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Key Points:
- Strong relationship between sunshine duration and temperatures in Europe
- DTR and Tmax show the strongest signal, especially in summer
- Dimming/brightening has modulated temperature decadal changes since the 1960s

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3

Correspondence to:
E. J. M. van den Besselaar,
besselaar@knmi.nl

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Relationship between sunshine duration and temperature trends across Europe since the second half of the twentieth century

E. J. M. van den Besselaar[1], A. Sanchez-Lorenzo[2,3], M. Wild[4], A. M. G. Klein Tank[1], and A. T. J. de Laat[1]

[1]Royal Netherlands Meteorological Institute, De Bilt, Netherlands, [2]Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas, Zaragoza, Spain, [3]Department of Physics, University of Girona, Girona, Spain, [4]Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland

Abstract Global radiation is a fundamental source of energy in the climate system. A significant impact of global radiation on temperature change is expected due to the widespread dimming/brightening phenomenon observed since the second half of the twentieth century. This work describes the analysis of 312 stations with sunshine duration (SD) series, a proxy for global radiation, and temperature series in the European Climate Assessment & Dataset (ECA&D) with data over the period 1961–2010. The relationship between SD and temperature series is analyzed for four temperature variables: maximum (T_{max}), minimum (T_{min}), mean temperature (T_{mean}), and diurnal temperature range (DTR). The analyses are performed on annual and seasonal basis. The results show strong positive correlations between SD and temperatures over Europe, with highest correlation for DTR and T_{max} during the summer period. These results confirm the strong relationship between SD and temperature trends over Europe since the second half of the twentieth century. This study supports previous suggestions that dimming (brightening) has partially decreased (increased) temperatures thereby modulating the greenhouse gas induced warming rates over Europe.

1. Introduction

Global radiation ($E_g\downarrow$) is one of the important factors influencing the local and global energy budget [*Wild*, 2012]. Specifically, *Wild* [2012] shows that the period between the 1950s and 1980s was a dimming period, a time period where solar radiation declined by about 3–9 W m^{-2}. In the period after the late 1980s, many areas in the world showed a brightening, where the solar radiation experienced an overall increase of about 1–4 W m^{-2}.

Taking into account these $E_g\downarrow$ variations, *Wild et al.* [2007] suggested that the dimming period has partially masked the greenhouse warming and only after 1980s, during the brightening period, the greenhouse effect has revealed its full dimension on a global scale. In the Netherlands, *van Oldenborgh et al.* [2009] found the dimming/brightening in $E_g\downarrow$ over 1970–2007 in spring and summer, overlaid by a positive $E_g\downarrow$ trend over the whole period. The dimming and subsequent brightening canceled each other to some extent with respect to their influence on the temperature increase of the 1970–2007 period, but overall the brightening effect dominated and made a sizeable contribution to the warming trend. Starting in 1980, *Philipona et al.* [2009] found a large contribution of $E_g\downarrow$ to the warming trend in Switzerland. Recently, *Nabat et al.* [2014] have reported, by using regional climate simulations, that the decrease in anthropogenic aerosols since the 1980s, a major cause of the brightening period, can explain around 25% of the warming over Europe.

Other studies described the relationship between changes in $E_g\downarrow$ and diurnal temperature range (DTR) [e.g., *Makowski et al.*, 2009; *Ye et al.*, 2010; *Ionita et al.*, 2012] or minimum and maximum temperature [e.g., *Campbell and Vonder Haar*, 1997]. Relationships between cloudiness, normally inversely correlated with $E_g\downarrow$, and temperatures, especially with maximum temperatures, have also been found [e.g., *Campbell and Vonder Haar*, 1997; *Dai et al.*, 1997, 1999; *Stone and Weaver*, 2003; *Xia*, 2013].

These previous studies are limited by the lack of long-term $E_g\downarrow$ series, especially before the 1980s. Proxies for $E_g\downarrow$, such as sunshine duration (SD), are useful to fill in the gaps [*Wild*, 2009; *Stanhill and Cohen*, 2001; *Wang et al.*, 2012]. SD is defined as the total amount of time the disk of the Sun is above the horizon and not obscured

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by cloud, fog, or haze. Sunshine recorders are of the oldest and most robust types of radiation measurements. They measure the time over a day during which direct solar radiation is of sufficient intensity to exceed a certain threshold (usually at 120 W m^{-2}) and activate the recorder. In Europe, SD is traditionally measured by means of the Campbell-Stokes heliograph since the nineteenth century [*Stanhill*, 2003; *Sanchez-Lorenzo et al.*, 2013a].

Wang et al. [2012] have compared E_g↓ estimates derived from SD measurements with measured E_g↓ over several areas of the world including Europe (see e.g., their Figures 4 and 6) and determined that the E_g↓ can be accurately derived from SD measurements. They showed that in Europe at monthly and interannual scales, variations of cloud cover determined the E_g↓, but at a decadal scale the variability is determined by aerosols. There have been more studies that analyzed the suitability of SD as a proxy for E_g↓, e.g., *Sanchez-Lorenzo and Wild* [2012] for Switzerland, *Stanhill and Ahiman* [2014] for Potsdam (Germany), and *Stanhill and Cohen* [2005] and *Magee et al.* [2014] for the United States. Most of these studies show a very good agreement between observed E_g↓ and estimated E_g↓ from SD series.

Following *Wild et al.* [2007] we hypothesize that the dimming and brightening have an effect on surface air temperature variations in Europe and might have influenced the observed long-term warming. In the current study we analyze the relationship, using statistical methods, between SD and four temperature variables: minimum temperature (T_{min}), mean temperature (T_{mean}), maximum temperature (T_{max}), and DTR. Recently, *Matuszko and Węglarczyk* [2014] and *Deng et al.* [2014] have determined this relationship using statistical methods for individual sites in Poland and China. The current study aims at determining the effect of dimming and brightening on air temperatures for a large part of Europe.

In section 2 we describe the data and method used. Section 3 gives the results, and we end with a discussion and conclusions in section 4.

