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Key Points:

- Trends revealed in the residual of the Angstrom-Prescott regression for Potsdam
- Temporal parameter variations were related to the fossil fuel combustion
- Direct aerosol effect on recent brightening in the previously reported range

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Direct aerosol effects during periods of solar dimming and brightening hidden in the regression residuals: Evidence from Potsdam measurements

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Abstract A recent empirical study of *Stanhill et al.* (2014), which was based on the Angstrom-Prescott relationship between global radiation and sunshine duration, was evaluated. The parameters of this relationship seemed to be rather stable across the dimming and brightening periods. Thus, the authors concluded that the variation in global radiation is more influenced by changes in cloud cover and sunshine duration than by the direct aerosol effects. In our study, done for the Potsdam station (one of six globally distributed stations, the source of one of the longest observational records and closely located to former hot spots of aerosol emission), we tested and rejected the hypothesis that the dimming of global radiation directly caused by aerosols is negligible. The residuals of the Angstrom-Prescott regression reveal a statistically significant positive temporal trend and a temporal level segmentation. The latter was consistent with the temporal emission patterns around Potsdam. The trend in the residuals only disappeared when the model intercept varied according to the temporal level segmentation. The magnitude of the direct aerosol effect on the level changes in global radiation derived from the modified Angstrom-Prescott relationship was in the range indicated in previous studies. Thus, from here, a specific request cannot be made for a revision of current climate models state-of-the-art representation of both the cooling effect directly caused by aerosols and the temperature sensitivity to the increase of greenhouse gases.

1. Introduction

Recently, *Stanhill et al.* [2014] have questioned the current understanding of aerosols as key factors that might explain observed phases of dimming and brightening during the last 70 years, which was suggested by other studies [*Ohmura*, 2009]. Aerosols can affect climate conditions in either a direct or indirect way. While the first is generated by direct absorption and scattering (including reflection) of aerosols, the second is mediated by aerosols affecting the formation, structure, and longevity of clouds [*Ruckstuhl et al*., 2008]. The magnitude of the direct and indirect aerosol effects given in literature differs. For example, *Ohmura* [2009] concluded from a global selection of zenith transmittance records an equal share of direct and indirect aerosol effects. In contrast, *Ruckstuhl et al*. [2008] found only a minor contribution of the indirect aerosol effect (17%) to a general trend increase of about 1 W/m^2 per decade for the period between 1981 and 2005 (excluding 2003) at the German and Swiss observational sites.

Stanhill et al. [2014] used a regression technique, following Angstrom-Prescott, and related mean monthly values of global radiation (E_g) and sunshine (n) duration to each other for a set of stations globally.

Global radiation and sunshine duration were divided by the solar irradiance at the top of the atmosphere (E_0) and by day length (N), respectively. The resulting regression equation (1)

$$E_g/E_0 = an/N + b \tag{1}$$

was applied to monthly data. The Angstrom-Prescott equation is commonly recommended for two major applications: (a) for the spatial interpolation of scarce global radiation records to a denser network of stations where sunshine duration is available and (b) for the calculation of the clear-sky transmissivity.

The authors [*Stanhill et al*., 2014] suggest that both indirect and direct effects of the altered aerosol load during the last 70 years should have changed the parameters of the Angstrom-Prescott equation. The Potsdam station is one of the stations considered. It has one of the longest records of E_g and n worldwide and is located in the center of a former hot spot region of aerosol emissions. However, for Potsdam, as well as for the other stations, a remarkable invariability of the Angstrom-Prescott parameters was found. The parameter values

