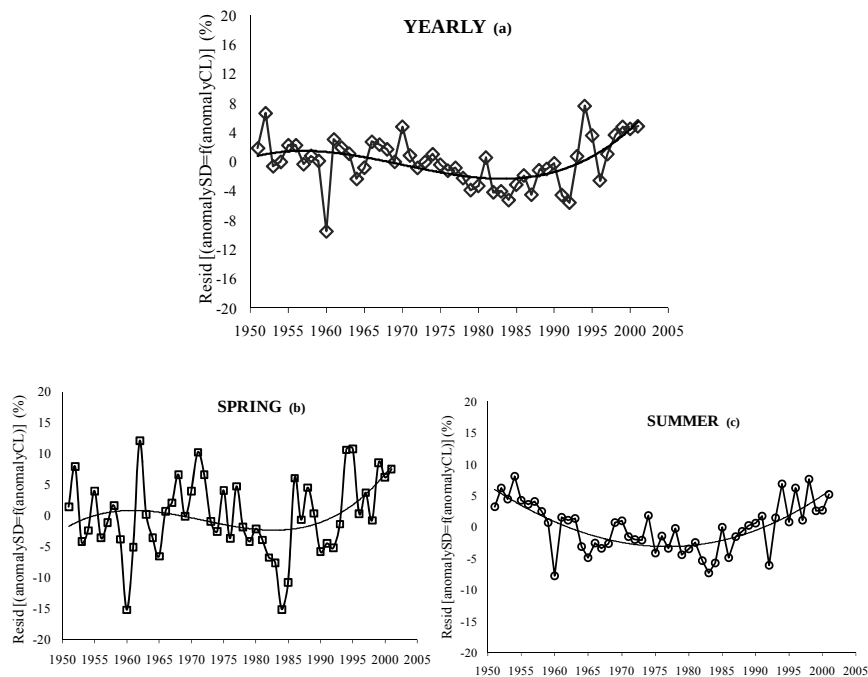


Figure 3 - Annual (a), spring (b), summer (c) time evolution of residuals from the linear regression of anomaly SD and anomaly CL in Athens during the period 1951-2001.

Thus, after removing the CL effect there is a clear decrease in residual SD time series especially after 1960s and a clear increase during the last two decades that cannot be explained by cloud cover. Yearly, Spring and Summer SD series are best fitted to a third-order equation (R^2 is equal to 0.30, 0.14 and 0.52 respectively). It must be noticed that trends in Autumn do not confirm dimming /brightening periods. Seasonal (Spring and Summer) residual SD time series are similar in shape to the annual residual records (fig. 3). A negative trend especially after 1960s up to minimum (at the early 80s) is obvious in either Spring or Summer residual time series and then a partial recovery until the end of the analyzed period is shown, following the globally detected solar dimming/brightening periods.

The nonparametric Mann-Kendall test, indicates statistically significant decreasing trend of the yearly residual SD time series (at 99% level), for the period

1951-1982 or increasing (at 99.9% level), for the period 1983-2001. The residual SD trend for summer also shows a statistically significant decrease (at 99.9% level) or increase (at 99.9% level), during the period 1951-1982 or 1983-2001, respectively, confirming the dimming/brightening periods in Athens. The residual SD trend for Spring is found negative, (but not statistically significant) during the period 1951-1982 and significant positive (at 99.9% level) during the period 1983-2001. Mann-Kendall tests pointed positive or negative trends for winter or autumn residuals SD series for both subperiods, respectively.

Furthermore, the consistency of trends in radiation records and their implications for the hydrological cycle and especially the trends in reference evapotranspiration are examined, for highlighting the dimming/brightening periods. In order to investigate the reference evapotranspiration trends and evaluate in what seasons the strongest decreases/increases are occurring the yearly and seasonal ET_{DIOBEL} anomalies are calculated during the period 1951-2001. In Fig.4 the correlation coefficients (R) for Spring and Summer ET_{DIOBEL} anomalies seem to be higher (0.69 and 0.74, respectively), as compared with Winter and Autumn ET_{DIOBEL} anomalies (0.47 and 0.48, respectively). The annual, Spring and Summer evolution of anomalies in ET_{DIOBEL} , during the half past century, are shown in figure 4.