2. Data and Methods

In this study we made use of the data from data providers in the European Climate Assessment & Dataset (ECA&D) [*Klein Tank et al.*, 2002; *Klok and Klein Tank*, 2008]. The daily series underwent a basic quality control procedure. Temperatures are checked to be between −90 and 60°C, not repetitive for more than 5 days, and that the value is between five standard deviations of their long-term mean. Furthermore, T_{min} should be lower than T_{mean} and T_{mean} should be lower than T_{max}. The hours of sunshine should be between 0 and 24 h. If a daily value does not pass these tests, it is flagged as suspect and not used further in our calculations. More details regarding the quality control procedure can be found in *ECA&D Project team* [2013]. Annual and seasonal values are derived from the daily series when there are at least 10 years of data for a particular station and there are more than 350 or 85 days with valid data per year or season, respectively. This makes it possible that, in some cases, a seasonal value cannot be calculated, but the annual value can, or the other way around, depending on where in the year the invalid data occur.

No statistical homogeneity tests have been applied as the expected transition from dimming to brightening might be seen as an inhomogeneity in the series when tested by means of absolute methods as implemented by ECA&D [*Wijngaard et al.*, 2003; *ECA&D Project team*, 2013]. For the majority of the stations, the metadata to determine if a detected break is real or due to artificial changes (e.g., instrument changes or relocations) are unknown to us. As we also use country averages which might dim possible problems in one station, we decided to take all available series.

Some countries have changed from traditional manual instruments (such as Campbell-Stokes and Jordan heliographs) to automatic electronic recorders since the 1980s, which produce readings that are not identical and can introduce inhomogeneities in the time series [e.g., *Kerr and Tabony*, 2004; *Legg*, 2014; *Matuszko*, 2015; *Sanchez-Romero et al.*, 2015; *Stanhill and Cohen*, 2008]. Over Europe, the Campbell-Stokes recorders still dominate in the climatological network [e.g., *Sanchez-Lorenzo et al.*, 2007, 2008; *Legg*, 2014], and in some of the countries with documented changes in the instruments, such as Switzerland (at the end of the 1970s and early 1980s) and the Netherlands (early 1990s), the influence of it are reported to be minor [*Sanchez-Lorenzo and Wild*, 2012; *Hinssen and Knap*, 2007]. Therefore, we expect no large influence of the change to automatic recorders in the results of our analyses.

The sunshine and temperature data sets were downloaded from the ECA&D website (http://www.ecad.eu/download/millennium/millennium.php), most of them only available since 1961. To include both the

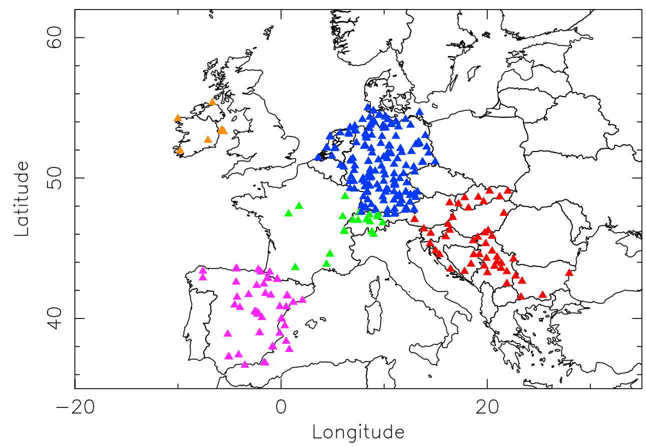

Figure 1. Location of all stations used in this study. Colors define the different regions, see Table 1.

dimming and brightening periods and still selecting as much stations as possible, the period 1961–2010 was chosen for this study. We selected those stations for which the seasonal values of T_{min}, T_{mean}, T_{max}, DTR, and SD could be determined given our criteria. Next, we selected only those stations for which 80% of the years in the full period 1961–2010 and 80% of the years in the climatology period (1981–2010) were present. There are much more temperature stations than stations with sunshine duration in ECA&D, so the number of SD stations is a limiting factor too. Finally, when combining variables for our analysis, we selected only the stations which have both SD and each of the four temperature variables. Taking all requirements into account resulted in 312 out of the 1254 available stations with SD over the whole European region (Figure 1), excluding three stations in Norway due to the small number of stations in that area. The selected stations are irregularly spaced over Europe, but each region used in this study has at least nine stations. The regions are defined by grouping several nations or on a national basis (see Table1). Differences in station density are taken into account by using the region-averaged series.

The relationship between SD and temperature is analyzed based on the four temperature variables T_{min}, T_{mean}, T_{max}, and DTR. The correlation analysis described below is done on these region-averaged series as well as for each of the stations separately. The analysis is performed on annual and seasonal bases, where the seasons are defined as winter (December-January-February, DJF), spring (March-April-May, MAM), summer (June-July-August, JJA), and autumn (September-October-November, SON).

For each station we determined climatologies over the 1981–2010 period to be able to calculate anomalies and ratios with respect to this normal period. For the temperature variables the anomaly series are used (observed minus climatology), and for the SD series the ratio (observed divided by climatology). The anomaly and ratio series were averaged over the stations for each of the five regions and over all regions together (European series). These anomaly and ratio series are the ones used in the remainder of this paper.

For the correlation analysis we calculated the Pearson correlation coefficients between SD and the temperature series. The statistical significance is determined by using the critical values for $p < 0.05$ via the Student's t test. We also determined the Spearman correlation coefficients as a nonparametric test, but the differences with the Pearson correlation coefficients are only very minor. Therefore, we only provide the Pearson correlation coefficients.

Table 1. Regions and the Number of Stations Per Region

ID	Nr	Countries
North	183	Netherlands and Germany
East	48	Austria, Slovakia, Hungary, Slovenia, Croatia, Serbia, Bosnia, and Bulgaria
South	52	Spain
West	9	Ireland
Central	20	France and Switzerland
Europe	312	All countries above

The trends and their significance are determined by means of linear regression. We analyzed the trends for the subperiods 1961–1985 and 1985–2010 with a fixed break point at 1985. Selecting the subperiods before and after ∼1985 will result in trends for the dimming period and trends for the brightening period over Europe [*Chiacchio and Wild*, 2010; *Sanchez-Lorenzo et al.*, 2013b], respectively.

2.1. Theoretical Relationship

It is worth noting that this study presents a statistical relationship between SD and temperatures without presenting a detailed physically based quantitative explanation of the findings. Nevertheless, a theoretical approximation of the relationship between solar radiation and surface temperature changes has been given in Appendix A. Although the relation is only an approximation, it gives insight in the complexity of coupling changes in incoming solar radiation to changes in surface temperatures. It depends on a larger number of parameters.