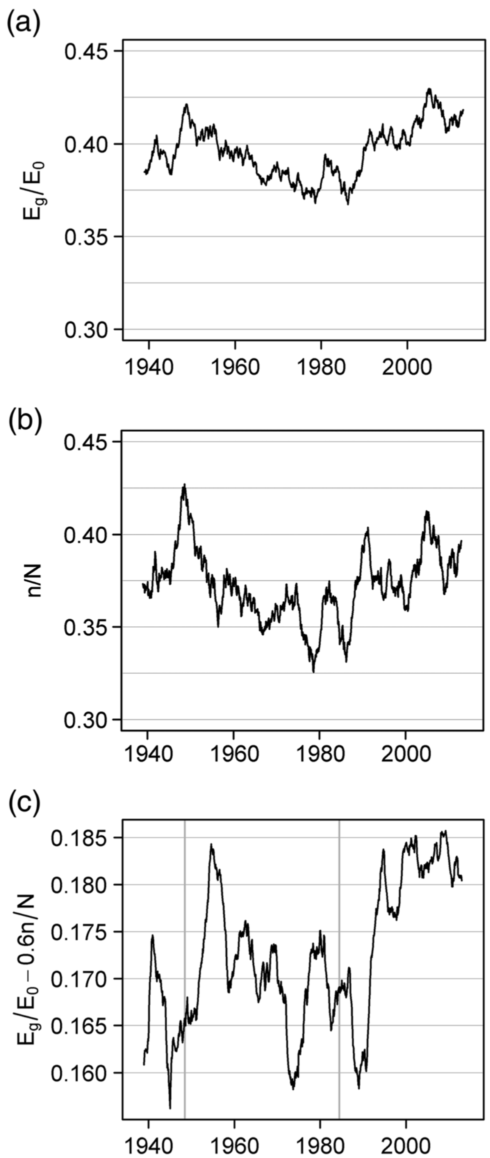

Figure 1. (a) Moving averages (48 month) of the normalized monthly values of solar radiation, (b) sunshine duration derived from the daily measurements of solar radiation and sunshine duration at the Potsdam meteorological station, and (c) the moving averages (48 month) of the difference between the two scaled normalized variables. The beginning and the end of the dimming period suggested by *Stanhill et al.* [2014] are shown by vertical reference lines.

mostly remained practically constant during the dimming and brightening periods in the presented results. The invariability was particularly remarkable for the Potsdam station.

The findings of *Stanhill et al.* [2014] would be relevant for the radiative forcing associated to aerosols and for the regional interpolation of global radiation data based on available measurements of sunshine duration. If the direct aerosol effect had been overestimated in the past, the same would be the case for the cooling effect of aerosols. And the lower cooling by aerosols would subsequently imply lower temperature sensitivity (i.e., lower warming) to the increase in greenhouse gases from preindustrial to current levels [*Otto et al.*, 2013, Table S2].

A downadjustment of current estimates of the temperature sensitivity (often more generally termed as climate sensitivity) to a doubling of preindustrial CO_2 would be one consequence. Besides those implications for the expected climate change, the invariability of the Angstrom-Prescott equation also means that changes in the past aerosol concentration could be largely neglected when interpolating global radiation records using sunshine duration as a covariable.

The current uncertainty about the questioned direct aerosol effect is acknowledged by the recent statement that the radiative forcing of aerosols is the largest current contributor to imprecisions in estimating climate sensitivity [*Intergovernmental Panel on Climate Change*, 2013, p. 662; *Lewis and Curry*, 2014].

In this study, we evaluate the conclusions drawn by *Stanhill et al.* [2014] using their original approach complemented by our further analysis. We focus on data from the Potsdam station, and we show a significant temporal structure in the residuals of the Angstrom-Prescott relationship for this station, which could be explained with the direct aerosol effect.

2. Material and Methods

2.1. Data

The monthly time series of sunshine duration and global radiation from the Potsdam meteorological station for the period 1937 to 2012 were used. The monthly averages are identical with those used by *Stanhill et al.* [2014].

The monthly values of E_0 and N were calculated on a daily basis and aggregated to monthly values. For that, the formulas suggested by *Allen et al.* [1998] and implemented in the R package "sirade" [*Bojanowski*, 2013] were used.