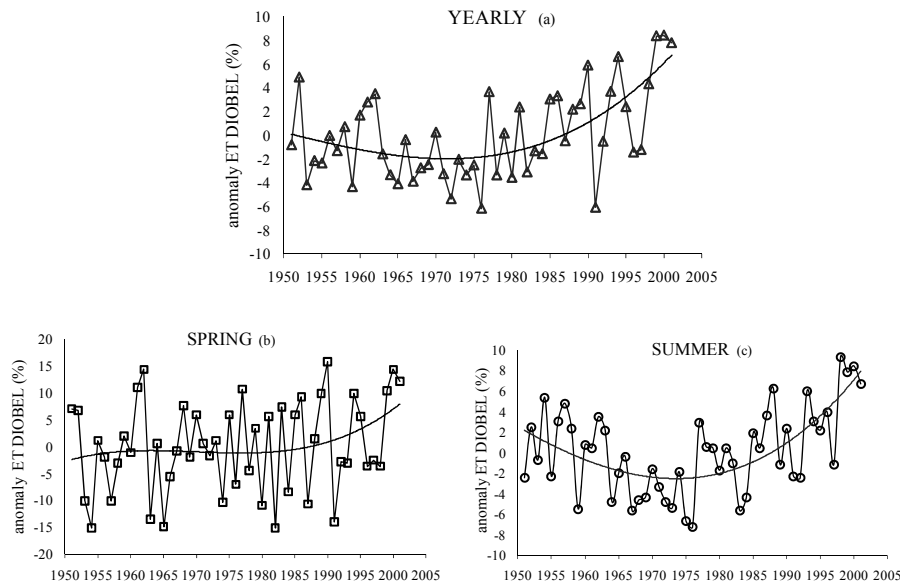


Figure 4 - Annual (a), spring (b), summer (c) time evolution of anomalies of ET_{DIOBEL} during the period 1951-2001

All series, calculated as relative deviations from their corresponding 1971-2000 mean are best fitted to a third-order equation (R^2 is equal to 0.39 and 0.43, respectively). A negative trend of annual, Spring and Summer ET_{DIOBEL} anomalies lasting some decades, up to minimum (at the late 70s) and then a partial recovery until the end of the

analyzed period are shown, following the globally detected solar dimming/brightening periods.

According to the nonparametric Mann-Kendall test, the yearly ET_{DIOBEL} anomaly trends are found significantly either decreasing (at 99.9% level), for the period 1951-1982 or increasing (at 99% level), for the period 1983-2001. Summer ET_{DIOBEL} anomalies also show statistically significant decrease (at 90% level) or increase (at 99% level), during the period 1951-1982 or 1983-2001, respectively. Not statistically significant trends for spring ET_{DIOBEL} anomalies are found as decreasing or increasing during the dimming or brightening periods, respectively. It must be noticed that trends in Winter and autumn ET_{DIOBEL} anomalies, do not confirm the dimming/brightening periods, highlighted from yearly, Summer and Spring data series in Athens.

4 DISCUSSION AND CONCLUSIONS

4.1 Reference Evapotranspiration

The reference evapotranspiration model for complex terrains (REMCT), employing the locally calibrated parameters for Greece (Papaioannou et al. 2011), has been applied successfully to estimate reference evapotranspiration in NOA. The locally calibrated REMCT estimates are independently validated from available monthly ET_{PENMON} estimates which are regarded worldwide as a good reference evapotranspiration estimator. The correlation between the monthly values of ET_{DIOBEL} and ET_{PENMON} (figure 1) is found very high ($R^2=0.977$). Thus, REMCT based on minimum data (air temperature and rainfall occurrence) shows to be suitable to estimate accurately the monthly mean reference evapotranspiration in Athens and hence to investigate its time evolution for longer time periods.

4.2 Trends in Sunshine Duration, Cloud Cover and Reference Evapotranspiration

The relationship between sunshine duration and cloudiness anomalies in Athens during the period 1951-2001 detected a negative correlation between both variables in the annual and seasonal series, as in previous studies in different areas of the world. The correlations are greater during Winter and Autumn and lower during Summer, indicating that a part of interannual variation in SD is not a result of cloudiness variations. The time evolution of yearly, Spring and Summer SD anomalies shows a decrease especially after 1960s till early 1980s that is not associated with an increase in CL anomalies. After the early 1980s there is a good agreement between both variables since SD and CL increase until 2001. These results for SD anomalies match generally the globally detected global dimming/brightening periods and they are in agreement with SD trends reported for the Iberian Peninsula (Sanchez-Lorenzo et al., 2007) and the Western Europe (Sanchez-Lorenzo et al. 2008).