For example, the change in surface temperature due to a change in the incoming solar radiation depends on (1) the surface albedo, (2) the surface radiation balance (which in turn depends on the shortwave irradiance and the net longwave flux), (3) the ratio of latent versus sensible heat flux (which in turn depends on, for example, vegetation, boundary layer humidity and soil moisture availability, and thus on ground water levels with boundary layer humidity also depending on, for example, wind speed and wind direction as well as on cloudiness), and (4) the background meteorological conditions (which determine boundary layer depth). Furthermore, most of these parameters are coupled: incoming shortwave radiation determines evaporation and humidity, which in turn influences cloudiness which then again modifies incoming shortwave radiation. Finally, this relation only holds for the convective (unstable) atmospheric boundary layer, whereas several other types of boundary layers exist.

As a consequence, it is not straightforward to establish a quantitative relation between sunshine duration and surface temperature, or can it be expected to be similar/uniform for all observational locations and atmospheric conditions. Rather, the relation will very much depend on local environmental conditions and feedbacks [*Pinker and Laszlo*, 1992; *Betts et al.*, 1996; *Essery et al.*, 2003; *Takemura et al.*, 2005; *Sheffield et al.*, 2006; *Wild*, 2009; *Arneth et al.*, 2010; *Zhang et al.*, 2010; *Barbaro et al.*, 2013, 2014]. Determining this theoretical relation would require complex three-dimensional climate model simulations, which is beyond the scope of this paper.

3. Results

3.1. Correlations

The correlation coefficients between the SD series and each of the temperature variables are determined for each station. These coefficients are shown in Figure 2 for each combination of SD and temperature variable, and for each of the four seasons. The correlations are lowest for T_{min} in all seasons. This is not surprising as T_{min}, normally the nighttime temperature, is least affected by solar radiation. T_{mean} and T_{max} have lower coefficients in winter and spring, compared to summer and, to a lesser extent, autumn. Also, a large number of stations in winter and spring have negative correlations for T_{min} and T_{mean}, and also in autumn for T_{min}. The annual station series (not shown) show higher correlations for DTR and T_{max} than for T_{min} and T_{mean}.

The correlation results for the region-averaged series between SD and DTR, T_{max}, and T_{min} are given in Tables 2–4, respectively, for the year and four seasons. The correlation between SD and T_{mean} is given in the supporting information. The tables show that the highest correlations are found between SD and DTR, and between SD and T_{max}. The lowest regional correlations are found between SD and T_{min}, which is similar to the station correlations. All region-averaged and European averaged series have significant positive correlations between DTR and SD with 66.7% of the seasonal and annual series correlation coefficients higher than 0.80.

Looking at the European series, all correlations are statistically significant except in winter for T_{min}, T_{mean}, and T_{max} and in autumn for T_{min}.

3.2. Trends

Trends are determined for all region-averaged series with a possible break in the trend at 1985. This is done to allow for different slopes in the dimming (1961–1985) and brightening (1985–2010) periods, considering 1985 as the central year of the transition period from dimming to brightening in Europe [*Chiacchio and Wild*, 2010]. The period 1961–1985 is fitted with $(a + da) * (\text{year} - 1985)$ and the period 1985–2010 with

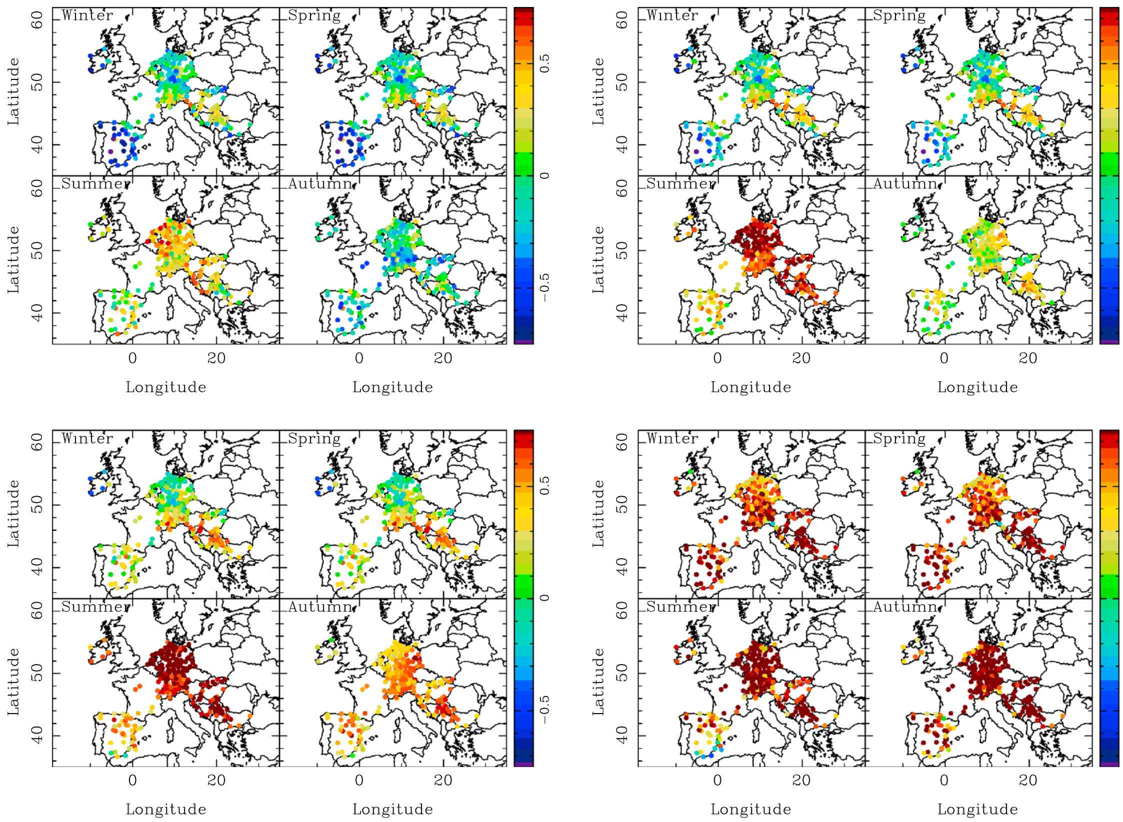

Figure 2. Correlation coefficients between (top left) SD and T_{min}, (top right) T_{mean}, (bottom left) T_{max}, and (bottom right) DTR for the four seasons for the period 1961–2010.