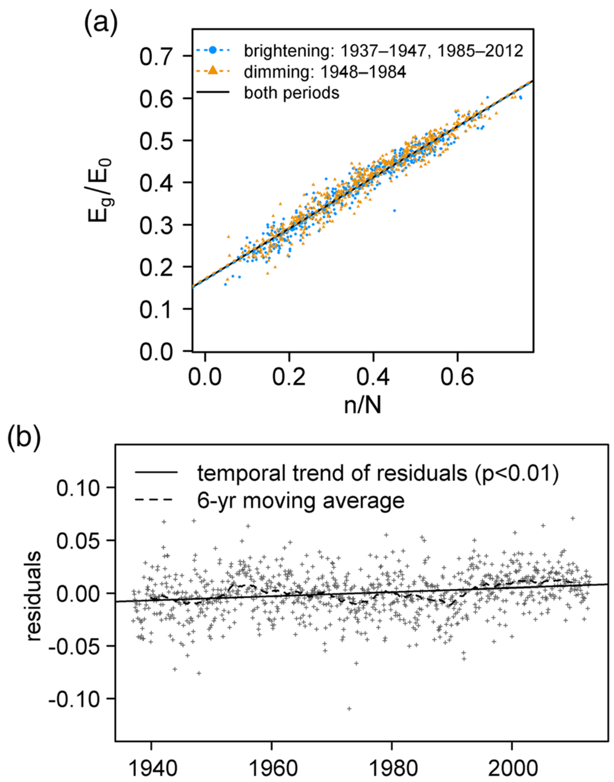

Figure 2. (a) The Angstrom-Prescott relationship between the normalized values of sunshine duration and global radiation derived from the monthly values of sunshine duration and global radiation at the Potsdam station and (b) the residuals of this regression plotted over time.

The data on regional fossil fuel combustion were taken from *Stanhill et al.* [2014], and data on lignite coal mining in eastern Germany were supplied by *Deutscher Braunkohlen-Industrie-Verein e.V.* [2014].

2.2. Statistical Analysis

The Angstrom-Prescott equation (1) was used as a basic model. Following the study of *Stanhill et al.* [2014], it was applied to the whole period of record, and the dimming and brightening phases were identified visually from the graphs. Complementing their analysis, we performed an analysis of residuals for the regression exploring the distribution of the residuals over time, first using the time constant regression parameters.

In the next step, we tested the phase invariability of these parameters. For that, the model with the time constant parameters was extended by the constant and interaction terms that allowed a variation of the slope and the intercept in subperiods. The modified form of the regression model is given below (2) for the two sequential subperiods T_1 and T_2 $t \in [T_1, T_2]$ as an example.

$$E_g/E_0 = a_0 n/N + \alpha a_1 n/N + b_0 + \alpha b_1, \quad \alpha = \left\{ \begin{array}{l} 1, t \in T_2 \\ 0, t \in T_1 \end{array} \right\} \tag{2}$$

The modified model (2) was tentatively extended with the purpose to check the potential finer temporal segmentation of the time series. The finer segmentation was deemed necessary as the residuals of the adjusted model (2) showed temporal trends (see below).

In addition, we used the regression tree technique [*Breiman et al.*, 1984] to identify phases of mean underestimations and overestimations of the normalized global radiation from the residuals of the regression having time constant parameters. The regression tree technique (or tree model) first splits the data into two groups by maximizing the differences between the groups. Then the process is repeated separately to each subgroup until either a minimum size is reached (6 years of data in our case), or until no further model improvement (explained variability) can be made. The resultant individual phases were then used to compare with the previously distinguished subperiods of dimming and brightening by *Stanhill et al.* [2014].

The software package R was used for all calculations. The ordinary least squares method implemented in the R procedure "lm" was applied to estimate the parameters of all linear regressions and of all factor effects. The R procedure "rpart" was used to estimate the tree model.