When the cloud effect is removed, the computed annual residual SD series (figure 3) highlight the period of dimming especially from the 1960s to early 1980s followed by a period of brightening in the recent decades, as a signal linked to other factors. The seasonal residual time series for Spring and Summer, show a decreasing trend until

early 1980s and thereafter an increasing trend, similar to the annual residual record, confirming the dimming/brightening phenomenon on a seasonal basis as well (figure 3). The dimming and brightening periods detected in Athens show clear resemblance with that obtained for Central Europe from more sophisticated methods and data sets (Norris and Wild 2007) and might thus be regarded as not a local but a large scale phenomenon. The trends detected for Winter and Autumn do not highlight the dimming/brightening periods. The results from the seasonal analysis indicating similar behavior of Spring or Summer residual SD series with the annual series are in agreement with findings referred for Europe (Chiacchio and Wild 2010). It must be noticed though that similarity only between Spring and annual series is found in West Europe (Sanchez-Lorenzo et al. 2008). The potential causes for the annual mean evolution of residual SD trends for Athens during 1951-2001 may be generally related to the changes in aerosol radiative effects. A possible connection between the decreasing global solar radiation trends and changes in aerosols has firstly pointed by Stanhill and Moreshet (1992) and recently, an increasing number of studies suggest that changes in aerosol concentrations have contributed to the observed dimming and the subsequent brightening around the globe (Wild et al. 2005; Streets et al. 2006; Ohmura 2006; Norris and Wild 2007; Ruckstuhl et al. 2008; Ohvri et al. 2009; Vautard et al. 2009; Hatzianastassiou et al. 2009; Chiacchio and Wild 2010). During early 1980s to 2001 the overall trend in the residual SD is positive and is consistent with reduction of local aerosol amounts due to air-quality control measures and stringent measures taken all over European Union during this period.

Time evolution of yearly, Spring and Summer ET_{DIOBEL} anomalies (figure 4) also indicates a negative trend, especially after late 1960s until a minimum at the late 70s and then a partial recovery until the end of the analyzed period. This has been attributed to the changes in the available radiative energy at the surface, during the dimming and brightening periods. During the dimming period the greenhouse gas induced enhancement of the downward thermal radiation has not exceeded the decreasing global solar radiation (Wild et al. 2004, 2008) and as a consequence, reduced evaporative cooling at the land surface was observed, consistent with reported decreasing pan evaporation for many regions throughout the world with widely different climates. In contrast, during the brightening period increased latent heat flux was estimated in accordance with increased surface net radiation caused by the concurrent increased downward solar radiation (due to a more transparent atmosphere) and increased thermal greenhouse effect (Wild et al. 2008). This increasing trend is also supported by pan evaporation measurements especially in energy-limited environments, which partially indicate, after decades of decrease (Roderick and Farquhar 2002; Ohmura and Wild 2002), a recent recovery, in line with changes in surface solar radiation (Liu et al. 2004). The Spring and Summer ET_{DIOBEL} anomalies show also correlation ($R > 0.69$) and a temporal behaviour that resembles the annual series. The ET_{DIOBEL} evolution is roughly in general correspondence with the annual Spring and Summer evolution of SD anomalies (figures 3 and 4). The reversal of reference evapotranspiration anomalies (from dimming to brightening) is evident a bit earlier (late 1970s) as compared to the reversal of residual SD anomalies. This may be due to rising maximum air temperature and decreasing precipitation and number of rainy days during the period 1970-1990 [caused by the urbanization effect in Athens according to Philandras et al. (1999)] which counteract the dimming phenomenon.

Acknowledgments. The authors thank the National Observatory of Athens for providing the data. Gianna Kitsara is awarded a scholarship from the operational programme ‘Education and lifelong learning investing in knowledge society’ (IRAKLITOS II) which is co-funded by the European Union and Greece.

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