$(a - da) * (\text{year} - 1985)$, where $a + da$ is the trend in the first period and $a - da$ the trend in the second period. The term da is used to determine if the two trends are significantly different.

Figures 3 and 4 show the time series of SD and T_{mean}, respectively, together with the linear trend for the whole of Europe for the two subperiods. The corresponding figures for T_{min}, T_{max}, and DTR are given in the supporting information. The dimming/brightening break around 1985 is most visible in the annual series and less visible in some of the seasons.

The SD and T_{mean} trend results are given in Tables 5 and 6, respectively. The tables for the other temperature variables are given in the supporting information. For each fit we determined the trend in the two periods as well as the uncertainty in da. If da is significantly (1σ) different from zero, we assume that the trends in the two periods are significantly different.

Table 2. Correlation Between DTR and SD Series[a]

ID	Ann	DJF	MAM	JJA	SON
North	**0.92**	**0.74**	**0.93**	**0.94**	**0.94**
East	**0.90**	**0.88**	**0.91**	**0.90**	**0.91**
South	**0.43**	**0.91**	**0.86**	**0.62**	**0.81**
West	**0.51**	**0.43**	**0.61**	**0.79**	**0.56**
Central	**0.90**	**0.77**	**0.95**	**0.93**	**0.92**
Europe	**0.92**	**0.78**	**0.94**	**0.94**	**0.92**

[a]IDs are defined in Table 1. Ann = annual, DJF = winter, MAM = spring, JJA = summer, and SON = autumn. Values in boldface indicate statistically significant ($p < 0.05$), determined via Student's t test.

Table 3. Same as Table 2 but for Correlation Between T_{max} and SD Series

ID	Ann	DJF	MAM	JJA	SON
North	**0.62**	0.06	**0.67**	**0.83**	**0.51**
East	**0.79**	**0.47**	**0.73**	**0.81**	**0.53**
South	**0.57**	0.08	**0.78**	**0.55**	**0.51**
West	**0.52**	**−0.04**	**0.37**	**0.70**	0.28
Central	**0.53**	**0.36**	**0.55**	**0.66**	**0.54**
Europe	**0.68**	0.27	**0.70**	**0.79**	**0.52**

It is seen that for SD in most regions, the trend has a different sign between the 1961–1985 and 1985–2010 periods. This is expected due to the dimming/brightening phenomenon mentioned earlier. All annual trends are negative (i.e., dimming) in the first period and positive (i.e., brightening) in the second period. This is also true for most of the seasonal series, although a few regions and seasons have positive trends in both periods and region central has negative trends in both periods.

A significant difference in trends between the dimming and brightening period in the annual and summer SD series is observed for all regions. Eighty-three percent of the regions show a significantly different trend in spring. In autumn this value is 50%, and in winter 33%. The European series shows a significant difference for all seasons except winter.

For T_{mean}, none of the regions or European series show a significant difference between the dimming and brightening period in winter. The spring and annual T_{mean} series show a significant difference for 100% and 83% of the regions, respectively, and autumn and summer for 66%. There is thus a large difference between winter and the other seasons for T_{mean}. Tables for T_{min}, T_{max}, and DTR are given in the supporting information.

The transition from dimming to brightening probably did not take place in 1 year but over a period of a few years. Therefore, we repeated the trend calculations by using 1980 and 1990 as transition years (not shown) to determine the sensitivity of the trends with respect to the choice of transition year. Although there are slight differences in significance between seasons and regions, the signs of the trends are the same for the other transition years, and for the large majority of the cases the values of the trends fall within the given uncertainties. This shows that the overall results that we present here by using 1985 as transition year did not change much by using 1980 or 1990 as transition year, and our overall results are therefore robust.

To show the relation between the trends in SD and those in the temperature variables, the annual trends for all regions and variables are plotted against each other in Figure 5, and in Figure 6 the seasonal trends are shown. From these figures, it is clear that a relation between these trends exist. The correlation between the annual SD trends and the temperature trends is highest for the T_{max} trends (0.85). The correlation in the spring trends are the highest, with 0.93 between SD and T_{max}. The lowest correlation is observed for winter trends with values near zero. For winter, none of the correlations are significant, while in spring all correlations between the trends are significant. For the annual and summer trends, the correlations are significant for T_{min}, T_{mean}, and T_{max}, and for the autumn trends only for T_{mean} and T_{max}. Except for spring, none of the DTR trends correlate significantly with the SD trends.

Table 4. Same as Table 2 but for Correlation Between T_{min} and SD Series

ID	Ann	DJF	MAM	JJA	SON
North	0.27	−0.09	0.27	**0.52**	−0.07
East	**0.45**	0.16	**0.38**	**0.39**	−0.07
South	**0.46**	**−0.58**	**0.43**	**0.39**	−0.03
West	**0.31**	**−0.20**	**0.07**	**0.37**	−0.00
Central	**0.10**	**0.14**	**0.04**	**0.27**	−0.18
Europe	**0.42**	0.10	**0.38**	**0.53**	0.06