3. Results and Discussion

The observed time series of E_g/E_0 and n/N are depicted in Figures 1a and 1b, respectively. Both variables show the pattern also described by other authors [*Ohmura*, 2009; *Stanhill et al.*, 2014; *Wild et al.*, 2005, 2007, 2009]: a brightening period before 1950 is followed by a long period of decline of both variables

Table 1. Model Parameters of the Angstrom-Prescott Equation (1) for the Potsdam Meteorological Station Estimated Using Two Different Normalization Approaches for Global Radiation and Sunshine Duration[a]

Periods		Model	Slope, a	±CI	Intercept, b	±CI	R^2
All data 1937–2012	I	*Stanhill et al.* [2014]	0.60	0.01	0.17	0.01	0.95
	II	Equation (1) and *Allen et al.* [1998]	0.6065	0.009	0.169	0.004	0.95
B: 1937–1947, 1985–2012	I	*Stanhill et al.* [2014]	0.60	0.01	0.17	0.01	0.95
	II	Equation (1) and *Allen et al.* [1998]	0.605	0.01	0.17	0.005	0.94
D: 1948–1984	I	*Stanhill et al.* [2014]	0.60	0.01	0.17	0.00	0.95
	II	Equation (1) and *Allen et al.* [1998]	0.607	0.01	0.167	0.005	0.95

[a]CI indicates the 95% confidence interval for the parameter (slope, intercept) to the left.

until the late 1980s. After 1990, the normalized values of global radiation and sunshine duration return to the levels reached during the first brightening. The visual comparison of both data series already indicates differences in patterns that are confirmed by a plot of the differences $E_g/E_0 - an/N$ (Figure 1c). The difference between the normalized global radiation (E_g/E_0) and the normalized and scaled (an/N) sunshine duration shows a nonrandom pattern. This should not be the case when the dynamics of global radiation would be solely driven by changes in sunshine duration as suggested by *Stanhill et al*. [2014]. We will come to a similar conclusion when we will follow the regression approach introduced above and applied by *Stanhill et al*. [2014].

The parameters of the Angstrom-Prescott relationship were estimated across the full data set (1937–2012, Figure 2a) and also separately for the dimming (1948–1984) and brightening (1937–1947 and 1985–2012) periods (Table 1). The results can be compared with those from *Stanhill et al*. [2014]. The coefficients differ slightly from those reported previously, which might be due to differences in the calculation of E_0 and N. However, our coefficients show a similar invariability across subperiods related to the dimming and brightening, as in *Stanhill et al*. [2014].

However, a temporal analysis of the regression residuals for the regression using the full data set (Figure 2a) reveals a highly significant trend ($p \leq 0.01$) in the residuals (Figure 2b).

The original regression was expanded as explained above in order to test whether the slope and intercept estimates vary in subperiods (i.e., T_1, dimming: 1948–1984 and T_2, brightening: 1937–1947 and 1985–2012) for a model with stationary residuals free of temporal trend (equation (2)).

However, the expansion of the model to including two different slopes and different intercepts for the two subperiods did not result in significant terms, but the intercepts showed smaller p values. Following the general way of model simplification, we therefore removed the interaction term $\alpha a_1 n/N$ from equation (2), which led to three significant model parameters (a, b_0, α) and to the following equation:

$$E_g/E_0 = an/N + b_0 + \alpha b_1,$$
$$\alpha = \begin{Bmatrix} 1, t \leq 1947 \vee t \geq 1985 \\ 0, \text{else} \end{Bmatrix}. \quad (3)$$

The estimated parameter values of equation (3) are given in Table 2. Comparing Tables 1 and 2 with their parameterizations of equations (1) and (3) they indicate significant overestimations (b(equation (1)) $>$ b_0 (equation (3)))

Table 2. Model Parameters of the Extended Angstrom-Prescott Equation Allowing for the Variation of the Intercept Among Time Subperiods as Separated by Stanhill (Equation (3)) and by Tree Regression (Equation (4)) and Using the *Allen et al.* [1998] Approach for Normalization[a]

Periods	Model	Slope, a	±CI	Intercept	±CI	R^2
1948–1984	equation (3)	0.60593	0.0092	$b_0 = 0.16807$	0.0039	
1937–1947, 1985–2012	equation (3)			$b_1 = 0.00342$	0.002	0.95
01/1937–01/1947; 04/1971–08/1992	equation (4)	0.601	0.009	$b_0 = 0.16$	0.003	0.95
02/1947–03/1971	equation (4)			$b_1 = 0.0085$	0.003	
09/1992–12/2012	equation (4)			$b_2 = 0.017$	0.003	

[a]CI indicates the 95% confidence interval for the parameter (slope, intercept) to the left.