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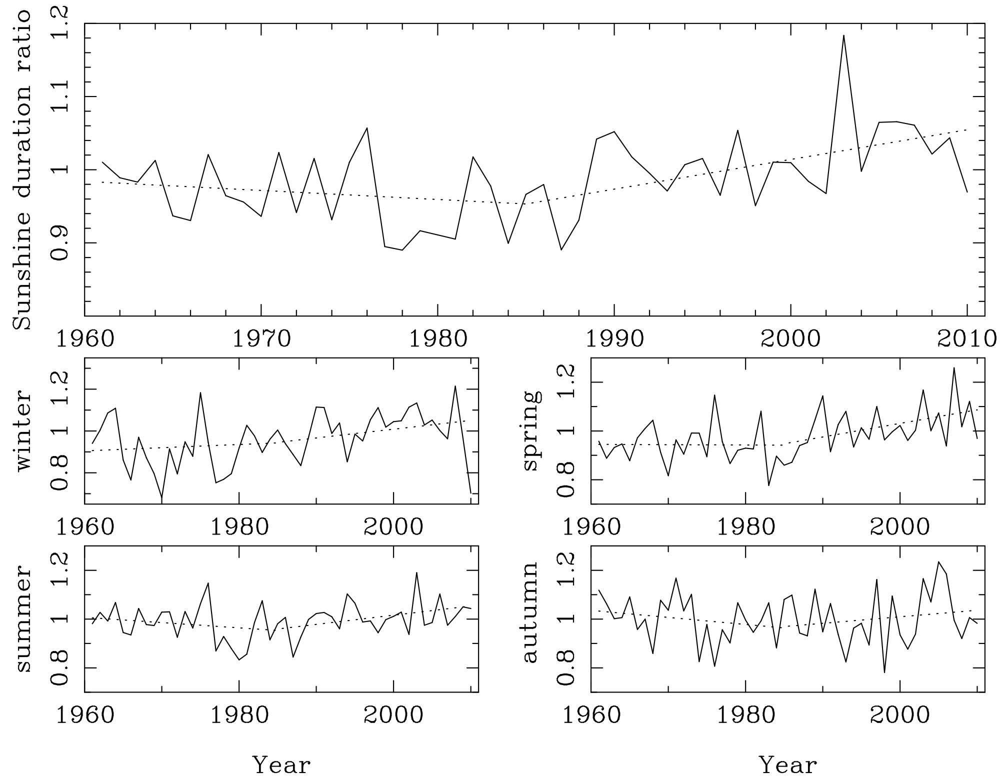

Figure 3. Time series of SD ratios for the European series. (top) The annual series and the bottom part shows (top left) winter, (top right) spring, (bottom left) summer, and (bottom right) autumn. The trends for the two subperiods are included as well. Note the that the scale is different between the panels.

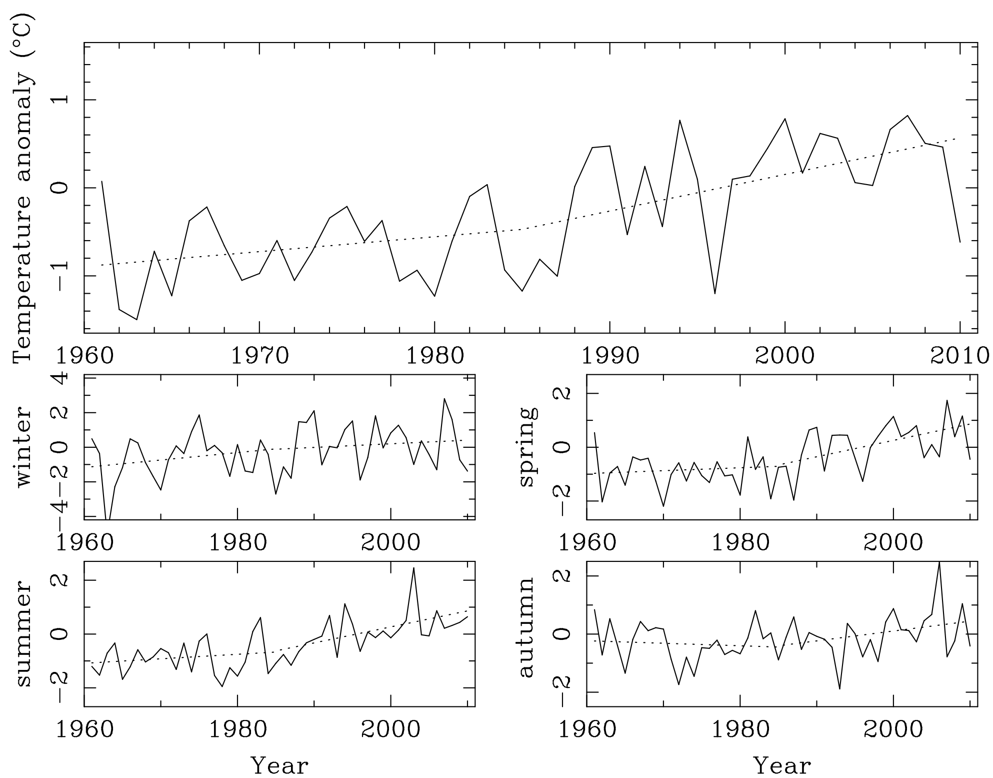

Figure 4. Same as Figure 3 but for T_{mean} anomalies.

Table 5. Trends and Parameter *da* for SD (%/decade) Series With the 1 Standard Error in Parantheses[a]

ID	Ann	DJF	MAM	JJA	SON
			North		
1961–1985	**−0.70 (1.58)**	1.15 (3.34)	1.66 (2.48)	**−1.46 (2.38)**	**−3.99 (3.35)**
1985–2010	**3.96 (1.58)**	4.84 (3.34)	4.95 (2.48)	**3.28 (2.38)**	**3.67 (3.35)**
da	**−2.33 (1.41)**	−1.84 (2.98)	−1.65 (2.22)	**−2.37 (2.12)**	**−3.83 (3.00)**
			East		
1961–1985	**−0.91 (1.21)**	5.52 (3.61)	**−1.68 (2.05)**	**−1.89 (1.47)**	−1.97 (2.29)
1985–2010	**3.97 (1.21)**	2.00 (3.61)	**6.40 (2.05)**	**5.13 (1.47)**	−0.06 (2.29)
da	**−2.44 (1.08)**	1.76 (3.22)	**−4.04 (1.84)**	**-3.51 (1.32)**	−0.95 (2.05)
			South		
1961–1985	**−2.10 (0.77)**	0.96 (2.49)	**−1.88 (1.90)**	**−3.39 (0.94)**	−0.19 (1.53)
1985–2010	**3.93 (0.77)**	1.96 (2.49)	**5.39 (1.90)**	**4.09 (0.94)**	1.86 (1.53)
da	**−3.02 (0.69)**	−0.50 (2.22)	**−3.63 (1.70)**	**−3.74 (0.83)**	−1.03 (1.37)
			West		
1961–1985	**−5.54 (1.70)**	**−8.01 (2.90)**	**−5.14 (2.48)**	**−7.91 (3.36)**	**−2.22 (2.42)**
1985–2010	**7.56 (1.70)**	**12.47 (2.90)**	**8.95 (2.48)**	**6.16 (3.36)**	**5.69 (2.42)**
da	**−6.55 (1.52)**	**−10.24 (2.59)**	**−7.05 (2.21)**	**−7.04 (3.00)**	**−3.96 (2.15)**
			Central		
1961–1985	**−3.43 (1.94)**	**0.54 (3.60)**	**−5.76 (3.36)**	**−4.81 (2.62)**	−1.19 (3.48)
1985–2010	**4.94 (1.94)**	**7.81 (3.60)**	**10.58 (3.36)**	**4.84 (2.62)**	−2.07 (3.48)
da	**−4.18 (1.72)**	**−3.64 (3.19)**	**−8.17 (2.98)**	**−4.82 (2.32)**	0.44 (3.09)
			Europe		
1961–1985	**−1.24 (1.10)**	1.53 (2.58)	**−0.13 (1.81)**	**−2.16 (1.52)**	**−2.88 (2.28)**
1985–2010	**4.06 (1.10)**	4.19 (2.58)	**5.56 (1.81)**	**3.78 (1.52)**	**2.68 (2.28)**
da	**−2.65 (0.99)**	−1.33 (2.31)	**−2.85 (1.62)**	**−2.97 (1.36)**	**−2.78 (2.04)**

[a]Values in boldface indicate significantly different trends between the two periods.

4. Discussion and Conclusions

We have analyzed the relationship between four temperature variables and SD using correlation and trend analyses. The correlation analysis shows that there is a strong relationship between SD and the DTR, in line with the results shown by *Wang and Dickinson* [2013]. The relation is also large in summer for the other temperature variables. The relationship between SD and T_{min} is the weakest.

Overall, the results show that sunny weather (i.e., high SD) leads to larger responses of daytime temperatures (T_{max}) and therefore a larger DTR due to an increase of the downward $E_g\downarrow$, in line with *Makowski et al.* [2009]. This results in highly positive correlations between SD and DTR and T_{max}, especially in summer, as shown in Tables 2 and 3. Nevertheless, it is worth noting that a close relationship between SD in the season with the highest amount of radiation does not necessarily imply a higher sensitivity (i.e., a larger temperature change per unit of change of SD). In fact, results shown in Figures 5 and 6 suggest a higher (lower) sensitivity in spring (winter) as compared to the other seasons. The clear lower sensitivity during winter can be due to the fact that latent heat release is not limited by the soil moisture content (i.e., less energy goes into the heating of the surface) as the ground is generally wetter in winter over northern midlatitudes [*Seneviratne et al.*, 2010].

It appears that the correlations between SD and DTR are higher on interannual scales (Figure 2) but decrease when trends are related (Figures 5 and 6). This suggests that T_{max} is more sensitive than DTR to the same unit of SD change.

Table 4 shows negative correlations between T_{min} and SD for part of the regions and seasons. The fact that not all regions show a negative correlation might be related to these regions experiencing a large number of overcast days. The expected relation with negative correlations in winter between SD and T_{min} is for sunny cloud-free conditions. Analyzing the effect of clear-sky and overcast days can be the subject of a further study.

Table 6. Trends and Parameter *da* for T_{mean} (°C/decade) Series With the 1 Standard Error in Parantheses[a]

ID	Ann	DJF	MAM	JJA	SON
			North		
1961–1985	0.23 (0.14)	0.50 (0.39)	**0.22 (0.20)**	0.21 (0.18)	**−0.08 (0.19)**
1985–2010	0.39 (0.14)	0.25 (0.39)	**0.57 (0.20)**	0.51 (0.18)	**0.34 (0.19)**
da	−0.08 (0.12)	0.12 (0.35)	**−0.18 (0.18)**	−0.15 (0.16)	**−0.21 (0.17)**
			East		
1961–1985	**−0.02 (0.11)**	0.33 (0.33)	**−0.04 (0.21)**	**−0.02 (0.15)**	**−0.47 (0.20)**
1985–2010	**0.56 (0.11)**	0.27 (0.33)	**0.59 (0.21)**	**0.88 (0.15)**	**0.55 (0.20)**
da	**−0.29 (0.10)**	0.03 (0.29)	**−0.31 (0.19)**	**−0.45 (0.14)**	**−0.51 (0.18)**
			South		
1961–1985	**0.13 (0.10)**	0.27 (0.19)	**−0.08 (0.15)**	**0.17 (0.15)**	0.18 (0.17)
1985–2010	**0.39 (0.10)**	0.05 (0.19)	**0.71 (0.15)**	**0.65 (0.15)**	0.14 (0.17)
da	**−0.13 (0.08)**	0.11 (0.17)	**−0.40 (0.14)**	**−0.24 (0.13)**	0.02 (0.16)
			West		
1961–1985	**0.11 (0.08)**	0.11 (0.26)	**0.08 (0.14)**	0.27 (0.15)	**0.04 (0.15)**
1985–2010	**0.37 (0.08)**	0.18 (0.26)	**0.50 (0.14)**	0.22 (0.15)	**0.41 (0.15)**
da	**−0.13 (0.07)**	−0.04 (0.23)	**−0.21 (0.12)**	0.03 (0.13)	**−0.19 (0.13)**
			Central		
1961–1985	**0.18 (0.11)**	0.49 (0.28)	**−0.02 (0.18)**	**0.20 (0.18)**	0.03 (0.18)
1985–2010	**0.47 (0.11)**	0.14 (0.28)	**0.81 (0.18)**	**0.67 (0.18)**	0.31 (0.18)
da	**−0.14 (0.10)**	0.17 (0.25)	**−0.42 (0.16)**	**−0.24 (0.16)**	−0.14 (0.16)
			Europe		
1961–1985	**0.17 (0.11)**	0.43 (0.31)	**0.11 (0.16)**	**0.17 (0.14)**	**−0.09 (0.16)**
1985–2010	**0.42 (0.11)**	0.21 (0.31)	**0.61 (0.16)**	**0.59 (0.14)**	**0.34 (0.16)**
da	**−0.12 (0.10)**	0.11 (0.27)	**−0.25 (0.14)**	**−0.21 (0.13)**	**−0.21 (0.14)**

[a]Values in boldface indicate significantly different trends between the two periods.

For SD in most regions, the trend is different between the 1961–1985 and 1985–2010 periods. This is expected due to the dimming/brightening phenomenon mentioned earlier. All annual trends are negative (i.e., dimming) in the first period and positive (i.e., brightening) in the second period. The seasonal series show a mix between dimming and brightening trends. In addition, the trends in the European series of the temperature values are higher in the 1985–2010 period compared to the earlier period. These results are in line with an observed temperature shift in Europe around 1987–1988 [*de Laat and Crok*, 2013].