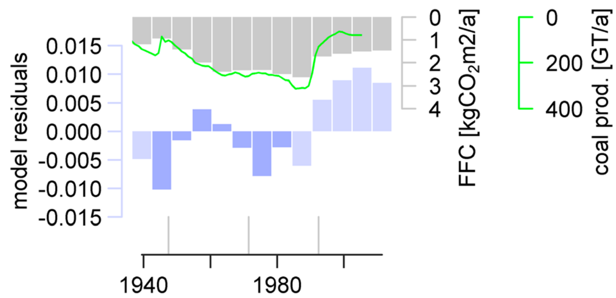

Figure 3. Model residuals of the Angstrom-Prescott relationship in Figure 2a (blue) plotted together with the fossil fuel combustion (FFC, gray) and the regional coal production from lignite mining (green line). The dark blue model residuals are for the dimming years, following the Stanhill classification. Our slightly alternative separation in subperiods is indicated by short vertical lines on the *x* axis.

during the dimming subperiod (1948–1984) and significant underestimations (b(equation (1)) $< b_0 + b_1$ (equation (3))) during the brightening subperiods (1937–1947 and 1985–2012) when predicting E_g/E_0 using equation (1) instead of equation (3).

Ideally, the modification of (1) by (3) would result in the model residuals without trend. However, the trend is now smaller, but it is still significant. As a consequence, we questioned the original segmentation into dimming and brightening subperiods based on the visual assessment and used the tree regression technique to identify different mean level segments within the residuals of equation (1). As a result, three different levels were identified I: 01/1937–01/1947 and 04/1971–08/1992, II: 02/1947–03/1971, and III: 09/1992–2012 (Figure 3).

The tree regression results were used for a slightly different time assignment of the dimming and brightening processes, which can be confirmed by a visual assessment of the original data. In comparison to the original structure used by *Stanhill et al*. [2014], the first brightening period (B1) would be similar, the former dimming period was subdivided in two subperiods (D1 and D2), and the final brightening period (B2) is starting later.

The regression model with specific slope and intercept variation terms (equation (2)) was applied to the data according to this period setting. Again, the slope variation among subperiods remained insignificant, and therefore, the according terms have not been taken into account in the final model:

$$E_g/E_0 = an/N + b_0 + \alpha b_1 + \beta b_{2,}$$
$$\alpha = \left\{ \begin{array}{c} 1, 02/1947 \leq t \leq 03/1971 \\ 0, \text{else} \end{array} \right\},$$
$$\beta = \left\{ \begin{array}{c} 1, t \geq 09/1992 \\ 0, \text{else} \end{array} \right\}. \tag{4}$$

In this case the residuals of regression (4) were free of a linear temporal trend.

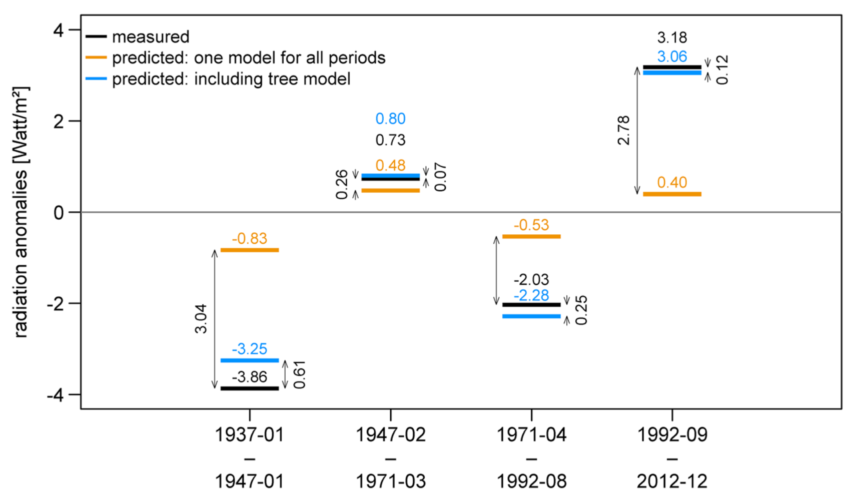

Figure 4. Mean anomalies of the measured global radiation values and the unnormalized estimations using the Angstrom-Prescott relationship without and with considering the residual pattern for the brightening and dimming periods identified using tree regression.