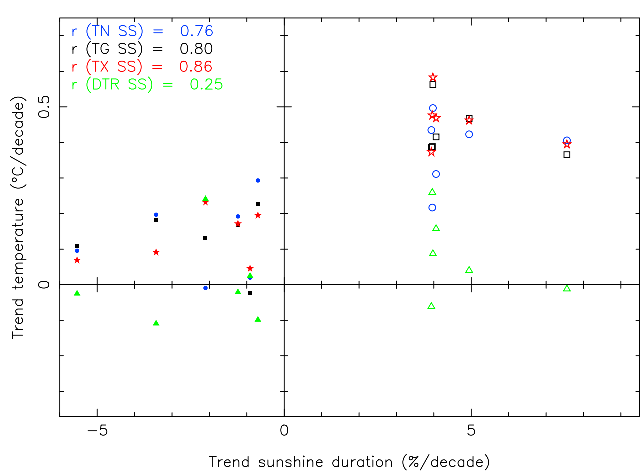

Figure 5. Relation between the annual trends in the temperature variables and the annual trends in SD. Plotted are the trends for all regions, including the full European one, and both periods. Blue circles are for T_{min}, black squares are for T_{mean}, red stars are for T_{max}, and green triangles are for DTR. Closed symbols are for 1961–1985 and open symbols for 1985–2010.

The relationship between DTR and $E_g\downarrow$ has been analyzed by *Makowski et al.* [2009] on the basis of 31 stations over Europe with collocated temperature and radiation measurements. They found a strong correlation of 0.87 between $E_g\downarrow$ and DTR for the annual mean nondetrended anomalies over the period 1970–2005. In our study we find a correlation of 0.92 for the annual

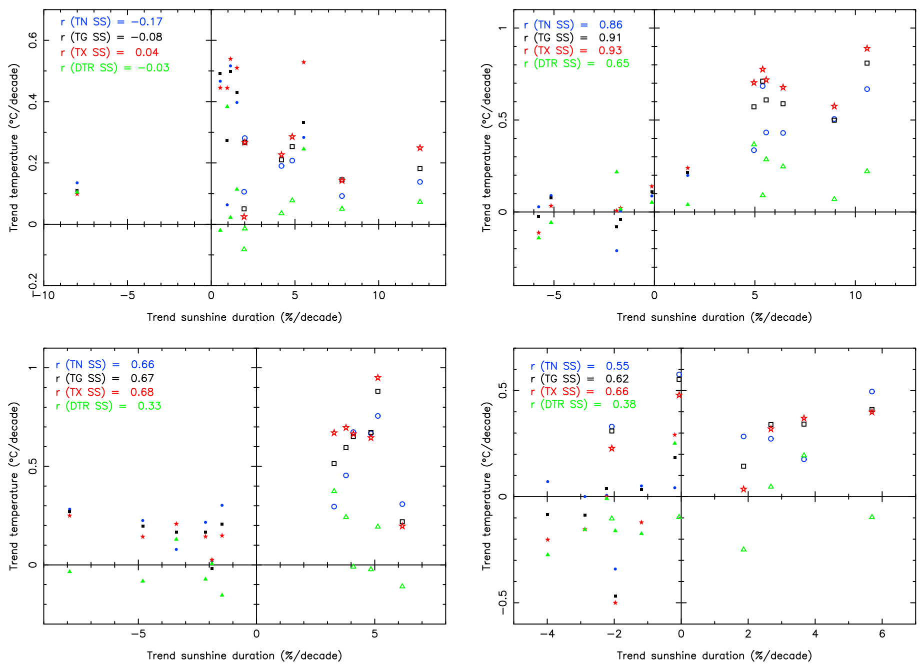

Figure 6. Same as Figure 5 but for (top left) winter, (top right) spring, (bottom left) summer, and (bottom right) autumn.

correlation between SD and DTR for the period 1961–2010. Our study uses more stations (312 versus 31) and a longer time period than *Makowski et al.* [2009], and we used SD instead of $E_g\downarrow$. Despite these differences, the results between their study and ours are very similar.

One of the studies focusing on sunshine duration in Europe has been performed by *Sanchez-Lorenzo et al.* [2008]. On the basis of 79 series, they found for western Europe a decrease in SD from the 1950s until the early 1980s with an increase afterward. Based on the current study using more stations, but only starting in 1961, we found a similar behavior of the SD as found by *Sanchez-Lorenzo et al.* [2008]. Equally, there is a coincident transition from dimming to brightening phases over Europe in SD and in a recently homogenized data set of $E_g\downarrow$ [*Sanchez-Lorenzo et al.*, 2015]. As an example, Figure 7 shows the mean summer standardized anomaly series of this $E_g\downarrow$ data set (using 56 stations) and our SD data set (312 stations) showing the very similar interannual and decadal variations over the period 1961–2010. This highlights that the coincident change in SD instrumentation in some countries around the 1980s is not the cause of the transition from dimming to brightening.

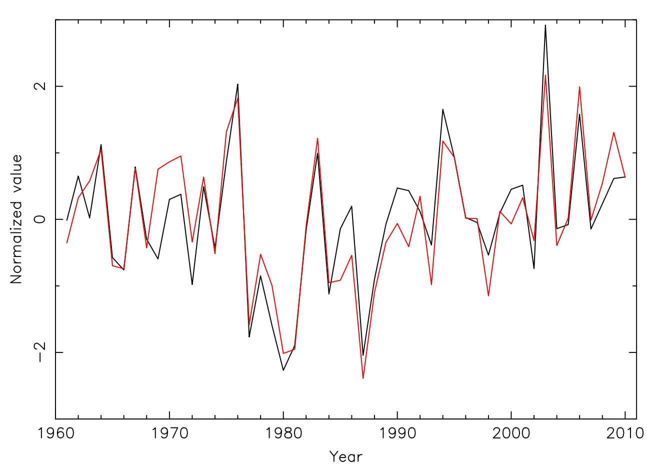

Figure 7. Mean time series of summer SD using 312 stations (black, this work) and $E_g\downarrow$ using 56 stations (red, from *Sanchez-Lorenzo et al.* [2015]) over Europe from 1961 to 2010. The series are expressed as standardized anomalies.

Wild et al. [2007] have analyzed trends in temperature to disentangle global radiation and greenhouse gas influences on global warming. On the global terrestrial scale, they found that T_{max} was declining before 1985 and T_{min} increasing. On the other hand, both T_{max} and T_{min} experienced an increase after 1985, when the solar dimming had reversed into brightening. Furthermore, they found that DTR decreased until the mid-1980s and leveled off afterward due to the above mentioned behavior of T_{min} and T_{max} trends. On the global scale, the amount of $E_g\downarrow$ has not yet reached the level from 1960, while the land surface temperature has increased over this period. Therefore, *Wild et al.* [2007] conclude that the overall increase in temperature cannot be attributed to the $E_g\downarrow$ changes, but has to be due, at least partly, to greenhouse forcing. In our study, we only analyzed sunshine duration over the European area over the period 1961–2010, and not solar radiation on the global scale. Although for SD in Europe, the level of 2010 is above the level of 1961, while globally the recent value is below the level of 1960 [*Wild et al.*, 2007], our study does show a trend reversal in the SD series around 1985 (−1.24 versus 4.06%/decade for the annual European series in 1961–1985 and 1985–2010, respectively, Table 5).

Finally, we noticed that the European series for T_{min} and T_{max} have a positive trend in both periods (0.19 versus 0.31°C/decade for T_{min} and 0.17 versus 0.47°C/decade for T_{max}), while the trend in DTR is slightly negative in the first period and positive in the second period (−0.02 versus 0.16°C/decade). SD and $E_g\downarrow$ are mainly influencing the daytime temperatures (e.g., T_{max}), while the greenhouse forcing influences also the nighttime temperatures (e.g., T_{min}) [*Wild et al.*, 2007].

Overall, our results confirm the strong relationship between temperature and SD over Europe since the second half of the twentieth century, which has been suggested to partially decrease (increase) temperatures during the dimming (brightening) period [e.g., *Makowski et al.*, 2009; *Wild*, 2009; *Wang and Dickinson*, 2013; *Matuszko and Weęglarczyk*, 2014]. Comparing the trends for T_{min} and T_{max} with those for SD suggests that the trends cannot be explained by SD (or solar radiation) alone as the trends are different. Consequently, we do not put into question the importance of the greenhouse effect for warming over Europe. Some other influencing factors are the decline in low visibility days in Europe [e.g., *Vautard et al.*, 2009], circulation and cloud cover changes [e.g., *van Oldenborgh et al.*, 2009; *de Laat and Crok*, 2013; *Xia*, 2010], the changes in water vapor content of the lower atmosphere [*Stanhill and Ahiman*, 2014], and the impact of aerosols and greenhouse gases [e.g., *Philipona et al.*, 2009] which we did not explicitly study in our analysis. But cloud cover changes and visibility changes, for example, are implicit in the SD records [e.g., *Sanchez-Romero et al.*, 2014], thus have entered the present analyses. Further research is needed to estimate global radiation changes by means of sunshine duration series. Equally, the cause-effect relationship needs to be confirmed using more robust methods, and also the temperature sensitivity to global radiation changes needs to be estimated.

Appendix A: Theoretical Background

Consider a convective (unstable) atmosphere anywhere on the globe and imagine two situations. One situation without aerosols (*A*) and the other with aerosols present (*B*). Under *A*, the shortwave radiant downward flux (daytime only) $I_{\downarrow g}$ will arrive at the surface unencumbered and the convective Atmospheric Boundary Layer (ABL) temperature changes as stated in *Tennekes* [1973].

$$\frac{d\theta}{dt} = \frac{H + \Delta\frac{dz}{dt}}{z} \tag{A1}$$

Here z is ABL depth, θ the potential temperature of the ABL, and H the surface sensible heat flux, while the convective ABL is covered by a temperature inversion Δ. Using the Tennekes assumption

$$\Delta\frac{dz}{dt} = cH,$$

with c being the Tennekes Factor [*Gyr and Rys*, 1995], equation (A1) is rewritten as

$$\frac{d\theta}{dt} = \frac{(1+c)H}{z}. \tag{A2}$$

The surface sensible heat flux H derived from the surface energy balance can be written as [*Garratt*, 1992, Chapter 5]

$$H = I_{\downarrow g}(1-A) + IR_{\downarrow} - IR_{\uparrow} - LE - G, \tag{A3}$$

with LE the latent heat flux, G the ground flux, $IR_{\downarrow}$ and $IR_{\uparrow}$ the infrared radiant downward and upward fluxes at the surface, respectively, and A the surface albedo. Note that we have separated the net radiative flux into a shortwave part (the I term modified by the surface albedo) and a longwave part (the IR terms), with $E_g\downarrow = I_{\downarrow g} + IR_{\downarrow} - IR_{\uparrow}$. The first three terms on the right-hand side form the radiative balance. Under the following simplifications

1. $B = \frac{H}{LE}$ (Bowen ratio),
2. $IR = IR_{\downarrow} - IR_{\uparrow} = C$ (net longwave irradiance), and
3. $G = \alpha \left(I_{\downarrow g} (1 - A) + C \right)$ (ground flux)

with α a proportionality fraction of the net shortwave irradiance plus the net longwave flux, equation (A3) reduces to

$$\alpha I_{\downarrow g}(1 - A) + \alpha C = I_{\downarrow g}(1 - A) + C - H - \frac{H}{B} \tag{A4}$$

and equation (A4) reduces to

$$I_{\downarrow g}(1 - A)(1 - \alpha) + C(1 - \alpha) = \frac{1 + B}{B} H. \tag{A5}$$

Or if we want to express the surface sensible heat flux exclusively in terms of the solar flux:

$$H = \frac{B}{1 + B} [I_{\downarrow g}(1 - A)(1 - \alpha) + C(1 - \alpha)]. \tag{A6}$$

Combined with equation (A2), we then finally get for the surface temperature change

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{(1 + C) \frac{B}{1+B} [I_{\downarrow g}(1 - A)(1 - \alpha) + C(1 - \alpha)}{z}. \tag{A7}$$

Although this equation is only an approximation for how the surface temperature changes with changes in the surface energy balance, it provides insight in the complexity of coupling changes in incoming solar radiation to changes in surface temperature.

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