When comparing the sequential subperiods, significant level differences between the mean residuals can be observed. The intercept for B1 (b_0) is lower than that of D1 ($b_0 + b_1$) and that of D2 (b_0) is lower than that of B2 ($b_0 + b_2$) (Table 2).

Consequently, neglecting the direct aerosol effect leads to an overestimation of E_g/E_0 (b(equation (1)) $> b_0$ (equation (4))) in the pooled subperiods B1 and D2 by equation (1). In contrast, the normalized global radiation is underestimated by equation (1) during B2 (b(equation (1)) $< b_0 + b_2$(equation (4))) and almost unbiased only during D1 (parameters from Tables 1 and 2).

The consequences in simulated E_g when applying equations (1) and (4) to the full period are depicted in Figure 4. The estimations were compared to the observed global radiation. Figure 4 compares the estimated and measured anomalies from the full time mean. It clearly shows that the regression using the time constant parameters, which neglects the direct aerosol effect, is not able to reproduce the temporal pattern in global radiation at the Potsdam meteorological station. Nevertheless, the simulated pattern reflects changes in sunshine duration due to natural variability and possibly also to the indirect aerosol effect.

The changes in the optical properties of clouds seem to be negligible effects considering the same slope coefficients in equations (3) and (4) (Table 1), and there are always insignificant variations. Thus, the differences in anomalies between time subperiods as depicted in Figure 4 can be primarily interpreted as a quantification of the direct aerosol effect when we account for the time varying fluctuation in sunshine duration. The uncorrected difference (119.21–113.87 W/m^2) is 5.34 W/m^2 between the tree model estimations for the periods 09/1992–12/2012 and 04/1971–08/1992. If we correct for the fluctuations in sunshine duration between these two periods ($119.2 - 0.4 = 118.8$ W/m^2, $113.87 + 0.53 = 114.4$ W/m^2) a difference of 4.4 W/m^2 or 3.85% of the corrected first period mean and a change of 1.1 W/m^2 per decade remains. This relates to a mean daily change in transmissivity under clear-sky conditions by 0.0085 ($b_2 - b_1$, equation (4), Table 2).

The calculated effects are within the order of magnitude of other estimates for the direct aerosol effect during the recent brightening for this area [*Ohmura*, 2009; *Ruckstuhl et al.*, 2008]. The causal link between the changes in the aerosol load and dimming and brightening processes is confirmed again by comparing the temporal courses for the aerosol indicators, i.e., coal production and fossil fuel combustion, in Figure 3 and the mean level changes of the newly estimated global radiation in Figure 4. While the low global radiation level during 01/1937–01/1947 seems to be unrelated to the aerosol load the decrease between 02/1947–03/1971 and 04/1971–08/1992, and the increase afterward might be explainable according to increases and decreases in the load of aerosols.

4. Conclusion

The direct aerosol effect could still be revealed in the residuals of the Angstrom-Prescott relationship. At the first glance, the low temporal variability of parameters of the Angstrom-Prescott relationship when compared across periods of dimming and brightening seems to suggest the absence of a direct aerosol effect. However, we show for Potsdam that the temporal distribution of the residuals of the Angstrom-Prescott relationship is not only heterogeneous but also furthermore indicates level changes that are consistent with the current understanding of the direct aerosol effect.

A global analysis of dimming and brightening periods using the Angstrom-Prescott equation might benefit from a deeper analysis of the temporal patterns within the residuals as we have carried out for Potsdam. In this context, a specification of the visually undertaken segmentation of time series into dimming and brightening subperiods using statistical methods can be meaningful. Regional interpolations of global radiation using the Angstrom-Prescott equation should still account for the direct aerosol effect.

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